EEA Report | No 1/2017

Climate change, impacts and vulnerability in Europe 2016

An indicator-based report

ISSN 1977-8449

European Environment Agency

EEA Report | No 1/2017

Climate change, impacts and vulnerability in Europe 2016

An indicator-based report

European Environment Agency

Cover design: EEA
Cover photo: © JanJBrand/iStockphoto
Left photo: © CoisaX/iStockphoto
Right photo: © Alexander Schwarzl
Layout: EEA/Pia Schmidt

Luxembourg: Publications Office of the European Union, 2017

ISBN 978-92-9213-835-6
ISSN 1977-8449
doi:10.2800/534806

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Contents

Acknowledgements

Report coordination

Hans-Martin Füssel (European Environment Agency (EEA)) with the support of André Jol (EEA), Andreas Marx (European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC-CCA), Helmholtz Centre for Environmental Research (UFZ), Germany) and Mikael Hildén (ETC-CCA, Finnish Environment Institute (SYKE), Finland).

Authors and contributors by chapter or section

Executive summary

Authors:
André Jol, Hans-Martin Füssel (EEA).

Contributors:
Tobias Lung (EEA), Mikael Hildén (ETC-CCA, SYKE, Finland), Andreas Marx (ETC-CCA, UFZ, Germany).

Chapter 1: Introduction

Author:
Hans-Martin Füssel (EEA).

Contributors:
André Jol, Tobias Lung (EEA).

Chapter 2: Policy context

Author:
Stéphane Isoard (EEA).

Contributors:
André Jol, Sergio Castellari (EEA), Mikael Hildén (ETC-CCA, SYKE, Finland), Gilles Chomat, Marianna Elmi (Permanent Secretariat of the Alpine Convention), Matthias Jurek (United Nations Environment Programme (UNEP) Vienna — Secretariat of the Carpathian Convention (SCC)), Eleonora Musco (European Academy of Bozen/Bolzano (EURAC) Vienna Office and SCC), Krista Kampus (Permanent Secretariat of the Council of the Baltic Sea States), Lorenzo Galbiati (UNEP Mediterranean Action Plan Coordinating Unit).

Chapter 3: Changes in the climate system

Section 3.1: Human influence on the climate system

Author:
Blaz Kurnik (EEA).

Contributors:
Hans-Martin Füssel (EEA), Paul van der Linden (ETC-CCA, Met Office (UKMO), United Kingdom).

Section 3.2: Atmosphere

Author:
Blaz Kurnik (EEA).

Contributors:
Hans-Martin Füssel (EEA), Paul van der Linden (ETC-CCA, UKMO, United Kingdom), Adrian Simmons (European Centre for Medium-Range Weather Forecasts (ECMWF)).

Section 3.3: Cryosphere

Author:
Mikael Hildén (ETC-CCA, SYKE, Finland).

Contributor:
Stefan Fronzek (ETC-CCA, SYKE, Finland).

Chapter 4: Climate change impacts on environmental systems

Section 4.1: Oceans and marine environment

Author:
Johnny Reker (EEA).

Contributors:
Trine Christiansen, Hans-Martin Füssel (EEA), David Vaughan, Bryony Meakins (Joint Nature Conversation Committee, United Kingdom).

Section 4.2: Coastal zones

Author:
Hans-Martin Füssel (EEA).

Contributors:
Andrus Meiner (EEA), Matthew Palmer (ETC-CCA, UKMO, United Kingdom), Kristine Skovgaard Madsen (Danish Meteorological Institute, Denmark).

Section 4.3: Freshwater systems

Authors:
Wouter Vanneuville, Peter Kristensen (EEA).

Contributors:
Blaz Kurnik, Hans-Martin Füssel (EEA), Luc Feyen (Joint Research Centre (JRC)).

Section 4.4: Terrestrial ecosystems, soil and forests

Authors:
Andreas Marx (ETC-CCA, UFZ, Germany), Annemarie Bastrup-Birk, Geertrui Louwagie, Frank Wugt-Larsen (EEA).

Contributors:
Katarzyna Biala, Hans-Martin Füssel, Blaz Kurnik (EEA), Oliver Schweiger (ETC-CCA, UFZ, Germany), Josef Settele (UFZ, Germany), Kristijan Civic, Ben Delbaere (European Topic Centre on Biological Diversity (ETC-BD), European Centre for Nature Conservation, the Netherlands), Pasquale Borrelli, Arwyn Jones, Emanuele Lugato, Panos Panagos, José Barredo (JRC).

Section 4.5 Ecosystems and their services

Author:
Markus Erhard (EEA).

Contributor:
Hans-Martin Füssel (EEA).

Chapter 5: Climate change impacts on society

Section 5.1: Impacts of climate-related extremes

Authors:
Wouter Vanneuville (EEA), Jaroslav Mysiak (ETC-CCA, Euro-Mediterranean Centre on Climate Change (CMCC), Italy).

Contributors:
Hans-Martin Füssel, Blaz Kurnik (EEA).

Section 5.2: Human health

Authors (Sections 5.2.1–5.2.4):
Vladimir Kendrovski (World Health Organization (WHO) Regional Office for Europe).

Authors (Sections 5.2.5–5.2.6):
Jan C. Semenza, Jonathan E. Suk (European Centre for Disease Prevention and Control).

Section 5.3: Agriculture

Author:
Jørgen E. Olesen (ETC-CCA, Aarhus University, Denmark).

Contributors:
Stefan Niemeyer, Andrej Ceglar (JRC), Pier Paolo Roggero (Universita di Sassari, Italy), Heikki Lehtonen (Natural Resources Institute, Finland), Martin Schönhart (University of Natural Resources and Life Sciences, Austria), Richard Kipling (Aberystwyth University, Institute of Biological, Environmental and Rural Sciences, United Kingdom).

Section 5.4: Energy

Author:
Andrea Bigano (ETC-CCA, CMCC, Italy).

Contributors:
Jürgen Vogt, Jonathan Spinoni (JRC), Adriaan Perrels (Finnish Meteorological Institute (FMI), Finland), Douglas Crawford–Brown (Cambridge Centre for Climate Change Mitigation Research, United Kingdom), Juha Kiviluoma (Technical Research Centre of Finland (VTT), Finland).

Section 5.5: Transport

Author:
Angel Aparicio (ETC-CCA, Universidad Politécnica de Madrid, Spain).

Contributors:
Birgit Georgi (EEA), Markus Leitner (ETC-CCA, Environment Agency Austria (EAA), Austria).

Section 5.6: Tourism

Author:
Andrea Bigano (ETC-CCA, CMCC, Italy).

Contributors:
Hans-Martin Füssel (EEA), Adriaan Perrels (FMI, Finland), Franz Prettenthaler (Joanneum Research, Austria).

Chapter 6: Multi-sectoral vulnerability and risks

Section 6.1: Socio-economic scenarios for Europe

Author:
Tobias Lung (EEA).

Contributor:
Mikael Hildén (ETC-CCA, SYKE, Finland).

Section 6.2: Multi-sectoral impacts and vulnerabilities across Europe

Author:
Tobias Lung (EEA).

Contributor:
Mikael Hildén (ETC-CCA, SYKE, Finland).

Section 6.3: Projected economic impacts of climate change in Europe

Author:
Paul Watkiss (Paul Watkiss Associates, United Kingdom).

Contributors:
Stéphane Isoard (EEA), Karl Steininger (University of Graz, Austria).

Section 6.4: Europe's vulnerability to climate change impacts outside Europe

Author:
Tobias Lung (EEA).

Contributors:
Hans-Martin Füssel (EEA), Lisa Eichler (Trinomics Consulting, the Netherlands).

Section 6.5: Vulnerability to climate change in European macro-regions

Author:
Sergio Castellari (EEA).

Contributors:
Tobias Lung (EEA), Mikael Hildén (ETC-CCA, SYKE, Finland), Gilles Chomat, Marianna Elmi, Matthias Jurek (SCC), Wolfgang Lexer (EAA, Austria), Marcus Reckermann (International Baltic Earth Secretariat, Helmholtz-Zentrum Geesthacht (HZG), Germany), Sandor Szalai (Szent István University, Hungary), Henk Zingstra (Zingstra Water and Ecosystem Management, the Netherlands).

Section 6.6: Vulnerability to climate change in urban regions

Author:
Birgit Georgi (EEA).

Chapter 7: Strengthening the knowledge base

Author:
André Jol (EEA).

Chapter 8: Abbreviations and acronyms

Authors:
Markus Leitner (ETC-CCA, EAA, Austria), Hans-Martin Füssel (EEA).

Members of the Advisory Group

Jacques Delsalle (European Commission, DG Environment), Edit Konya (DG Agriculture and rural development), Peter Pärt (JRC), Maria-Elisabeth Pittman (DG Health and food safety), Frank Raes (JRC), Alfonso Gutierrez Teira (DG Climate action), Karin Zaunberger (DG Environment); Lars Bärring (Swedish Meteorological and Hydrological Institute, Sweden), Simon Duffield (Climate Change Group of the European Network of Heads of Nature Conservation Agencies, Natural England, United Kingdom), Marianna Elmi (Permanent Secretariat of the Alpine Convention), Paula Harrison (Environmental Change Institute, Oxford University, United Kingdom), Matthias Jurek (SCC), Erland Källén (ECMWF), Krista Kampus (Permanent Secretariat of the Council of the Baltic Sea States), Willem Ligtvoet (EPA Interest Group on Climate Change Adaptation, Netherlands Environmental Assessment Agency (PBL), the Netherlands), Johannes Luckenkötter (Dortmund University of Technology, Germany), Eleonora Musco (EURAC and SCC), Hugo Potti Manjavacas (Ministry of Agriculture, Food and Environment, Spain), Anil Markandya (EEA Scientific Committee, BC3 Basque Centre for Climate Change, Spain), Bettina Menne (WHO Regional Office for Europe), Maxi Nachtigall (Council of the Baltic Sea States Secretariat), Jouni Paavola (EEA Scientific Committee, University of Leeds, United Kingdom), José Ramón Picatoste Rueggero (Ministry of Agriculture, Food and Environment, Spain), Jan Plesnik (Agency for Nature Conservation and Landscape Protection, Czech Republic), Jean-Noël Thépaut (ECMWF), Petra van Rüth (Federal Environment Agency (UBA), Germany), Robert Vautard (Climate and Environment Sciences Laboratory (IPSL/LSCE), France).

Comments from the European Commission

Maaike Bouwmeester (Eurostat), Jelena Milos (DG Climate action).

Comments from National Reference Centres for Climate Change Impacts, Vulnerability and Adaptation

Corinna Baumgarten (UBA, Germany), Fatma Nur Cebecioglu (Ministry of Environment and Urbanization, Turkey), Götz Ellwanger (Federal Agency for Nature Conservation, Germany), Diren Ertekin (Ministry of Environment and Urbanization, Turkey), Martin Fowell (Department for Environment, Food and Rural Affairs (DEFRA), United Kingdom), Alice Gaustad (Norwegian Environment Agency, Norway), Francesca Giordano (Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Italy), Carla Gross (Federal Office for the Environment (FOEN), Switzerland), Clemens Hasse (UBA, Germany), Roland Hohmann (FOEN, Switzerland), Julien Hoyaux (L'Agence wallonne de l'air et du climat (AwAC), Belgium), Kathryn Humphrey (UK Adaptation Sub-Committee, United Kingdom), Irenee Joassard (Ministre de l'Environnement, de l'Énergie et de la Mer, France), Lenka Kubričanová (Ministry of Environment, Slovakia), Jana Paluchova (Ministry of the Environment, Czech Republic), Mr. José Ramón Picatoste Ruggeroni (Spanish Climate Change Bureau, Spain), Thomas Probst (FOEN, Switzerland), Wolfgang Rabitsch (EAA, Austria), Klaus Radunsky (EAA, Austria), Inke Schauser (UBA, Germany), Veysel Selimoğlu (Ministry of Environment and Urbanization, Turkey), Luciana Sinisi (ISPRA, Italy), Pavel Stastny (Slovak Hydrometeorological Institute, Slovak Republic), Mihaela Stefanescu (Ministry of Environment, Waters and Forests, Romania), Tanja Stein (UBA, Germany), Jelle van Minnen (PBL, the Netherlands), Hans Visser (PBL, the Netherlands), Rene Vukelić (International cooperation and projects, Croatia), Rosalind West (DEFRA, United Kingdom).

Comments from other expert reviewers

Bas Amelung (Wageningen University & Research Centre (WUR), the Netherlands), Celine Bellard (University College of London, United Kingdom), Floor Brouwer (WUR, the Netherlands), Rachel Burbridge (European Organisation for the Safety of Air Navigation), Tiago Capela Lourenço (University of Lisbon, Portugal), Guillem Chust (AZTI, Spain), Enrica De Cian (Fondazione Eni Enrico Mattei and CMCC, Italy), Samuel Doyle (Aberystwyth University, United Kingdom), Jan Eichner (Munich Re, Germany), Xavier Fettweiß (University of Liège, Belgium), Rene Forsberg (Technical University of Denmark, Denmark), Hayley Fowler (Newcastle University, United Kingdom), Silvio Gualdi (CMCC, Italy), Jacqueline Hamilton (University of Hamburg, Germany), Mike Harley (Climate Resilience, United Kingdom), Christophe Heyndrinckx (Transport & Mobility Leuven, Belgium), Daniela Jacob (Climate Service Center Germany, Germany), Richard Johnson (Swedish University of Agricultural Sciences, Sweden), Michael Kunz (Karlsruhe Institute of Technology (KIT), Germany), Kerstin Konitzer (Swedish Geotechnical Institute, Sweden), Rita Lecci (CMCC, Italy), Marcus Lindner (European Forest Institute), Mara Manente (University of Venice, Italy), Evangelos Mitsakis (Hellenic Institute of Transport, Greece), Marko Nokkala (VTT, Finland), Heinz Jürgen Punge (KIT, Germany), Valentina Radic (University of British Columbia, Canada), Monia Santini (CMCC, Italy), Rob Swart (WUR, the Netherlands), Pierre-Yves Le Traon (Institut français de recherche pour l'exploitation de la mer, France), Emma Woods (the Royal Society, United Kingdom).

Executive summary

Key messages

- **All of the key findings from the 2012 European Environment Agency (EEA) report on climate change, impacts and vulnerability in Europe are still valid.**
- **Climate change is continuing globally and in Europe**. Land and sea temperatures are increasing; precipitation patterns are changing, generally making wet regions in Europe wetter, particularly in winter, and dry regions drier, particularly in summer; sea ice extent, glacier volume and snow cover are decreasing; sea levels are rising; and climate-related extremes such as heat waves, heavy precipitation and droughts are increasing in frequency and intensity in many regions.
- **New record levels of some climatic variables have been established in recent years**, notably global and European temperature in 2014 and again in 2015, global sea level in 2015 and winter Arctic sea ice extent in 2016. Some climatic changes have accelerated in recent decades, such as global sea level rise and the decline of the polar ice sheets.
- **Global climate change has substantially increased the probability of various recent extreme weather and climate events in Europe**. The reliability of this finding has been strengthened by recent progress in extreme weather attribution techniques.
- **The observed changes in climate are already having wide-ranging impacts on ecosystems, economic sectors and human health and well-being in Europe**. Recent studies show that various observed changes in the environment and society, such as changes in forest species, the establishment of invasive alien species and disease outbreaks, have been caused or enhanced by global climate change.
- **Ecosystems and protected areas are under pressure from climate change and other stressors, such as land use change. The observed impacts of climate change are a threat to biodiversity in Europe, but they also affect forestry, fishery, agriculture and human health**. In response to climate change, many land-based animal and plant species are changing their life cycles and are migrating northwards and to higher altitudes; regional extinctions have been observed; various invasive alien species have established themselves or have expanded their range; and various marine species, including commercially important fish stocks, are migrating northwards.
- **Most impacts of climate change across Europe have been adverse, although some impacts have been beneficial**. The rise in sea level has increased flood risks and contributed to erosion along European coasts. The observed increase in heat waves has had significant effects on human health, in particular in cities. Heat waves are also increasing the risk of electricity blackouts and forest fires. Transport and tourism have also been affected by climate change, with large regional differences. Examples of beneficial impacts of climate change include a decrease in heating demand and some benefits to agriculture in northern Europe.
- **Climate change will continue for many decades to come, having further impacts on ecosystems and society**. Improved climate projections provide further evidence that future climate change will increase climate-related extremes (e.g. heat waves, heavy precipitation, droughts, top wind speeds and storm surges) in many European regions.
- **The magnitude of future climate change and its impacts from the middle of the century onwards depend on the effectiveness of global climate mitigation efforts**. The magnitude of climate change and its impacts can be substantially reduced by an ambitious global mitigation policy compatible with the mitigation goal of the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels.

Key messages (cont.)

- **Future climate change will interact with other socio-economic developments**, including the ageing of the population and increasing urbanisation across Europe, projected decreases in population size in eastern Europe, and a narrowing economic gap between eastern and western parts of Europe. **The water sector, agriculture, forestry and biodiversity show strong interdependencies**, and are also related to changing land-use patterns and population change.
- **Climate change is affecting all regions in Europe, but the impacts are not uniform**. South-eastern and southern Europe are projected to be hotspot regions, having the highest numbers of severely affected sectors and domains. Coastal areas and floodplains in the western parts of Europe are also multi-sectoral hotspots. The Alps and the Iberian Peninsula are additional hotspots for ecosystems and their services. Ecosystems and human activities in the Arctic will be strongly affected owing to the particularly fast increase in air and sea temperatures and the associated melting of land and sea ice.
- **Economic costs can potentially be high, even for modest levels of climate change**, and these costs rise significantly for scenarios of greater levels of warming. The projected damage costs from climate change are **highest in southern Europe**. However, estimates of the projected economic impacts of climate change in Europe consider only some sectors and show considerable uncertainty.
- **Europe is vulnerable to climate change impacts outside Europe** through six major pathways: the trade of agricultural commodities, the trade of non-agricultural commodities, infrastructure and transport, geopolitics and security risks, human mobility related to migration and finance. The strongest evidence for Europe's vulnerability to cross--border impacts are the economic effects seen as a result of climate-related global price volatilities and disruptions to transportation networks. The Mediterranean area is most vulnerable to shocks in the flow of agricultural commodities, while small, open and highly developed European economies are particularly vulnerable to shocks in the flow of non-agricultural commodities. **European vulnerability to cross-border effects is expected to increase** in the coming decades, but quantitative projections are not available.
- **Climate change adaptation strategies, policies and actions, including the mainstreaming of them into other policies, are progressing at all governance levels** (European Union (EU), transnational, national and local levels). Further actions could include enhancing policy coherence across EU environmental and sectoral policies; effective and efficient action across all levels of governance, through multi-level governance and transnational cooperation platforms; enhancing flexible 'adaptive management' approaches; combining technological solutions, ecosystem-based approaches and 'soft' measures; involving the private sector; and more emphasis on 'transformational' adaptation actions as a complement to 'incremental' adaptation.
- **The knowledge base regarding climate change impacts, vulnerability, risk and adaptation assessments in Europe could be enhanced**, e.g. through improved monitoring and reporting of climate-related extremes and the associated damage, enhanced national and sectoral assessments and their reporting, and further monitoring, reporting and evaluation of adaptation actions at the national level. More knowledge would also be useful on the costs and benefits of adaptation options and on interdependencies, synergies and trade-offs between adaptation policies and other policies and actions. The use of European, transnational and national climate change and adaptation services by stakeholders could be further improved. The European Commission's 'adaptation preparedness scoreboard', which assesses the progress of Member States using process-based indicators (and is due to be published in 2017 as part of its report on the EU Adaptation Strategy), could be complemented by quantitative information. The indicators of the Sendai Framework for Disaster Risk Reduction (which are to be agreed by the end of 2016) for weather- and climate-related hazards are expected to be relevant for climate change adaptation. EU-funded and national research can address adaptation knowledge gaps and stimulate innovation.

ES.1 Introduction

The climate is changing globally and in Europe. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) concluded that the warming since the mid-20th century has predominantly been due to greenhouse gas emissions from human activities, in particular the combustion of fossil fuels, agriculture and other changes in land use.

There is a need to reduce global greenhouse gas emissions substantially to avoid the most adverse impacts of climate change. However, even with substantial reductions in greenhouse gas emissions, the climate will continue to change, and the impacts will be felt across the world, including in Europe. Climate change is having a variety of impacts on our health, ecosystems and economy, often in interaction with other factors such as land-use changes. These impacts are likely to become more severe in the coming decades. If not addressed, these impacts could prove very costly, in terms of ill health, adverse effects on ecosystems and damaged property and infrastructure, and some impacts may be irreversible. As mitigation cannot prevent all of the impacts of climate change, there is also a need to adapt to our changing climate.

This report presents a largely indicator-based assessment of past and projected climate change, impacts and the associated vulnerabilities of and risks to ecosystems, human health and society in Europe, based on a wide range of observations and model simulations. It identifies regions that are experiencing particularly severe climate change impacts. The report also shows how Europe is vulnerable to climate change impacts outside Europe. The principal sources of uncertainty for the indicators and modelling results are discussed and, where appropriate, reflected in the assessments and key messages of all indicators.

The report summarises key adaptation policy developments at European, transnational and national levels and highlights the need for further adaptation actions. Furthermore, the report notes how monitoring, information sharing and research can improve the knowledge base for adaptation.

This report is part of a series of European Environment Agency (EEA) reports, prepared in collaboration with other organisations, and to date has been published at four-year intervals. Publishing this report at this frequency serves the policy need for a regular comprehensive European-wide assessment and allows new scientific knowledge accumulated over that period to be included. In particular, the report aims to support the implementation and review process of the 2013 European Union (EU) Adaptation Strategy (EC, 2013) foreseen for 2018.

This report compiles information from a wide variety of data and information sources. It builds on, among others, the IPCC Fifth Assessment Report, but a substantial amount of information that became available afterwards has also been included. Major new information that has become available since the 2012 EEA report on climate change, impacts and vulnerability in Europe (EEA, 2012) is highlighted in this summary.

The indicators included in this report are based on many different information sources. As a result, they cover different past and future time periods, and information is presented at different levels of regional aggregation.

ES.2 Policy context

Adaptation policies aimed at limiting the adverse impacts of climate change interact with many other policies, such as broader environmental, climate change mitigation and disaster risk reduction policies. This section gives an overview of relevant policies at different governance levels.

Global policies

In December 2015, the member countries of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement, which includes the long-term goals of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels and of pursuing efforts to limit the increase to 1.5 °C above pre-industrial levels, since this would significantly reduce risks and the impacts of climate change (UNFCCC, 2015). Countries also agreed on the need for global emissions to peak as soon as possible, recognising that this will take longer for developing countries, and the need to undertake rapid reductions thereafter in accordance with the best available science. However, the combined emissions reduction foreseen under currently available national climate action plans is not enough to keep global warming below 2 °C; in fact the current plans may lead to an increase of 3 °C or more (UNEP, 2015). Subsequent meetings of the UNFCCC aim to address this gap.

Within the Paris Agreement, countries also established an adaptation goal of 'enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change', and an aim to strengthen societies' ability to deal with the impacts of climate change, to engage in national adaptation planning processes and to provide continued and enhanced international support for adaptation to developing countries.

Climate change action has increasingly become an integrated part of economic analyses and a prominent element of risk assessments by public and private bodies. For example, the most recent Global Risks Report of the World Economic Forum (WEF, 2016) indicates that the most impactful risk (i.e. the risk with the greatest potential damage) for the years to come is a failure in climate change mitigation and adaptation.

In 2015, the Sendai Framework for Disaster Risk Reduction was adopted (UN, 2015a). It is a voluntary agreement that includes four priorities for action: understanding disaster risk, strengthening disaster risk governance to manage disaster risk, investing in disaster risk reduction for resilience and enhancing disaster preparedness. The framework acknowledges climate change as one of the drivers of disaster risk. An important element is alignment with the other post-2015 international agendas on climate change (UNFCCC, 2015) and on sustainable development (UN, 2015b). The 2030 agenda for sustainable development has 17 overarching sustainable development goals and within each is a range of targets, and the challenges to address the effects of climate change are explicitly acknowledged.

EU 7th Environment Action Programme

In the 7th Environment Action Programme (EAP), 'Living well, within the limits of our planet' (EU, 2013b), the EU formulates a vision of the future up to 2050: a low-carbon society, a green, circular economy and resilient ecosystems as the basis for citizens' well-being. Achieving this 2050 vision requires a focus on actions in three key areas:

- protecting the natural capital that supports economic prosperity and human well-being;
- stimulating resource-efficient, low-carbon economic and social development; and
- safeguarding people from environmental health risks.

The 7th EAP mentions explicitly that action to mitigate and adapt to climate change will increase the resilience of the EU's economy and society, while stimulating innovation and protecting the EU's natural resources.

According to the EEA report *The European environment — state and outlook 2015* (SOER 2015), the implementation of environment and climate policies during the last 40 years has delivered substantial benefits for the functioning of Europe's ecosystems and for the health and living standards of its citizens (EEA, 2015b). Reduced pollution, nature protection and better waste management have all contributed to this. However, the SOER 2015 also highlights that substantial challenges remain in each of the above-mentioned three areas.

Europe's natural capital is not yet being protected, conserved or enhanced sufficiently. The loss of soil functions, land degradation and climate change remain major concerns. Europe is not on track to meet its overall target of halting biodiversity loss by 2020. Looking ahead, climate change impacts are projected to intensify, and the underlying drivers of biodiversity loss are expected to persist.

Regarding resource efficiency and the low-carbon society, EU greenhouse gas emissions have decreased since 1990, despite an increase in economic output. Other environmental pressures have also been decoupled in absolute terms from economic growth. Fossil fuel use has declined, as have emissions of some pollutants from transport and industry. However, the greenhouse gas emissions reductions projected under current policies are insufficient to bring the EU onto a pathway in line with its 2050 target.

Environment and climate change issues are characterised by many systemic factors, including feedbacks, interdependencies and lock-ins in environmental and socio-economic systems; unsustainable systems of production and consumption; and increasingly globalised environmental drivers, trends and impacts. Relevant global megatrends include diverging global population trends; a change towards a more urban world; changing disease burdens and risks of pandemics; accelerating technological change; decreasing economic growth; an increasingly multi-polar world; intensified global competition for resources; increasing environmental pollution; diversifying approaches to governance; and increasingly severe consequences of climate change (SOER 2015: EEA, 2015c).

Transforming key systems such as the transport, energy, housing and food systems will be needed to achieve the 7th EAP vision for 2050.

Climate change impacts may hamper the achievement of the 2050 vision for Europe set out in the 7th EAP and, on a global level, the realisation of the sustainable development goals. Therefore, climate change and its impacts should be assessed in conjunction with the above-mentioned factors.

EU climate policy

EU climate change mitigation policy aims to put the EU on track towards a low-carbon economy and to reduce EU greenhouse gas emissions by 80 to 95 % by 2050. The EU is on track towards its 2020 climate targets (EEA, 2015d), but to achieve the longer term goals of the EU for 2030 and 2050 new policies and a more fundamental change are needed in the way the EU produces and uses energy, goods and services.

The 7th EAP calls for decisive progress to be made in adapting to climate change to make Europe more climate-resilient. In 2013, the European Commission adopted the communication 'An EU Strategy on adaptation to climate change' (EC, 2013), which encourages all Member States to adopt comprehensive adaptation strategies; promotes action in cities (through the Covenant of Mayors for Climate and Energy); aims to mainstream adaptation into relevant EU policies and programmes; provides funding for adaptation actions; and enhances research and information sharing (e.g. through the European climate adaptation platform Climate-ADAPT). In 2018, the Commission will present the evaluation of the EU Strategy and will propose a review, if needed. The report will assess the progress made by Member States, including an adaptation preparedness scoreboard, the progress in mainstreaming at the EU level, and new knowledge and policy demands.

The European Multiannual Financial Framework (2014–2020) includes the objective that a minimum of 20 % of the EU budget contributes to climate-related expenditure (including adaptation). Initial analysis shows that this objective will be achieved, but its effectiveness in terms of enhanced resilience and reduced greenhouse gas emissions is yet to be evaluated.

Mainstreaming requires that climate change adaptation is taken into account in implementing EU policies and legislation. Mainstreaming has been increasingly covered in guidance documents and legal texts since 2013. Examples include the EU's Civil Protection legislation (EU, 2013a), which aims to develop a more resilient European society. Since 2015, Member States have had to report on their risk assessments and risk management capabilities, including climate- and weather-related risks, to the European Commission every three years. An analysis of this information by the Commission is expected by the end of 2016. Guidance under the Water Framework Directive required Member States to present river basin management plans by December 2015, and guidance under the Floods Directive required Member States to establish flood risk management plans and to report these by March 2016. The extent to which climate change adaptation was taken into account in these plans has not yet been assessed. Other key EU policies in which adaptation mainstreaming has taken place, to varying degrees, include the EU Biodiversity Strategy, the Marine Strategy Framework Directive, the Habitats Directive, the Birds Directive, the nature protection network Natura2000, the invasive species regulation and regulations addressing environmental sectors such as agriculture and forestry.

A recent review of the EU biodiversity policy in the context of climate change has identified a number of policy gaps: conservation targets need to better match conservation needs; targets need to be set in a spatially coherent manner across national scales; and current monitoring appears insufficient to address these gaps.

National and transnational adaptation policies in Europe

There has been a steady increase over the last five years in national adaptation strategies and plans. By September 2016, 23 EEA member countries (of which 20 are EU Member States) had adopted a national adaptation strategy and 12 (of which nine are Member States) had developed a national adaptation plan. Most progress regarding action plans has been reported for freshwater management, flood risk management, agriculture and forestry, with a focus on mainstreaming adaptation in these national sectoral policy areas. Several countries have also developed national health strategies and action plans. Only a few EEA member countries have started to monitor and report on their progress in adaptation strategies, policies and actions at the national level, and even fewer have started an evaluation of their effectiveness (EEA, 2015a).

Transnational cooperation (e.g. on strategies and on knowledge sharing) in adaptation to climate change has increased, with the importance of adaptation as a cross-cutting policy area being recognised. Adaptation actions take place, for example, within the EU strategies for the Baltic Sea region and the Alpine region, the Danube and Rhine Commissions, the Carpathian and Alpine conventions, the Working Community of the Pyrenees and the Mediterranean Action Plan/ Barcelona Convention. Transnational adaptation action is often linked to the sharing of natural resources, such as transboundary water catchments or terrestrial ecosystems.

ES.3 Climate change and its impacts

This section gives an overview of the observed and projected changes in the climate system and in climate-sensitive environmental systems and social domains. The degree of certainty related to specific observations and projections and the importance of non-climatic factors differ substantially across domains and indicators. More detailed quantitative information, including a discussion of relevant uncertainties, is available in the main part of this report.

Climate system

The average concentration of CO_2 in the atmosphere in 2016 reached 400 parts per million (ppm), which is about 40 % higher than the pre-industrial level.

The global average annual near-surface temperature in the decade 2006–2015 was 0.83 to 0.89 °C higher than the pre-industrial average (mid- to the end of the 19th century). Globally, 2015 was the warmest year on record, namely about 1 °C warmer than the pre-industrial temperature. The IPCC Fifth Assessment Report concluded that 'It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century' (IPCC, 2013).

For most emissions scenarios, global average temperature is projected to exceed 2 °C above pre-industrial levels (the upper limit according to the Paris Agreement under the UNFCCC) by 2050. Even if anthropogenic greenhouse gas emissions were to fall to zero in the very near future, the climate would continue to change for many decades, and sea level would continue to rise for many centuries.

European land temperatures in the decade 2006–2015 were around 1.5 °C warmer than the pre-industrial level, and they are projected to continue increasing by more than the global average temperature increase. Europe has experienced several extreme summer heat waves since 2003, which have led to high mortality and economic impacts. Heat waves of a similar or larger magnitude are projected to occur as often as every two years in the second half of the 21st century under a high emissions scenario. The impacts will be particularly strong in southern Europe.

Precipitation has increased in most of northern Europe, in particular in winter, and has decreased in most of southern Europe, in particular in summer. The projected changes in precipitation show the same pattern of regional and seasonal changes. Heavy precipitation events have increased in several regions in Europe over recent decades, in particular in northern and north-eastern Europe. Heavy precipitation events are projected to become more frequent in most parts of Europe, in particular in winter.

Recent progress in the attribution of extreme weather to specific causes has facilitated many studies, which showed that the probability of occurrence of various recent heat waves and other damaging extreme weather and climate events in Europe has substantially increased as a consequence of anthropogenic climate change.

Observations of wind storm location, frequency and intensity show considerable variability. Most studies agree that the risk of severe winter storms, and possibly of severe autumn storms, will increase in the future for the North Atlantic and northern, north-western and central Europe.

The number of hail events is highest in mountainous areas and the pre-Alpine regions. Despite improvements in data availability, trends and projections of hail events are still uncertain.

Observations show a shrinking and thinning of Arctic sea ice, a decrease of snow cover, a shrinking of glaciers and increased melting of the large polar ice sheets in Greenland and Antarctica. It is estimated that the melting of the polar ice sheets will contribute up to 50 cm to global sea level rise during the 21st century.

The nine lowest Arctic sea ice minima since records began in 1979 have been the September ice cover in each of the last nine years (2007–2015), and the annual maximum ice cover in March 2015 and March 2016 were the lowest on record. The ice is also getting thinner. For high emissions scenarios, a nearly ice-free Arctic Ocean in September is likely before the middle of the 21st century, but there will still be substantial ice in winter.

The vast majority of glaciers in the European glacial regions are in retreat. Glaciers in the European Alps have lost approximately half of their volume since 1900, with clear acceleration since the 1980s. Glacier retreat affects freshwater supply and run-off regimes, river navigation, irrigation and power generation and may lead to natural hazards and damage to infrastructure.

Snow cover extent in the northern hemisphere has declined significantly since the 1920s, with most of the reductions occurring since 1980.

Further reductions of the cryosphere are projected for the future. The melting of ice and snow and the thawing of permafrost soil cause positive feedbacks that can accelerate climate change further.

Ecosystems and their services

Ecosystems globally and in Europe are under five major pressures (Millennium Ecosystem Assessment, 2005; EEA, 2016a): habitat change (e.g. land and sea take, urban sprawl, fragmentation and land abandonment);

dispersal of invasive alien species; exploitation and management (e.g. land-use change and intensification, unsustainable agriculture and forestry, natural resource consumption); pollution and nutrient enrichment (e.g. atmospheric deposition, fertiliser and pesticide use, irrigation and acidification) and climate change.

Climate change significantly affects ecosystems, their biodiversity and consequently their capacity to provide services for human well-being; it may already have triggered shifts in ecological regimes from one state to another. Climate change also increasingly exacerbates the impact of other human stressors, especially in natural and semi-natural ecosystems.

The knowledge about the combined effects of climate change and other pressures on ecosystems and their capacity to provide services is improving. The relative importance of climate change as a major driver of biodiversity and ecosystem change is projected to increase further in the future, depending on the environmental domain (terrestrial, freshwater or marine) and geographical region.

Oceans, the marine environment and coastal zones

Key observed changes in the ocean are acidification, increased ocean heat content and increased sea surface temperature, and sea level rise. Changes in temperature cause significant shifts in the distribution of marine species towards the poles, but also in depth distribution. For example, a major northwards expansion of warmer water plankton in the North-east Atlantic and a northwards retreat of colder water plankton have been observed, which seems to have accelerated since 2000. Sub-tropical species are occurring with increasing frequency in Europe's seas, and sub-Arctic species are moving northwards. Wild fish stocks are changing their distribution, which can have impacts on local communities that depend on those fish stocks.

Oxygen-depleted zones in the Baltic Sea and in other European seas have substantially increased. The primary cause of oxygen depletion is nutrient input from agricultural fertilisers, but the effects are exacerbated by climate change.

Further changes in the distribution of marine species, including fish stocks, are expected with the further climate change projected. These impacts, in combination with other anthropogenic stressors, in particular overfishing, are projected to cause widespread changes to marine ecosystems and their services.

Mean and extreme sea level have increased globally and along most coasts in Europe. Evidence for an acceleration in the rate of global mean sea level rise during recent decades has increased. The IPCC Fifth Assessment Report has projected that global mean sea level in the 21st century will rise by 26–81 cm, depending on the emissions scenario, and assuming that the Antarctic ice sheet remains stable. Several recent model-based studies and expert assessments have suggested an upper bound (with a probability of 5 % of being exceeded) for global mean sea level rise in the 21st century in the range of 1.5–2.0 m. Sea level will continue to rise for many centuries, even if greenhouse gas emissions and temperature are stabilised.

The projected increases in extreme high coastal water levels are primarily the result of increases in local relative mean sea level, but increases in storm activity can also play a substantial role, in particular along the northern European coastline.

The projected sea level rise, possible changes in the frequency and intensity of storm surges, and the resulting coastal erosion are expected to cause significant ecological damage, economic loss and other societal problems for low-lying coastal areas across Europe unless additional adaptation measures are implemented.

Freshwater systems

River flows have generally increased in winter and decreased in summer, but with substantial regional and seasonal variation. Climate change is an important factor in this, but other factors, such as water abstractions, man-made reservoirs and land-use changes, also have a strong influence. Summer flows are projected to decrease in most of Europe. Where precipitation changes from snow to rain, spring and summer peak river flow will shift to earlier in the season.

The detection of a clear trend in the number and intensity of floods in Europe is impeded by the lack of a consistent dataset for Europe. Reporting under the EU Floods Directive has so far improved this situation to only a limited extent. The reported number of very severe flood events has increased over recent decades, but with large interannual variability. It is not currently possible to quantify the contribution from observed increases in heavy precipitation in parts of Europe compared with the contribution from land-use changes and better reporting.

Without further action, climate change is projected to increase the magnitude and frequency of flood events in large parts of Europe. Pluvial floods and flash floods, which are triggered by intense local precipitation events, are likely to become more frequent throughout Europe. In regions with a projected reduced snow accumulation during winter, the risk of spring flooding could decrease.

The severity and frequency of droughts appear to have increased in parts of Europe, in particular in southern Europe and south-eastern Europe. Droughts are projected to increase in frequency, duration and severity in most of Europe. The strongest increase is projected for southern Europe, where competition between different water users, such as agriculture, industry, tourism and households, is likely to increase.

Climate change has increased the water temperature of rivers and lakes and has shortened seasonal ice cover. These trends are projected to continue.

Changes in river flows and increases in water temperature have important impacts on freshwater ecosystems, such as changes in phenology and in species distribution, the facilitation of species invasions and the deterioration of water quality, for example through enhanced algal blooms. They can also have an impact on energy production by reducing the availability of cooling water and by affecting hydropower potential.

Terrestrial ecosystems, soils and forests

Impacts of observed and projected climate change include changes in soil conditions, phenology, species distribution, species interactions, species composition in communities and genetic variability. Changes in soil moisture, such as significant decreases in the Mediterranean region and increases in parts of northern Europe, are having a direct effect on terrestrial ecosystems.

Earlier spring advancement is observed in many plant species, and the pollen season starts earlier and is longer. Many animal groups have advanced their life cycles, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies. The breeding season of many thermophilic insects has lengthened. These trends are expected to continue in the future.

Many species have changed their distribution range, generally northwards and uphill, and these trends are projected to continue. Species migration often lags behind changes in climate owing to intrinsic limitations, habitat use and fragmentation. Some local extinctions of species have been observed. All of these factors may contribute to a decline in European biodiversity, in particular in mountain regions. Climate change is likely to exacerbate the problem of invasive species, as some locations may become more favourable to previously harmless alien species. Climate change is also affecting the interaction of species that depend on each other. It can thus disrupt established interactions, but it can also generate novel ones.

14 % of habitats and 13 % of species of European interest have already been assessed to be under pressure because of climate change. The proportion of habitats threatened by climate change is projected to more than double in the near future. Many species in the Natura2000 network are projected to lose suitable climate niches.

Climate change and increasing CO_2 concentrations are affecting forest ecosystems and their services, as they are causing range shifts of tree species towards higher altitudes and latitudes, are leading to increases in the risk of forest fires, in particular in southern Europe, and are resulting in an increased incidence of forest insect pests. Cold-adapted coniferous tree species are projected to lose large fractions of their ranges to broadleaf species. In general, forest growth is projected to increase in northern Europe and to decrease in southern Europe, but with substantial regional variation.

Economic losses from extreme climate-related events

Climate-related extreme events accounted for almost EUR 400 billion of economic losses in the EEA member countries over the period 1980–2013. This accounts for 82 % of the total reported losses due to extreme events over this period, whereas geophysical events such as earthquakes and volcano eruptions are responsible for the remaining 18 %. The reported economic losses have increased in recent decades. This increase is due primarily to better reporting and to socio-economic trends, such as changes in population, human activities and infrastructure in hazard-prone areas, but the observed increase in heavy precipitation in parts of Europe may have also played a role. Future climate change will affect the frequency and intensity of climate-related extremes and associated losses differently across Europe, but most climate-related hazards are projected to increase across Europe.

The attribution of the observed changes in the number of events and the associated economic losses to specific causes is hampered by large interannual variability of climate-related extreme events, changes in reporting and the implementation of measures to reduce impacts (e.g. flood defences). Policies and actions would be facilitated by better collection of data concerning the economic, social and environmental impacts of weather and climate-related extremes.

Human health

The main health effects of climate change are related to extreme weather events, such as floods and heat waves, changes in the distribution of climate-sensitive diseases and changes in environmental and social conditions.

River and coastal flooding has affected millions of people in Europe in the last decade. Health effects include drowning, injuries, infections, exposure to chemical hazards and mental health consequences.

Heat waves have caused tens of thousands of premature deaths in Europe since 2000. Since the length, frequency and intensity of heat waves are projected to increase substantially in the future, the associated health effects are also projected to increase in the absence of adaptation and physiological acclimatisation. Cold-related mortality is projected to decrease owing to better social, economic and housing conditions in many countries in Europe. The observed relationship between moderate and extreme cold and mortality is complex, and available studies for Europe provide inconclusive evidence of whether or not the projected warming will lead to a further substantial decrease in cold-related mortality.

Observations show a move to higher latitudes and altitudes of specific tick species and their associated vector-borne diseases (Lyme borreliosis and tick-borne encephalitis). Climate change is projected to lead to further northwards and upwards shifts of tick species. Climate change was, and is projected to be, a factor in the recent expansion of the Asian tiger mosquito and a sandfly species in Europe, which can disseminate several diseases (dengue and chikungunya by the Asian tiger mosquito and leishmaniasis by the sandfly species).

Recent outbreaks of vibriosis infections in Baltic Sea states have been linked to unprecedented increases in sea surface temperature.

Quantitative projections of future climate-sensitive health risks are difficult owing to the complex relationship between climatic and non-climatic factors, climate-sensitive diseases and other health outcomes, and future adaptation measures.

Agriculture

An increase in the duration of the thermal growing season has led to a northwards expansion of areas suitable for several crops. Changes in crop phenology have been observed, such as the advancement of flowering and harvest dates in cereals.

Recent heat waves, droughts, extreme precipitation and hail have greatly reduced the yield of some crops. Throughout Europe, an increased frequency of extreme events is expected to increase the risk of crop losses and to impose risks for livestock production.

Irrigation demand is projected to increase, in particular in southern Europe, where there is already considerable competition between different water users.

Climate change is projected to improve the suitability of northern Europe for growing crops and to reduce crop productivity in large parts of southern Europe. Projections based on different climate models agree on the direction of the change, but with some variation in its magnitude. Furthermore, effects will differ between crop types and livestock categories, and they are moderated by short- and long-term adaptation efforts.

Energy and transport

The energy demand for heating has decreased in northern and north-western Europe, whereas the demand for cooling has increased in southern and central Europe. The total energy demand in Europe is not expected to change substantially, but significant seasonal shifts and effects on the energy mix are expected, with large regional differences.

Increasing temperatures, changing precipitation patterns, increases in extreme precipitation and possible increases in storm severity and frequency can have an impact on both renewable and conventional electricity energy generators. Most of the projected impacts of climate change will be adverse. For example, further increases in temperature and droughts may limit the availability of cooling water for thermal power generation in summer. However, climate change may have some positive impacts, in particular related to hydropower production in northern Europe.

Energy and transport infrastructures are exposed to substantial risks from the increasing frequency and magnitude of extreme events across Europe. Infrastructures in mountain regions are threatened by geological instability as a result of increased precipitation and melting of mountain permafrost. North-western European countries appear to be ahead of other countries in terms of preparedness regarding coastal energy infrastructure.

The main climate-related events relevant for transport are heat waves in southern and eastern Europe, cold spells and snow in northern Europe and heavy precipitation and floods across all of Europe.

Transport systems in mountain regions, coastal areas and regions prone to more intense rain and snow are generally expected to be most vulnerable to future climate change. Projections suggest that rail transport will face particularly high risks from extreme weather events, mostly because of the projected increase in heavy rain events and the limited routing alternatives. However, there is no comprehensive overview of climate-related risks for transport across Europe owing to widely different methodological approaches in the currently available assessments. The impacts projected by 2050 have been assessed and found to be manageable, provided that proper adaptation measures are taken.

According to a Joint Research Centre (JRC) study, climate-related damage to large investments and critical infrastructures could triple by the 2020s, could increase six-fold by the middle of the century and could increase by more than ten-fold by the end of the century, compared with the 1981–2010 baseline (Forzieri et al., 2015). The greatest increase in damage is projected for the energy and transport sectors, and for EU regional investments in environment and tourism. Southern and south-eastern European countries will be most affected.

Tourism

Climatic suitability for summer and beach tourism is currently best in southern Europe. The touristic attractiveness of northern and central Europe is projected to increase in most seasons. The suitability of southern Europe for tourism will decline markedly during the key summer months, but will improve in other seasons.

The projected reductions in snow cover will negatively affect the winter sports industry in many regions. Regions close to the low elevation limit for winter sports are most sensitive. Therefore, winter sport locations on the southern slopes of the Alps are, on average, more vulnerable than those on the northern slopes.

The projected climate change could have substantial consequences for regions where tourism is an important economic sector. The magnitude of the economic impacts is strongly influenced by non-climatic factors, such as the ability of tourists to adjust the timing of their holidays.

ES.4 Multi-sectoral impacts, vulnerabilities and risks

Summary

Table ES.1 presents an overview of past trends and projected changes for all indicators and for some other climate-sensitive impact domains. The main part of the table shows the predominating direction of observed and projected changes for each indicator and for each of the four main terrestrial regions and regional seas in Europe. Different symbols have been used to reflect situations where the direction of observed or projected changes is not uniform across a region. Empty cells for particular indicators and regions reflect a lack of available information ([1]).

Table ES.1 clearly shows the heterogeneity of climate change impacts across European regions and across indicators and thematic areas. Some indicators exhibit changes in the same direction across Europe (e.g. temperature, absolute sea level), while others show a clear regional pattern (e.g. mean precipitation), and still others show a complex spatial pattern with changes in both directions in individual regions.

The direction of past trends and projections agrees well for most indicators/variables and regions. There are some discrepancies, which are partly due to differences in the consideration of non-climatic factors for observed and projected changes ([2]).

Many indicators include quantitative data on past trends and projections for all regions; others include data on either past trends or projections, and/or data for selected regions only. When data availability is insufficient for showing the direction of past and/or projected changes for all regions, an estimate of the direction of observed and/or projected change averaged over Europe is presented, if possible.

([1]) The regionalisation of land areas generally follows that used in Map ES.1. However, the 'boreal' and 'Arctic' regions are merged into a 'northern' region because insufficient information was available for a separate assessment of all indicators in the Arctic region; the 'mountain' region is not explicitly represented because it is too heterogeneous for making aggregated statements.
The information on regional changes in this table relies primarily on the maps included in the main report; complementary information in the text was used in some cases. The aggregation of the diverse information sources in this report into the common format of Table ES.1 represents the consensus of all authors of this executive summary, which was reached after several iterations, whereby their initially independent assessments were reviewed and made consistent.

([2]) Whenever 'observations' and 'projections' for a region agree, this is represented by a single symbol in the centre of the column rather than two separate symbols. Information under 'observations' reflects past trends in a variable, independent of their attribution. In contrast, information under 'projections' reflects the projected impacts of climate change (and, where relevant, increases in CO_2 concentration) only; these projections do not consider future changes in non-climatic factors or future adaptation policy. Further information on the importance of climatic versus non-climatic factors for a particular indicator, and some information on the scope of adaptation policy, can be found in the main report.

Table ES.1 Key observed and projected climate change and impacts for the main regions in Europe

Direction of observed and projected climate change and impacts for the main regions in Europe													
Section	Indicator/impact domain	Variable	Sensitivity to adaptation policy	Northern		Temperate				Southern		European average	
				Boreal and Arctic		Atlantic		Continental		Medi-terranean			
				Obs	Proj	Obs	Proj	Obs	Proj	Obs	Proj	Obs	Proj
3	**Changes in the climate system**												
3.2	**Atmosphere**												
3.2.2	Global and European temperature	Temperature	No	↗		↗		↗		↗			
3.2.3	Heat extremes	Frequency of warm days/heat wave magnitude index	No	↗		↗		↗		↗			
3.2.4	Mean precipitation	Annual precipitation	No	↗		↗↘	↗→	↗↘	↗→	→↘			
3.2.5	Heavy precipitation	Intensity	No	↗		↗→		→	↗	→↘	↗↘		
3.2.6	Wind storms	Maximum wind speed	No		↗→		↗→		↗→		→↘		
3.2.7	Hail	Potential hail index	No			↗→	→↘	↗↘	↗→	↗↘			
3.3	**Cryosphere**												
3.3.2	Arctic and Baltic sea ice	See end of table											
3.3.3	Greenland and Antarctic ice sheets	Mass	No	↘									
3.3.4	Glaciers	Mass	No	↗↘	→↘			↘		↘			
3.3.5	Snow cover	Duration/amount	No									↘	
4	**Climate change impacts on environmental systems**												
4.1	**Oceans and marine environment** (see end of table)												
4.2	**Coastal zones**												
4.2.2	Global and European sea level	Absolute sea level	No	↗		↗		↗		↗→			
		Relative sea level	No	↗↘		↗		↗		↗→	↗		
		Coastal flooding frequency	Variable		↗↘		↗		↗		↗		
4.3	**Freshwater systems**												
4.3.2	River flows	Mean flow (near-natural rivers)	Domain	↗		↗→		↗↘		↘			
4.3.3	River floods	Frequency and magnitude	Trend		↗↘	↗→	↗		↗→		↗↘	↗	
4.3.4	Meteorological and hydrological droughts	Frequency and severity of meteorological droughts	Domain	↗↘	↘	↗↘		↗↘		↗↘	↗		
		Minimum river flow	Domain		↗		↘		↗↘		↘		
4.3.5	Water temperature	Lake and river temperature	No	↗		↗		↗		↗			
4.4	**Terrestrial ecosystems, soil and forests**												
4.4.2	Soil moisture	Summer soil moisture	No	↗→		→↘	↗↘	→↘	↗↘	→↘	↘		
4.4.3	Phenology of plant and animal species	Day of spring events	No					↘				↘	
4.4.4	Distribution shifts of plant and animal species	Latitude and altitude	Domain	↗		↗		↗→	↗	↗→	↗		
4.4.5	Forest composition and distribution	Latitude and altitude	Domain									↗→ *	↗
4.4.6	Forest fires	Area burnt	Trend							→↘	↗		↗
		Forest fire risk index	Domain	→↘	↗→	↗↘	↗→	↗→	↗	↗↘	↗		
4.4.7	*Forest pests and diseases*	*Occurrence of insect pests*	Domain	↗→		↗→		↗→		↗→			↗↘ *
5	**Climate change impacts on society**												
5.1	**Impacts of climate-related extremes**												
5.1.3	Economic losses from climate-related extremes	Costs	Trend									↗	
5.2	**Human health**												
5.2.3	Floods and health	Mortality and morbidity	Variable				↗						↗
5.2.4	Extreme temperatures and health	Heat-related mortality	Trend						↗		↗	↗	
		Cold-related mortality	Variable										↘
5.2.5	Vector-borne diseases	People infected	Trend									↗→ *	
5.2.6	Water- and food-borne diseases	People infected (vibriosis)	Trend									↗→ *	↗

Table ES.1 Key observed and projected climate change and impacts for the main regions in Europe (cont.)

<table>
<tr><th colspan="14">Direction of observed and projected climate change and impacts for the main regions in Europe</th></tr>
<tr><th rowspan="3">Section</th><th rowspan="3">Indicator/impact domain</th><th rowspan="3">Variable</th><th rowspan="3">Sensitivity to adaptation policy</th><th colspan="2">Northern</th><th colspan="4">Temperate</th><th colspan="2">Southern</th><th colspan="2" rowspan="2">European average</th></tr>
<tr><th colspan="2">Boreal and Arctic</th><th colspan="2">Atlantic</th><th colspan="2">Continental</th><th colspan="2">Medi-terranean</th></tr>
<tr><th>Obs</th><th>Proj</th><th>Obs</th><th>Proj</th><th>Obs</th><th>Proj</th><th>Obs</th><th>Proj</th><th>Obs</th><th>Proj</th></tr>
<tr><td>5.3</td><td colspan="13">Agriculture</td></tr>
<tr><td>5.3.2</td><td>Growing season for agricultural crops</td><td>Duration</td><td>No</td><td colspan="2">↗</td><td colspan="2">↗</td><td colspan="2">↗</td><td colspan="2">↗→</td><td></td><td></td></tr>
<tr><td>5.3.3</td><td>Agrophenology</td><td>Day of spring events</td><td>Domain</td><td colspan="2">↘</td><td colspan="2">↘</td><td colspan="2">↘</td><td colspan="2">↘</td><td></td><td></td></tr>
<tr><td rowspan="2">5.3.4</td><td rowspan="2">Water-limited crop yield</td><td>Average yield</td><td>Variable</td><td></td><td>↗</td><td></td><td>↗↘</td><td></td><td>→</td><td></td><td>↘</td><td></td><td></td></tr>
<tr><td>Adverse climatic conditions</td><td>Domain</td><td></td><td>↗</td><td></td><td>↗</td><td></td><td>↗→</td><td></td><td>↗→</td><td></td><td></td></tr>
<tr><td>5.3.5</td><td>Crop water demand</td><td>Water deficit</td><td>Domain</td><td></td><td></td><td colspan="2">↗↘</td><td colspan="2">↗↘</td><td>↗↘</td><td>↗→</td><td></td><td></td></tr>
<tr><td>5.4</td><td colspan="13">Energy</td></tr>
<tr><td rowspan="2">5.4.2</td><td rowspan="2">Heating and cooling degree days</td><td>Heating degree days</td><td>No</td><td colspan="2">↘</td><td colspan="2">↘</td><td colspan="2">↘</td><td colspan="2">→↘</td><td></td><td></td></tr>
<tr><td>Cooling degree days</td><td>No</td><td>→</td><td>↗→</td><td colspan="2">↗→</td><td>↗→</td><td>↗</td><td colspan="2">↗</td><td></td><td></td></tr>
<tr><td>5.4.4</td><td>Electricity production</td><td>Production potential</td><td>Domain</td><td></td><td>↗</td><td></td><td>↗↘</td><td></td><td>→↘</td><td></td><td>↘</td><td></td><td></td></tr>
<tr><td>5.5</td><td colspan="13">Transport</td></tr>
<tr><td>5.5.2</td><td>Impacts of climate and weather extremes</td><td>Costs of adverse weather events</td><td>Domain</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>↗→*</td></tr>
<tr><td>5.6</td><td colspan="13">Tourism</td></tr>
<tr><td>5.6.2</td><td>Summer and beach tourism</td><td>Attractivity (summer season)</td><td>Domain</td><td></td><td>↗</td><td></td><td>↗↘</td><td></td><td>↗↘</td><td></td><td>↘</td><td></td><td></td></tr>
<tr><td>5.6.3</td><td>Winter and mountain tourism</td><td>Winter sport potential</td><td>Domain</td><td></td><td>→↘</td><td></td><td></td><td></td><td>↘</td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td colspan="13">Multi-sectoral vulnerability and risks</td></tr>
<tr><td>6.3</td><td>Projected economic impacts</td><td>Welfare</td><td>Variable</td><td></td><td>→</td><td></td><td>→</td><td></td><td>↘</td><td></td><td>↘</td><td></td><td></td></tr>
<tr><th></th><th></th><th></th><th></th><th colspan="2">Arctic Ocean</th><th colspan="2">Atlantic and North Sea</th><th colspan="2">Baltic Sea</th><th colspan="2">Mediterra-nean and Black Sea</th><th colspan="2">European seas average</th></tr>
<tr><td>3.3.2</td><td>Arctic and Baltic sea ice</td><td>Extent</td><td>No</td><td colspan="2">↘</td><td colspan="2"></td><td colspan="2">↘</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>4.1</td><td colspan="13">Oceans and marine environment</td></tr>
<tr><td>4.1.2</td><td>Ocean acidification</td><td>Acidity</td><td>No</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2">↗</td></tr>
<tr><td>4.1.3</td><td>Ocean heat content</td><td>Heat content</td><td>No</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2">↗</td></tr>
<tr><td>4.1.4</td><td>Sea surface temperature</td><td>Temperature</td><td>No</td><td colspan="2">↗</td><td colspan="2">↗</td><td colspan="2">↗</td><td colspan="2">↗</td><td colspan="2"></td></tr>
<tr><td>4.1.5</td><td>Range shifts of marine species</td><td>Latitude (migration and immigration)</td><td>No</td><td>↗</td><td></td><td>↗</td><td></td><td></td><td></td><td>↗</td><td></td><td></td><td>↗</td></tr>
<tr><td>4.1.5</td><td>Fisheries</td><td>Catch potential</td><td>Domain</td><td>↗↘</td><td>↗</td><td>↗↘</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4.1.6</td><td>Ocean oxygen content</td><td>Number of dead zones</td><td>Trend</td><td colspan="2"></td><td colspan="2"></td><td colspan="2">↗</td><td colspan="2"></td><td colspan="2">↗</td></tr>
</table>

Legend:

↗	Increase throughout most of a region	Dominating trend in at least two-thirds, opposing trend in less than 10 %	Beneficial change
↘	Decrease throughout most of aregion		Adverse change
↗→	Increase in substantial parts of a region	Trend in between one-thirds and two-thirds, opposing trend in less than 10 %	Change classified as neither adverse nor beneficial/small change
→↘	Decrease in substantial parts of a region		
↗↘	Increases as well as decreases in a region	Trends in both directions in at least 10 %	
→	Only small changes		
*	The direction of change (European average) differs depending on the forest species, insect pest, disease and transport mode		

Notes: Obs = observation/past trend; Proj = projection.

An arrow centred between the 'Obs' and 'Proj' columns indicates agreement between observed trends and projections.

Information refers to different time horizons, emissions scenarios and socio-economic scenarios.

Impact domains in italics are not presented in indicator format.

The Continental region comprises also the Pannonian and Steppe regions.

The Mediterranean region comprises also the Black Sea region.

The Mountain region (comprising the Alpine and Anatolian regions) is too diverse to be shown separately in this table.

For 34 out of the 49 variables assessed, changes in a given direction can be described as either beneficial (green) or adverse (red). For the other 15 variables (black), a given change can be (predominantly) beneficial in one region and (predominantly) adverse in another region, depending on climatic, environmental and other factors.

Some variables exhibit changes that are either beneficial or adverse across all or most regions; other indicators show a more complex regional pattern of beneficial and adverse changes. On a more aggregate level, most sectors covered by several indicators and/or variables exhibit both beneficial and adverse changes in most regions (e.g. agriculture, energy and tourism). Sectors with predominantly adverse impacts for most regions are coastal zones and human health; none of the sectors show predominantly beneficial impacts of climate change.

The table also specifies whether an indicator and variable ('sub-indicator') are sensitive to adaptation policies. Out of the 49 variables assessed, seven include observed *trends* that are sensitive to actual or potential adaptation policies (in a broad sense); five further *variables* were assessed as being sensitive to adaptation policies, but only information on projections is presented here; another 15 variables represent impact *domains* that are sensitive to adaptation policies, but the particular variable is not (e.g. because of data limitations). The remaining 22 variables are *not* sensitive to adaptation policies (e.g. climate variables). Out of the seven variables with trends that are potentially sensitive to adaptation policies, three show trends for one out of four regions only, and the other ones show trends for the European average only. Thus, the current information base is clearly insufficient for assessing the effectiveness of adaptation policies across Europe in any of the sectors considered here.

Map ES.1 shows examples of key observed and projected changes in climate and their impacts for the main biogeographic regions in Europe ([3]). The inclusion of specific climatic changes and impacts reflects a qualitative assessment of their relative importance for the majority of a particular regions. However, there is considerable variation within each region, and impacts mentioned for a specific region can also occur in other regions, where they are not mentioned.

Key climate change impacts and vulnerabilities in European regions

The following text presents a selection of the key impacts and vulnerabilities for the main biogeographical regions in Europe. For further information about these regions, see Map ES.1.

Arctic region (northern Europe)

The Arctic environment will, because of the faster than average rise in air and sea temperatures, undergo major changes, which will affect both ecosystems and human activities. Habitats for flora and fauna (including sea ice, tundra and permafrost peat lands) have already been partially lost. Arctic vegetation zones are likely to shift further, having wide-ranging secondary impacts. Some species of importance to Arctic people and species of global significance are declining. Marine ecosystem acidification may become a serious threat, as acidification can progress more rapidly in Arctic oceans as a result of low temperatures and the considerable influx of freshwater. Climate change is the most far-reaching and significant stressor on Arctic biodiversity.

Indigenous people with traditional livelihoods live in the Arctic. Many of these livelihoods depend directly on ecosystem services, and local communities are already experiencing climate change impacts. Traditional livelihoods, such as reindeer herding, that are under pressure from various socio-economic and political developments may suffer further from climate change impacts.

Infrastructures are at risk from sea level rise and thawing of Arctic permafrost, which poses challenges to communities and to economic activities such as forestry and mineral extraction. Conditions for shipping across the Arctic Ocean and exploitation of non-renewable natural resources may become more favourable in the future, but these new opportunities are associated with numerous risks for the environment. Utilising Arctic oil and natural gas resources would challenge the transition to a low-carbon society, as it is recommended that two-thirds of known global fossil resources remain in the ground if the 2 °C warming limit of the UNFCCC is to be met.

(3) The regionalisation in Map ES.1 is based on the map of biogeographical regions set up under the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention). The following changes were made to reflect limited data availability for some regions: 'Continental Europe' also includes the 'Pannonian' and 'Steppic' regions; the 'Mediterranean' region also includes the Black Sea region; 'mountain areas' comprise the 'Alpine' and 'Anatolian' regions; and the 'Macaronesian' region is not explicitly shown.

Map ES.1 Key observed and projected climate change and impacts for the main biogeographical regions in Europe

Arctic region
Temperature rise much larger than global average
Decrease in Arctic sea ice coverage
Decrease in Greenland ice sheet
Decrease in permafrost areas
Increasing risk of biodiversity loss
Some new opportunities for the exploitation of natural resources and for sea transportation
Risks to the livelihoods of indigenous peoples

Atlantic region
Increase in heavy precipitation events
Increase in river flow
Increasing risk of river and coastal flooding
Increasing damage risk from winter storms
Decrease in energy demand for heating
Increase in multiple climatic hazards

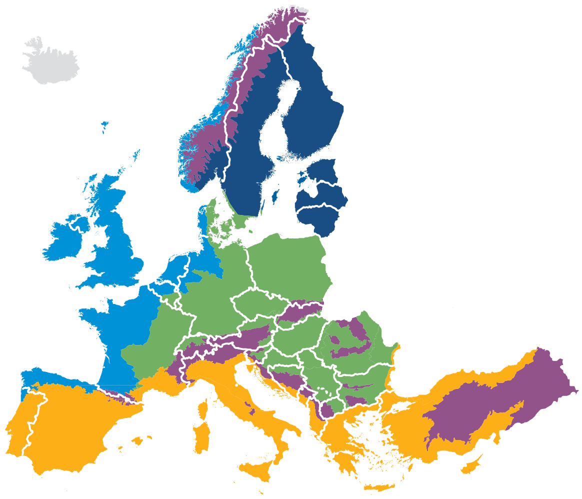
Mountain regions
Temperature rise larger than European average
Decrease in glacier extent and volume
Upward shift of plant and animal species
High risk of species extinctions
Increasing risk of forest pests
Increasing risk from rock falls and landslides
Changes in hydropower potential
Decrease in ski tourism

Coastal zones and regional seas
Sea level rise
Increase in sea surface temperatures
Increase in ocean acidity
Northward migration of marine species
Risks and some opportunities for fisheries
Changes in phytoplankton communities
Increasing number of marine dead zones
Increasing risk of water-borne diseases

Boreal region
Increase in heavy precipitation events
Decrease in snow, lake and river ice cover
Increase in precipitation and river flows
Increasing potential for forest growth and increasing risk of forest pests
Increasing damage risk from winter storms
Increase in crop yields
Decrease in energy demand for heating
Increase in hydropower potential
Increase in summer tourism

Continental region
Increase in heat extremes
Decrease in summer precipitation
Increasing risk of river floods
Increasing risk of forest fires
Decrease in economic value of forests
Increase in energy demand for cooling

Mediterranean region
Large increase in heat extremes
Decrease in precipitation and river flow
Increasing risk of droughts
Increasing risk of biodiversity loss
Increasing risk of forest fires
Increased competition between different water users
Increasing water demand for agriculture
Decrease in crop yields
Increasing risks for livestock production
Increase in mortality from heat waves
Expansion of habitats for southern disease vectors
Decreasing potential for energy production
Increase in energy demand for cooling
Decrease in summer tourism and potential increase in other seasons
Increase in multiple climatic hazards
Most economic sectors negatively affected
High vulnerability to spillover effects of climate change from outside Europe



Boreal region (northern Europe)

Projections suggest that there will be a larger than average temperature increase, in particular in winter, an increase in annual precipitation and river flows, less snow and greater damage by winter storms in this region. Climate change could offer some opportunities in northern Europe, including increased crop variety and yields, enhanced forest growth, higher potential for electricity from hydropower, lower energy consumption for heating and possibly more summer tourism. However, more frequent and intense extreme weather events are projected to have an adverse impact on the region, for example by making crop yields more variable and by increasing the risk from forest pests and forest fires. Heavy precipitation events are projected to increase, leading to increased urban floods and associated impacts.

Atlantic region (north-western Europe)

Coastal flooding has had an impact on low-lying coastal areas in north-western Europe in the past. These risks are expected to increase as a result of sea level rise and potentially stronger storm surges, with North Sea countries being particularly vulnerable. Stronger extreme precipitation events, in particular in winter, are projected to increase the frequency and intensity of winter and spring river flooding, urban floods and associated impacts. The risk of severe winter storms, and possibly of severe autumn storms, is projected to increase.

Continental region (central and eastern Europe)

Increasing heat extremes are a key hazard in central and eastern Europe. Together with reduced summer precipitation, they can increase drought risk, health risks and energy demand in summer. The intensity and frequency of river floods in winter and spring is projected to increase in various regions as a result of increases in winter precipitation. Climate change is also projected to lead to an increased risk of river floods, higher crop-yield variability and an increased occurrence of forest fires.

Mediterranean region (southern Europe)

The Mediterranean region is facing decreasing precipitation and increasing temperatures, in particular in summer. The main impacts are decreases in water availability and crop yields, increasing risks of droughts and forest fires, biodiversity loss and adverse impacts on human health and well-being and on livestock. Environmental water flows, which are important for aquatic ecosystems, are threatened by climate change and by socio-economic developments. Overall, the competition between different water users is expected to increase. The observed invasion and survival of alien species in the Mediterranean Sea is partly due to the warming trend in sea surface temperature. The energy sector will be affected by decreasing water availability and increasing energy demand for heating, in particular in summer. The suitability for tourism will decline markedly during the key summer months, but will improve in other seasons. The Mediterranean region is a hotspot of climate change impacts, having the highest number of economic sectors severely affected. It is also particularly vulnerable to the spill-over effects of climate change impacts in neighbouring regions, in particular related to disruptions in agricultural trade and to migration flows.

European Union Outermost Regions and the Overseas Countries and Territories

The European Union Outermost Regions and the Overseas Countries and Territories are particularly vulnerable to climate change impacts, in particular to sea level rise and extreme weather events. Water resources are highly sensitive to sea level rise because of the risk of saltwater intrusions. The very rich biodiversity and high concentration of endemic species are sensitive to changes in temperature and precipitation and to the introduction or increase of pests and invasive species. The high concentration of population, socio-economic activities and infrastructures in low-lying coastal zones make these regions and territories very vulnerable to sea level rise and coastal flooding. The economic dependence on a small number of products and services (e.g. fishing and tourism) make them highly vulnerable to any potential changes.

Mountain regions

Many mountain regions are experiencing a particularly large increase in temperature, as well as reduced snow cover, loss of glacier mass, thawing of permafrost and changing precipitation patterns, including less precipitation falling as snow. Mountain ecosystems are particularly vulnerable to climate change. Impacts include a shift in vegetation zones and extensive biodiversity loss. Plant and animal species living close to mountain tops face the risk of becoming extinct owing to the inability to migrate to higher altitudes.

Most mountain regions are expected to be adversely affected in relation to their water resources. The retreat of the vast majority of glaciers also affects water availability in downstream areas. Additional impacts include a reduced potential for winter tourism, in particular in lower lying regions, and increasing risks to infrastructure and settlements from floods, landslides and rock falls in some regions. Hydropower potential is projected to change, with positive impacts in some regions (e.g. Scandinavia) and negative impacts in others (e.g. the Alps).

Coastal zones and regional seas

Coastal zones across Europe are facing an increasing risk of flooding from rising sea levels and a possible increase in storm surges. Climate change is leading to major changes in marine ecosystems as a result of warming and ocean acidification. It can also exacerbate oxygen depletion from eutrophication, leading to dead zones. Impacts on fisheries can be both adverse and beneficial, with the highest risks faced by coastal fisheries with limited adaptation potential. Increasing sea surface temperatures can also adversely affect water quality (e.g. through algal blooms) and facilitate the spread of water-borne diseases, such as vibriosis.

Cities and urban areas

The climate resilience of Europe's cities, which are inhabited by almost three-quarters of the population, is decisive for their functioning and for Europe's growth, productivity and prosperity.

Cities face specific climate threats. Having a high proportion of elderly people makes cities sensitive to heat waves and other climatic hazards. The urban heat island effect exacerbates the impacts of heat waves and is increasingly also affecting cities in central and north-western Europe. High soil sealing and urban sprawl in combination with more extreme precipitation events and sea level rise increase the risk of urban flooding. Many cities have continued to spread noticeably into areas potentially prone to river floods, thus increasing their exposure to floods. Urban sprawl with low-density housing into previously wild land has increased the risk of forest fires in many residential areas over the last decades, in particular around cities in southern Europe.

Socio-economic scenarios for Europe

A comprehensive assessment of the vulnerability of regions, sectors, population groups and infrastructure to climate change needs to consider potential changes in socio-economic factors, as well as multiple interdependencies across climate-sensitive sectors.

Population size in eastern Europe is projected to decrease considerably during the 21st century. For western Europe, some scenarios project increases throughout the century, while others project slight increases until the middle of the century followed by a decline thereafter, and still others assume a continuous decline throughout the 21st century. The population is projected to age substantially in both western and eastern Europe.

Urbanisation is projected to increase further. The difference between scenarios in the proportion of the population that is urban is relatively large in eastern Europe; in western Europe, the urban population is expected to increase to above 90 % in most countries and scenarios.

Available projections assume future growth in income per capita, but the magnitude of this growth varies significantly between scenarios, particularly in western Europe. The current fundamental gap in gross domestic product (GDP) per capita between eastern and western Europe is expected to significantly reduce throughout the century, but not to vanish completely.

Capacities to cope with the consequences of climate change appear to be increasing, but the current higher capacity in central and north-western parts of Europe than in southern and some eastern parts of Europe is expected to prevail to some degree. Opportunities for technological and social innovations are greater for scenarios that assume well-functioning governance and international cooperation.

Multi-sectoral vulnerabilities and projected costs

The water, agriculture, forestry and biodiversity sectors and domains show strong interdependencies with each other and with non-climatic developments, such as changing land-use patterns and population change. South-eastern and southern Europe are projected to be hotspot regions, based on the high number of sectors and domains severely affected. Regarding ecosystem services, the Alps and the Iberian Peninsula are also hotspots.

An assessment considering several climate hazards, including droughts, fires and sea level rise, has identified southern Europe, but also coastal areas and floodplains in western Europe, as multi-sectoral hotspots. The greatest challenges appear to be concentrated in south-eastern and southern parts of Europe.

Estimates of the projected economic impacts of climate change in Europe are emerging, but the coverage remains partial and there is considerable uncertainty. A JRC study indicates that there will be potentially high economic costs, even for modest levels of climate change, and these costs rise significantly for scenarios of greater levels of warming (Ciscar et al., 2014). Annual total damages from climate change in the EU could be around EUR 190 billion (with a net welfare loss estimated to be equivalent to 1.8 % of current GDP) by the end of the century under a reference scenario. There is a strong distributional pattern of costs, with notably higher impacts in southern Europe.

In recent years, more information has become available on the costs and benefits of adaptation, especially for coastal areas, water management, floods, agriculture and the built environment. The focus of these studies has been on national and regional rather than on pan-European estimates.

Europe's vulnerability to climate change impacts outside Europe

Climate change is having an impact on all world regions. Several recent studies have suggested that climate change will have much stronger negative impacts on the global economy than previously assumed, with poor countries being disproportionally affected. 'The Global Risks Report 2016' indicates that the most impactful risk in the years to come was found to be a failure in climate change mitigation and adaptation (WEF, 2016).

Europe is susceptible to spill-over effects from climate change impacts occurring outside European territories through six major pathways: the trade of agricultural commodities, the trade of non-agricultural commodities, infrastructure and transport, geopolitics and security risks, human migration and finance. The strongest evidence for Europe's vulnerability to cross-border impacts are the economic effects seen as a result of climate-related price volatilities and disruptions to transportation networks.

Recent climate extremes outside Europe have already had a negative impact on Europe. One example of global price volatilities caused by climate extremes is the Russian heat wave in 2010, which destroyed a substantial area of crops, thereby negatively affecting Russia's grain harvest. This led to an export ban on wheat by the Russian government, which contributed to a substantial increase in global wheat prices. An example of indirect effects through supply chains to Europe is the shortage of hard drives and the associated increase in price levels caused by a severe flood event in Thailand in 2011. An example of effects of climate-related hazards on infrastructure outside Europe is Hurricane Katrina (2005), which destroyed large parts of the port of New Orleans, causing a temporary shortage in global oil supply and thereby triggering a temporary increase in the global oil price. A potentially major climate-related impact on global trade relates to the opening of Arctic sea routes following the shrinkage of the Arctic sea ice.

The Mediterranean region has been identified as particularly vulnerable to shocks in the flow of agricultural commodities, owing to, among others, a high dependency on imports from outside Europe, whereas small, open and highly developed European economies are regarded as particularly vulnerable to shocks in the flow of non-agricultural commodities.

Climate change in North African regions, such as the Sahel and the Maghreb, as well as in the Middle East, may increase the strategic importance of these regions for Europe, with respect to both potential climate-induced human migration flows, and geopolitical and security considerations. The links between different triggering factors is extremely complex. An unprecedented drought that has affected parts of the Middle East in recent years has been suggested as one among many drivers (e.g. economic situation, governance) shaping local conflicts that triggered the Syrian civil war, which ultimately led to the current substantial increase in refugee flows to Europe.

European vulnerability to cross-border effects is expected to increase in the coming decades, but quantitative projections are not yet available.

ES.5 Possible ways forward on adaptation

The SOER 2015 highlights that, to achieve the 2015 vision of the 7th EAP, fundamental transitions are needed in key systems such as the transport, energy, housing and food systems. Four approaches are mentioned to enhance progress: mitigation through resource-efficient technological innovations; adaptation, by increasing resilience; avoiding harm to people's health and well-being and to ecosystems through precautionary and preventative action; and restoring and enhancing natural resources.

Adapting to the many changes that European society faces, as mentioned above, is a challenge, but it is also an opportunity for synergies and benefits if Europe implements adaptation measures in a coherent way. Achieving the desired policy coherence needs continued efforts to mainstream adaptation in many environmental and sectoral policies, regarding both policy development and implementation, and working towards similar goals. Enhancing the synergies between disaster risk reduction and climate change adaptation and including adaptation considerations in existing and new major infrastructural investments are particularly important. There is also a need to address interdependencies across sectors regarding major infrastructures (e.g. transport, electricity production and communication), for example through 'stress tests'.

A related challenge is to ensure the effectiveness, efficiency and coherence of action across the various levels of governance. EU adaptation policy should take into account national strategies and plans, as well as actions at transnational and city levels.

Adaptation policy responses must be flexible and tailor-made to address regional and local conditions and needs and must also take into account the progress made in the scientific understanding of disaster risks, decadal climate variability, and long-term climate and socio-economic changes. This understanding is evolving and lessons are being learned from implementing actions. It is important to adopt an 'adaptive management' approach, which means adjusting plans to these conditions as they unfold, taking account of the uncertainty on future developments and constantly updating adaptation policy with new information from monitoring, evaluation and learning.

Flexibility can also be advanced by using different types of adaptation measures. Implementing a combination of 'grey' (i.e. technological and engineering solutions), 'green' (i.e. ecosystem-based approaches) and 'soft' (i.e. managerial, legal, policy and market-based approaches) adaptation options is often a good way to deal with the interconnections between natural systems and social systems.

The involvement of stakeholders is important in creating a sense of 'ownership' in adaptation policy, a critical factor in the success of adaptation implementation. Stakeholder involvement also helps to improve the coherence of adaptation actions and builds adaptive capacity in the wider society. Multi-level governance bridges the gaps between the different levels of policy and decision-making and provides opportunities for ensuring that key actors are involved.

There is limited information about the vulnerability of and risks faced by businesses and about adaptation measures being taken by the private sector. This challenge could be addressed by the private sector through assessments of their vulnerabilities, including in their value and supply chains, and by implementing adaptation actions. These activities can be supported by emerging climate change and adaptation services. The development and implementation of innovative solutions for adaptation can provide business opportunities in many different sectors.

Incremental adaptation, such as improving existing flood defences and increasing existing water reservoirs, builds on existing adaptation measures and known solutions by improving on them, often based on proven knowledge gained over several decades. Incremental adaptation often focuses on individual measures, as appropriate, and as opportunities appear. Measures are relatively quick to put in place and can often deal sufficiently and effectively with short- and medium-term challenges.

Incremental adaptation may be sufficient to deal with most short- and medium-term challenges, but transformational adaptation is often required to address the long-term challenges of climate change. Transformational adaptation involves managing more radical change, rather than protecting or restoring a certain environmental or social state. As transformations require more fundamental changes, it is important to start considering them now and discussing possible pathways with stakeholders, in parallel to developing and implementing incremental options to address vulnerable hotspots.

Transformative adaptation follows a broad and systemic approach and addresses the root causes of vulnerability to climate change, which is often the result of human actions, such as settling in risk-prone areas, inadequate building design or other behaviours that aggravate the impacts of climate change. For example, the designs of a city, its buildings and its infrastructures are supposed to last for decades or even centuries. Transformative adaptation requires the rethinking of city planning and building to prepare for future climatic conditions. It may involve, for example, the redesign of parks and other open spaces to accommodate storm water, new building design to better cope with heat waves and developing transport infrastructure that is robust against extreme events. The transformative approach seeks to integrate adaptation with other aspects of urban development, offering the opportunity of a better functioning city and improved quality of life (EEA, 2016b).

Countries and cities, with a few exceptions, have not yet implemented comprehensive adaptation approaches that combine incremental and transformative actions, although some have taken transformative steps. In the future, further actions will be required, combining different types of actions and learning from experiences that are accumulating across EU, transnational, national and urban levels. Such learning will benefit from increasing activities at various governance levels in monitoring, reporting and evaluation. Sharing experiences and learning about the use of monitoring and evaluation results will further improve adaptation policy and practice (EEA, 2015a).

ES.6 Strengthening the knowledge base

The length of time series for, the geographical coverage of and the quality of climate change data and indicators have improved over recent years as a result of European and global efforts such as the Global Climate Observing System. Atmospheric and ocean observations are the most developed, but an integrated approach to terrestrial observations is still lacking.

Climate change impact indicators have also improved over recent years at EU and national levels, and many countries have performed climate change impact, vulnerability and/or risk assessments. However, improvements in such assessments are feasible, e.g. by better addressing indirect and cascading effects. Furthermore, there are no agreed common methods for indicator sets across Europe, which makes it difficult to compare information across countries. It can be useful to explore how existing thematic and sectoral EU legislation and policies could be used to improve data and indicators on climate change impacts.

Climate change services are emerging at national and EU levels (e.g. the Copernicus Climate Change Service and the Joint Programming Initiative 'Connecting Climate Knowledge for Europe'). They provide climate data and information, such as essential climate variables, reanalyses, observations, seasonal forecasts and long-term projections. Emerging adaptation services (at national and EU levels, e.g. the Climate Knowledge and Innovation Community) provide complementary information, e.g. on vulnerability and cost–benefit assessments, policies, tools and case studies. Climate change services and adaptation services are expected to become increasingly integrated in the future, thereby delivering the services needed by the intended users. Furthermore, enhanced knowledge and experiences facilitate the development, prioritisation and implementation of adaptation options, and the integration of them flexibly into other policies.

An increasing number of countries, and also city networks, are developing systems for the monitoring, reporting and evaluation of adaptation policies. An approach that combines quantitative indicators and qualitative information, including process-based indicators, can be a strong basis for assessments. Only a few countries have so far established such approaches.

The European Commission has developed a process-based 'adaptation preparedness scoreboard' to assess the progress of Member States, which will be included in its evaluation of the EU Adaptation Strategy, which is due to be published in 2018. There is an increasing need to complement this scoreboard with quantitative information at the EU level.

As part of the Sendai Framework for Disaster Risk Reduction, the finalisation of a set of indicators to measure progress in its implementation is planned by the end of 2016. Countries, including EU Member States, need to establish national databases of disaster impacts on ecosystems, human health and the economy. The Sendai Framework indicators for weather- and climate-related hazards are expected to be very relevant and useful for climate change adaptation.

Overall, the main knowledge gaps are regarding national and sectoral impact, vulnerability and adaptation assessments; economic damages and losses; costs and benefits of adaptation; options for effectively mainstreaming adaptation into public and private investments; adaptation services; interdependencies, synergies and trade-offs between policy objectives; and monitoring systems and tools. EU-funded research, in particular through Horizon 2020, and national research should address these adaptation knowledge gaps. However, transformative adaptation will require innovations and structural change, as well as reflexive learning from experience. The Horizon 2020 programme aims to facilitate such changes.

1 Introduction

1.1 Purpose and scope

1.1.1 Purpose

This report presents a primarily indicator-based assessment of past and projected climate change. It also looks at the observed and projected impacts of climate change, society's associated vulnerability to these impacts ([4]) and the risks they pose to European ecosystems and society. The European Environment Agency (EEA), in collaboration with other organisations, has so far published three four-yearly reports of this nature (EEA, 2004, 2008, 2012a). The four-year publication interval allows us to include new scientific knowledge that has been accumulated over that period while, at the same time, serving the policy need for a regular, comprehensive, Europe-wide assessment of our climate. The reports have changed in scope over time because of the increasing body of knowledge available and changing policy needs.

The main objectives of this report are to:

- present past and projected climate change, as well as selected impacts on ecosystems and society;
- identify the regions and sectors most at risk from climate change impacts;
- discuss the main sources of uncertainty in observations and projections;
- report on key adaptation policy developments at European, transnational and national levels;
- highlight the need for further adaptation actions; and
- demonstrate how monitoring, information sharing and research can improve the knowledge base for adaptation.

This report compiles information from a wide variety of sources in order to provide an overview of those aspects of climate change that are relevant for policymaking in Europe. It aims to achieve consistency with the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), in particular the contribution of Working Group I (IPCC, 2013) and the chapter on Europe in the contribution of Working Group II (Kovats et al., 2014). However, information that became available after the publication of the AR5 has also been considered. Major new information that has become available since the previous EEA report *Climate change, impacts and vulnerability in Europe 2012* (CCIV) is highlighted in the 'Executive summary'.

The key terms used to assess and communicate the effects of climate change (e.g. vulnerability and risk) put emphasis on the adverse impacts, and may suggest that all impacts of climate change are adverse, but some impacts may in fact be beneficial. This report includes climatic changes and impacts that are not per se adverse or beneficial (e.g. changes in precipitation or in plant phenology) as well as impacts that can be regarded as either adverse or beneficial (e.g. changes in health risks). Note that adverse and beneficial impacts tend to have rather different policy implications. Adverse impacts generally call for anticipatory, planned adaptation (e.g. increasing risk management efforts in order to maintain current risk levels under projected climate change), whereas the benefits of climate change can often be reaped by reactive adaptation (e.g. reducing risk management efforts that turn out to no longer be needed after observing climate change). On balance, most of the climate change impacts presented in this report are projected to be adverse, with details depending on the scenario and the time horizon (see 'Executive summary' for details).

([4]) For an explanation of the terms 'vulnerability' and 'risk', and their use in this report, see Section 1.4.

1.1.2 Content and data sources

This report includes the following:

- an assessment of past and projected climate change (Chapter 3), and its impacts on environmental systems (Chapter 4) and society (Chapter 5) in Europe, which is primarily based on indicators;
- a structured review of multi-sectoral climate change impact, vulnerability and risk assessments for ecosystem services (Section 4.5) and society at large (Chapter 6); and
- an overview of the policy background for climate change adaptation (Chapter 2) and the development of the associated knowledge base (Chapter 7).

Important information in this report is highlighted in 'Key messages' at different levels. Chapters 1 and 2 do not include key messages. Chapters 3, 4 and 5 include key messages for each section and for each indicator. Those key messages cover past trends, projections, where relevant, attribution (see Section 1.3.2), and in some cases, societal relevance. The key messages for individual indicators are generally more detailed and quantitative than the key messages for whole sections, which form the basis for the Executive summary. However, some overlaps between key messages at different levels cannot be avoided. Chapter 6 includes key messages for each section, and Chapter 7 includes key messages covering the whole chapter.

Indicator-based assessment

The main content of this report, presented in Chapters 3, 4 and 5, is about 40 indicators that describe observed and projected climate change and its impacts in Europe. Information for each indicator comprises 'Key messages', an explanation of its policy relevance, and an analysis of past trends and future projections, where available. Data quality issues and the main uncertainties are generally discussed jointly for a group of indicators. Some sections present information on specific climate impacts even though data availability and/or quality does not currently allow for an EEA indicator to be developed based on this information.

All indicators in the EEA CCIV reports are available on the EEA website ([5]) and accessible through the European Climate Adaptation Platform (Climate-ADAPT) (see Section 1.1.4). About half of the 42 indicators included in the 2012 report were updated online in 2014, primarily to include new information from the IPCC AR5, as well as from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Coordinated Downscaling Experiment — European Domain (EURO-CORDEX) climate modelling initiatives. The indicator base of the 2012 report was slightly modified for this report, as described in Section 1.1.3 below.

Where feasible, indicators cover the 33 member countries of the EEA. For some indicators, Europe-wide data were not available, so these indicators present information for fewer countries. Furthermore, some indicators have only limited geographical relevance (e.g. glaciers) and in such cases the aim was for full coverage of the relevant countries and regions.

The observed and projected impacts of climate change and society's vulnerability to them differ significantly across Europe owing to regional differences in current and future climate, as well as other environmental and socio-economic factors. Wherever possible, information on climate change and its impacts is provided for different macro-regions in Europe. Such regionalisation could be based on climatic, geographic, environmental, political or other criteria, but no generally accepted approach to regionalisation exists. For pragmatic reasons, the regionalisation in this report generally reflects that in the underlying data source. As a result, some inconsistencies across sections and indicators cannot be avoided.

An important question for the development of adaptation strategies and actions is to which magnitude and pattern of future climate change should Europe adapt? As future levels of greenhouse gas emissions and the resulting magnitude of global climate change are uncertain, this report provides impact projections for a range of emissions scenarios, where available and relevant. Furthermore, climate change and impact projections are based on an ensemble of climate projections from different models, whenever available. Further information on global emissions scenarios and the consideration of uncertainties in this report is provided in Sections 1.2 and 1.2.3, respectively.

The selection of topics and indicators for the previous report (EEA, 2012a) was guided by an expert assessment that applied 13 criteria grouped into five themes: policy relevance; causal links to climate change; methodological and data quality, and data accessibility; robustness; and acceptance

([5]) http://www.eea.europa.eu/themes/climate/indicators.

and intelligibility (Hildén and Marx, 2013). The final selection of indicators was done in consensus with the authors, considering all of the criteria mentioned above as well as the opinions of the external Advisory Group. The topics and indicators in this report were updated based, among others, on the feedback of a stakeholder survey (see Section 1.1.3 below for further details).

Some climate-sensitive sectors, systems and issues are not covered in this report owing to a lack of reliable information across Europe, including on industry and manufacturing, insurance, infrastructure (except for transport and energy infrastructure) and cultural heritage. Furthermore, immaterial impacts of climate change (such as aesthetic changes and changes in personal well-being) are not systematically covered because credible indicators are not available.

There is no reporting of climate change impacts and vulnerability data and information from EU Member States to the European Commission or the EEA. Some information is available in national communications to the United Nations Framework Convention on Climate Change (UNFCCC; UN, 1992) as well as in reporting under the Monitoring Mechanism Regulation (EU, 2013), the Floods Directive (EC, 2007) and the Water Framework Directive (EC, 2000). However, this information cannot be used for preparing quantitative indicators across EEA member countries because of a lack of comparability and quantification. Thus, the indicators presented in this report are based on data from *in situ* and satellite monitoring programmes, from EU and national research programmes, and from a few global databases.

The indicators presented in this report are in different stages of development, reflecting methodological and/or data challenges. Furthermore, they have broadly different policy purposes, which reflect the cross-cutting nature of climate change and determine the specific data needs of a particular indicator (see Table 1.1).

Integrated climate change impact, vulnerability and risk assessments

Section 4.5 combines indicator-based information on climate change impacts on environmental systems with other information sources using the framework of ecosystems services. Chapter 6 focuses on the interaction of the changing physical characteristics of the climate system with evolving characteristics of socio-economic systems. As such, the chapter synthesises the effects and consequences of climate change in Europe from an integrated perspective for different geographical scales and units (pan-European, macro-regions, cross-border effects and urban regions). The underlying assessments address a range of climate-sensitive sectors, and they generally consider future climate change in the context of anticipated changes in demographic and socio-economic conditions. This information is not presented in indicator format and, thus, is not available in the indicator section of the EEA website.

Policy background and knowledge base

Chapter 2 summarises the state of climate policies at the global level and in Europe, including adaptation policies at the national level and for various European macro-regions. A more comprehensive overview of European and national adaptation policies is available in other EEA reports (see Section 1.1.4). Chapter 6 gives an overview of the development of the knowledge base for adaptation as well as of the main remaining knowledge gaps and the strategies to address these gaps, including through various EU research programmes and the development of the Copernicus Climate Change Service.

Table 1.1 Type of indicator and policy objective

Type of indicator	Policy objective	Examples
Global climate change (Chapter 3)	Monitoring the main changes in the global climate system, which will provide the background for assessing regional climate change and its impacts	Global mean temperature Ocean heat content Arctic sea ice
Regional climate change (Chapters 3 and 4)	Tracing regional climate hazards to inform regional assessment and management of climate-sensitive risks	Heavy precipitation Regional sea level
Climate change impacts on environmental systems and society (Chapters 4 and 5)	Assessing the sensitivity of ecosystems and society to observed climate change, estimating future impacts of climate change and the resulting adaptation needs	River floods Species distribution Forest fires Damages from extreme events

1.1.3 Changes compared with the 2012 report

This section briefly describes changes in the structure of this report and the underlying indicator base, compared with the previous report published in 2012. Substantial new developments are highlighted in the 'Executive summary'.

In September 2014, the EEA conducted a stakeholder survey in order to get feedback on the scope, quality, comprehensibility and usefulness of the 2012 report, as well as on the scope, thematic focus and production process for the 2016 report. The results of this survey informed the scoping process of the current report.

The overall structure of the 2016 report has changed moderately from that of the 2012 report. First, information about the development of relevant policies at global, European, transnational and national levels is included in a new chapter on the policy context (Chapter 2). Second, the chapter on multi-sectoral vulnerability to climate change (Chapter 6 in the current report, Chapter 5 in the previous report) was completely restructured. This chapter synthesises the results of multi-sectoral climate change impact, vulnerability and risk assessments with relevance for Europe at different spatial scales. Furthermore, the formerly separate section on fisheries has been integrated into the section on oceans and the marine environment (Section 4.1), and the formerly separate sections on soils and on forests have been integrated into the section on terrestrial ecosystems (Section 4.4). Finally, a new section on ecosystems and their services under climate change has been included (Section 4.5).

The indicator base of the 2012 report was slightly modified for this report, taking into consideration, among others, feedback from the above-mentioned stakeholder survey and from the Advisory Group. As a result, in the 2016 report, several indicators have been dropped or discontinued, some indicators have been merged, and a few indicators have been extended or newly created. Table 1.2 shows the main changes in indicators between the 2012 and 2016 reports.

Table 1.2 Changes in indicators 2012–2016

Section	Indicator(s) in 2012 report	New, merged or modified indicator(s) in 2016 report
3.2 Atmosphere	Extreme temperature	Heat extremes
	Extreme precipitation	Heavy precipitation
	–	Hail
3.3 Cryosphere	Greenland ice sheet	Greenland and Antarctic ice sheets
	Permafrost (*)	–
4.1 Oceans and marine environment	–	Oxygen content
	Marine phenology (*)	–
4.2 Coastal zones	Storm surges	Integrated into: Global and European sea level
4.3 Freshwater systems	River droughts	Meteorological and river droughts
	Lake and river ice cover (*)	–
4.4 Terrestrial ecosystems, soil and forests	Soil organic carbon (*)	–
	Soil erosion (*)	–
	Species interactions	–
	Plant phenology; animal phenology	Plant and animal phenology
	Plant distribution; animal distribution	Plant and animal distribution
	Forest growth	Forest composition and distribution
5.2 Human health	Air pollution by ozone and health	–
	–	Water and food-borne diseases
5.3 Agriculture	Irrigation water requirement	Crop water demand
5.4 Energy	Heating degree days	Heating and cooling degree days

Note: The indicators in green are new in this report, indicators in blue have been merged or substantially modified since the previous report, and indicators in red are no longer presented in this report. An asterisk (*) denotes that limited information from an indicator removed from this report is presented in this report in a box.

Changes in the names of indicators without major changes in content are not explicitly reported in this table. Information related to some indicators that have been dropped from this report is still presented in the relevant thematic section (e.g. in boxes). An overview of all indicators, including the time periods covered by past trends and information on projections, is presented in Table 1.7.

1.1.4 Links to other EEA activities

Climate change impacts, vulnerability and adaptation information

Table 1.3 presents a summary of relevant EEA reports and information published on climate change impacts, vulnerability and adaptation since 2013. Some of the information in this report is taken from the reports presented in Table 1.3, in particular from the 2015 European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC-CCA) technical paper on 'Extreme weather and climate in Europe' (van der Linden et al., 2015) (in particular Sections 3.1 and 3.2), and the urban vulnerability map book (EEA, 2015h) (in particular Section 6.6).

EEA thematic reports including information on climate change

Apart from the reports mentioned above, several other EEA reports published since 2012 include relevant information on climate change impacts and vulnerability, which is summarised in Table 1.4. The information in the present report (in particular in Sections 4.2, 4.3, 4.4 and 5.2) is consistent with those reports, but some information has been updated and/or extended.

Table 1.3 Overview of EEA reports and information on climate change impacts, vulnerability and adaptation published since 2013

Year	Title	Scope
2013	EEA Report *Adaptation in Europe* (EEA, 2013a)	Climate change adaptation policies and actions, examples of adaptation actions in practice and the initial EU policy context
2014	EEA Report *National adaptation policy processes in European countries* (EEA, 2014b)	A first comprehensive and consistent overview of adaptation policies in European countries, based on a questionnaire ('self-assessment') completed for individual countries
2014	EEA Report *Adaptation of transport to climate change in Europe* (EEA, 2014a)	Overview of the challenges and state of adaptation action in transport and examples of various actions already taken across Europe
2015	EEA Technical report *Overview of climate change adaptation platforms in Europe* (EEA, 2015c)	State of play of adaptation platform in Europe and information on the scope, history, targeted users, selection and presentation of knowledge, and links to climate services and disaster risk reduction platforms
2015	EEA Technical report *National monitoring, reporting and evaluation of climate change adaptation in Europe* (EEA, 2015b)	Information and national cases on emerging monitoring, reporting and evaluation systems at national level and assessment of key aspects (e.g. drivers, governance, methodology and information channels)
2015	ETC-CCA technical paper *Extreme weather and climate in Europe* (van der Linden et al., 2015)	Information on frequency and intensity of extreme weather and climate events covering extreme temperature, heavy precipitation, drought (various types) and hail
2015	'Urban vulnerability to climate change in Europe — A map book' (EEA, 2015h)	Information on climate change threats (heat waves, drought and water scarcity, flooding and forest fires) and cities' capacity to respond
2016	EEA Report *Urban adaptation to climate change in Europe 2016* (EEA, 2016)	Overview of the state of urban adaptation action at different governance levels and how this interacts with other themes and policies (e.g. environmental, urban development, quality of life), based on information from member countries and the Mayors Adapt initiative ([6])

([6]) http://mayors-adapt.eu.

Table 1.4 Overview of other relevant EEA reports published since 2012

Year	Title	Scope
2012	EEA Report *Water resources in Europe in the context of vulnerability* (EEA, 2012b)	Analysis of droughts and water scarcity, pollution, and flood risks, which all increase the vulnerability of freshwater ecosystems and societies. Land-use change, water abstraction and climate change are key factors
2013	Joint EEA–JRC report *Environment and human health* (EEA, 2013c)	Overview of environmental issues with a direct or indirect influence on people's health and well-being, including climate change (e.g. heat waves and floods)
2013	EEA Report *Balancing the future of Europe's coasts — knowledge base for integrated management* (EEA, 2013b)	Key sustainability challenges for European coastal areas and waters, including the main climate change hazards and vulnerabilities in different European marine regions, i.e. sea level rise, increased coastal erosion, storm surges and loss of specific habitats
2015	EEA Report *State of Europe's seas* (EEA, 2015e)	Assessment of whether or not Europe's seas are healthy, clean, undisturbed and productive; the main sustainability challenges, and how the EU is responding. Climate change (e.g. sea surface temperature increases and potential ocean acidification) is one of the pressures that can further weaken the ecological resilience of Europe's seas
2015	EEA Technical report *State of nature in the EU: Results from reporting under the nature directives 2007–2012* (EEA, 2015f)	Description of the state of nature in the EU, based on reports from Member States under the Birds and Habitats Directives, including status and trends of species and habitats, and on the main pressures and threats identified by Member States, including climate change
2015	EEA Technical report *European ecosystem assessment — concept, data, and implementation* (EEA, 2015a)	Information on ecosystems and their conditions, as part of assessments of implementation of the EU Biodiversity Strategy to 2020. It identifies and analyses climate change as one of five main pressures affecting ecosystems and their services (the other four are habitat change, invasive species, land-use management, and pollution and nutrient enrichment)
2015	*The European environment — state of the environment and outlook 2015* (EEA, 2015d)	Comprehensive five-yearly assessment of the European environment's state, trends and prospects, in a global context. Analysis of policy implementation and opportunities to modify existing policies to achieve the EU 2050 vision of living well within the limits of the planet. It includes a synthesis report, various European briefings, including one on climate change impacts, vulnerability and adaptation, and a report on global megatrends, including on climate change

Climate-ADAPT

The various recent EEA reports on climate change, impacts and vulnerability and on adaptation are complemented by information in the European Climate Change Adaptation platform, 'Climate-ADAPT' ([7]). It is a publicly accessible web-based platform designed to support policymakers at EU, national, regional and local levels in the development and implementation of climate change adaptation policies and actions. Climate-ADAPT is hosted and managed by the EEA, in collaboration with the European Commission. Since its launch in March 2012, the website has been continuously updated with new information, for example from EU research projects, transnational projects, and national and local authorities.

1.1.5 Relevant assessment reports from other organisations

Since 2012, various international assessment reports with a focus on climate change impacts and adaptation in Europe have been published by other organisations. A selection of them is summarised in chronological order in Table 1.5, but several others have been published and used for this report.

([7]) http://climate-adapt.eea.europa.eu.

Table 1.5 Selection of relevant reports from other organisations published since 2012

Year	Organisation	Title	Content
2013	European Commission (DG CLIMA)	'Impact assessment' (EC, 2013) and underlying background reports (McCallum, Dworak et al., 2013; McCallum, Prutsch et al., 2013), related to its 2013 communication on the EU strategy on climate change adaptation	The information on climate change impacts and vulnerability in the impact assessment and the background reports were, to a large extent, based on the 2012 EEA CCIV report or on similar underlying information sources
2013/2014	Intergovernmental Panel on Climate Change (IPCC)	Contributions of Working Groups I and II to its Fifth Assessment Report (AR5; IPCC, 2013, 2014a, 2014b)	These IPCC AR5 reports are very relevant, in particular the chapter on Europe in the Working Group II contribution. The present report contains information in various chapters that is based on and consistent with information from these IPCC reports
2013	Norwegian Meteorological Institute (NMI), in collaboration with the European Academies Science Advisory Council (EASAC)	*Extreme Weather Events in Europe: preparing for climate change adaptation* (Hov et al., 2013)	The report covers information about changes over time in the probability distributions of extreme weather events across Europe and their impacts. Some similar and consistent information has also been included in the present report and the related ETC-CCA technical paper on extreme events (van der Linden et al., 2015)
2014	European Commission (JRC)	*Climate impacts in Europe: The JRC PESETA II project* (Ciscar et al., 2014)	The JRC PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) conducted a consistent multi-sectoral assessment of the impacts of climate change in Europe for the 2071–2100 time horizon. Some results from the follow-up project GAP-PESETA have also been published. The present report contains information from these and other JRC projects in a range of chapters

1.2 Global emissions and socio-economic scenarios

The indicators in this report are based on a wide range of studies published in peer-reviewed academic papers and reports of international organisations. Section 1.2.1 presents the global scenarios of greenhouse gas emissions and associated radiative forcing that underlie projections of climate change and impact indicators in the subsequent chapters. Section 1.2.2 presents global socio-economic scenarios known as shared socio-economic pathways (SSPs) that complement the representative concentration pathways (RCPs). More detailed information on socio-economic scenarios for Europe is presented in Section 6.1. Section 1.2.3 provides an overview of the data coverage and the scenarios applied in indicators and other quantitative projections throughout this report.

1.2.1 Global emissions scenarios

Until about 2010, most climate projections used the storylines and the associated emissions scenarios published by the IPCC in 2000 in the Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). These SRES scenarios provide internally consistent socio-economic storylines and greenhouse gas emissions scenarios for four world regions. They are 'baseline' (or 'reference') scenarios, which means that they do not take into account specific agreements or policy measures aimed at limiting the emission of greenhouse gases (e.g. the Kyoto Protocol to the UNFCCC). The SRES emissions scenarios are organised into families, which contain scenarios that are based on similar assumptions regarding demographic, economic and technological development. The six families of emissions scenarios discussed in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4) are A1B, A1FI, A1T, A2, B1 and B2. Based on their cumulative emissions throughout the 21st century, they can be broadly grouped into low (B1), medium–low (B2, A1T), medium–high (A1B) and high (A2, A1FI) scenarios.

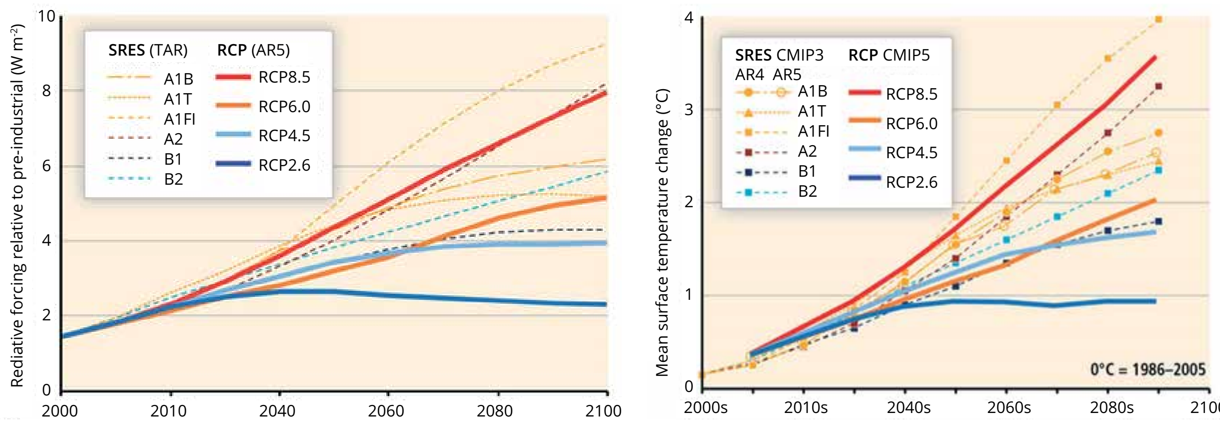
The follow-up generation of scenarios to support climate change research and assessments — developed from 2007 to 2010 through an innovative collaboration between integrated assessment modellers, climate modellers, terrestrial ecosystem modellers and emissions inventory experts — are called representative concentration pathways (RCPs). The RCPs provide a consistent set of trajectories for future atmospheric composition and land-use change up to the year 2100.

The four RCPs are named from RCP2.6 to RCP8.5 according to their approximate radiative forcing level in the year 2100. Extended concentration pathways (ECPs) extend the RCPs up to 2300 based on simple extension rules. All ECPs, including the highest, ECP8.5, assume that very low (or even negative) emission levels are reached by 2250 at the latest (Moss et al., 2010; van Vuuren et al., 2011). Minor differences in radiative forcing between the 'name' of an RCP and the values shown in Figure 1.1 (left) are due to different definitions of forcing (e.g. instantaneous, stratospherically adjusted, fixed sea surface, or effective radiative forcing) (Sherwood et al., 2015), how models implement the various radiatively active species (e.g. prescribed aerosol optical depth vs. prescribed aerosol precursor emissions), and uncertainties in converting concentrations to radiative forcing (Collins et al., 2013, Section 12.3).

There are two key 'technical' differences between the SRES scenarios and the RCP scenarios. One relates to the unit applied for specifying greenhouse gas 'emissions' and the other to the link between and socio-economic development. In the case of SRES, each scenario provides a trajectory of anthropogenic greenhouse gas emissions coupled with an underlying storyline of socio-economic development. In contrast, the RCPs are scenarios of radiative forcing, which is determined not only by direct anthropogenic greenhouse gas emissions but also by the future development of the global carbon cycle and other processes. Moreover, the process of RCP development has been separated from the socio-economic storyline development, which means that the different RCPs are not directly associated with a particular socio-economic scenario (see Section 1.2.2 for details on the development of socio-economic scenarios alongside the RCPs).

The key 'political' difference between the RCP and SRES scenarios is that the RCPs cover the full range of stabilisation, mitigation and baseline emissions scenarios available in the scientific literature, whereas all SRES scenarios are no-climate-policy scenarios. Therefore, the range of temperature projections between the highest and lowest RCP is larger than that between the highest and lowest SRES scenario (see Figure 1.1, right). Note that the highest RCP (RCP8.5) is less extreme than the highest SRES emissions scenario (A1FI), whereas the lowest RCP (RCP2.6), which requires ambitious mitigation policies, lies far below the range of the SRES scenarios (see Figure 1.1, left). As a result, the range of projected increases in global temperature for RCPs is smaller than the range of projections for SRES scenarios. Owing to the differences between RCP and SRES scenarios, the projections for global temperature increase during the 21st century in the IPCC AR5 (0.3 to 4.8 °C, based on the RCPs) (IPCC, 2013) and in the IPCC AR4 (1.1 to 6.4 °C, based on the SRES scenarios) (IPCC, 2007b) are not directly comparable. Further information on global temperature change projected for different RCPs is available in Section 3.2.2.

Figure 1.1 Relationship between SRES scenarios and RCPs



Note: Projected radiative forcing (left) and global mean surface temperature change (right) over the 21st century using the Special Report on Emissions Scenarios (SRES) and representative concentration pathway (RCP) scenarios.

Source: IPCC, 2014a (Figure 1.4). © 2014 Intergovernmental Panel on Climate Change. Reproduced with permission.

The primary characteristics of the four RCPs are as follows:

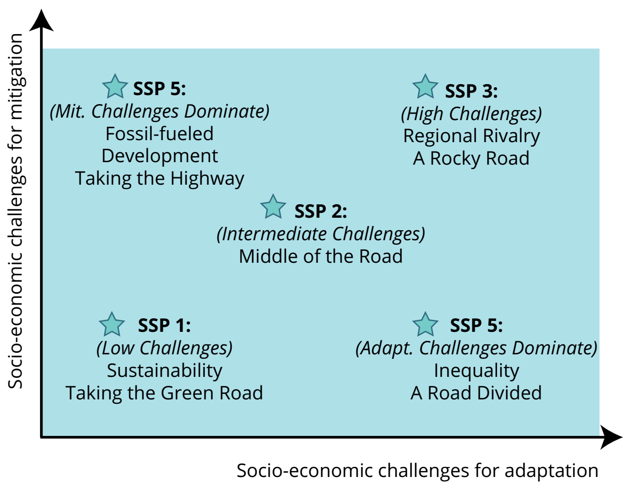
- RCP8.5 is a high-emissions scenario in which total radiative forcing reaches approximately 8.5 watts per square metre (W/m^2) in 2100 and continues to increase afterwards. Its extension, ECP8.5, stabilises at approximately 12 W/m^2 in 2250.
- RCP6.0 is a stabilisation scenario in which total radiative forcing is stabilised at approximately 6.0 W/m^2 shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions.
- RCP4.5 is a stabilisation scenario in which total radiative forcing is stabilised at approximately 4.5 W/m^2 shortly after 2100, without overshooting the long-run radiative forcing target level.
- RCP2.6 (also known as RCP3PD) is a 'peak-and-decline' scenario that leads to very low greenhouse gas concentration levels. Its radiative forcing level first reaches a value of around 3 W/m^2 by mid-century, and returns to approximately 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and, indirectly, emissions of air pollutants) are reduced substantially, leading to net negative carbon dioxide emissions at the end of the 21st century.

1.2.2 Global socio-economic scenarios

Not only are climate-related risks and vulnerabilities for geographic regions, economic sectors and people determined by the changing physical characteristics of the climate system, but they emerge from the interaction between changing climatic conditions and socio-economic changes. The development of non-climatic factors, such as demographic, economic, technological, environmental and political changes, play a crucial role in assessing the future consequences of climate change. On the one hand, the integration of climatic and socio-economic scenarios allows for more realistic and useful assessments for decision-makers, as they are more likely to cover conditions in which adaptation decisions need to be made. This is true, in particular, if future socio-economic trends are fairly well understood (e.g. certain demographic changes). Integrated assessments also facilitate estimates of the relative importance of various changes, such as rising sea level versus human settlement patterns in coastal zones. On the other hand, the inclusion of socio-economic scenarios may further increase the uncertainty of climate-related impact assessments, which may make them less amenable to decision-makers.

The different drivers of socio-economic change are characterised by strong inter-linkages and feedback loops in an increasingly interconnected world (EEA, 2015g), which requires a consistent and comprehensive consideration in scenario studies. Therefore, a coherent set of five global pathways describing potential alternative socio-economic futures — known as shared socio-economic pathways (SSPs) (O'Neill et al., 2014, 2015) — has recently been developed alongside the RCPs (see previous section). The five SSPs do not include climate policies or the impact of climate change in their underlying assumptions. Instead, they describe plausible future evolutions in key socio-economic variables that together imply a range of challenges for climate change mitigation and adaptation (see Figure 1.2). Each SSP consists of two main components: a narrative storyline (i.e. a qualitative description of potential future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources) and a set of quantifications for some of the key variables (e.g. population growth, gross domestic product (GDP), urbanisation, etc.). While the narrative storylines have been developed by means of a backcasting scenario approach based on expert opinion (O'Neill et al., 2015), the quantified variables result from various modelling exercises (Cuaresma, 2015; Dellink et al., 2015; Jiang and O'Neill, 2015; Samir and Lutz, 2015; Leimbach et al., 2015).

Figure 1.2 The five shared socio-economic pathways (SSPs)



Source: O'Neill et al., 2015. © 2015 Elsevier. Reproduced with permission.

The primary characteristics of the five SSPs are as follows (see also Figure 1.2 and Table 1.6):

- SSP1, 'Sustainability — Taking the Green Road', is characterised by low population growth associated with educational and health improvements, reductions in global inequality, increasingly effective international cooperation, and increasing environmental awareness that leads to improved resource efficiency, a boost in green technologies and low energy demand.

- SSP2, 'Middle of the Road', assumes a development path in which social, economic and technological trends do not significantly differ from historical patterns. This might lead to moderate population growth, slow progress towards achieving sustainability goals and the persistence of fossil fuel dependency, as well as income inequalities.

- SSP3, 'Regional Rivalry — A Rocky Road', assumes increased nationalism, regional conflict, weak international cooperation and more authoritarian forms of government in parts of the world. This would imply strong population growth in developing countries and low economic development with islands of moderate growth, but also widespread poverty, limited environmental concerns, and growing resource intensity and fossil fuel use.

- SSP4, 'Inequality — A Road Divided', is characterised by highly unequal development across world regions and countries with an increasing gap between industrialised, wealthy regions with high education levels, high technological development and moderate economic growth, and regions characterised by low levels of education, low economic development, weak institutions and increasing social unrest.

- SSP5, 'Fossil-fuelled Development — Taking the Highway', is characterised by rapid economic, technological and social development that is driven by increasingly integrated global markets, and based on the strong exploitation of fossil fuels and resource-intensive lifestyles. Global population growth peaks and declines in the 21st century.

Table 1.6 Summary of assumptions of SSPs for selected variables

	SSP1	SSP2	SSP3	SSP4	SSP5
Main objective	Global sustainability	Not defined	National security	Security	Economic growth
Population growth	Relatively low	Medium	High/low (*)	Relatively high/low (*)	Relatively low
Urbanisation	High	Medium	Low	High/medium (*)	High
Education level	High	Medium	Low	Low/medium (*)	High
Equity	High	Medium	Low	Medium	High
Economic growth	High/medium (*)	Medium, uneven	Slow	Low/medium (*)	High
International cooperation	Effective	Relatively weak	Weak, uneven	Effective (for small elite only)	Effective (but no environmental focus)
Institutions	Effective (all levels)	Uneven, modest effectiveness	Weak (global), strong (national)	Effective (for small elite only)	Effective (focus competitiveness)
Technological development	Rapid	Medium, uneven	Slow	Rapid (high-tech sectors only)	Rapid
Carbon intensity	Low	Medium	High (regions with large domestic resources	Low/medium (*)	High
Environment	Improving conditions	Continued degradation	Serious degradation	Degrading/ highly managed (*)	Highly engineered
SRES	B1 (A1T)	B2	(A2)	A2	A1FI

Note: (*) The information to the left of the slash refers to high-fertility countries (i.e. mostly developing countries) and the information to the right of the slash refers to rich Organisation for Economic Co-operation and Development (OECD) countries (KC and Lutz, 2015).

The bottom row with information on 'matching' SRES scenarios is only indicative, and some 'matches' are closer than others.

Source: Adapted from van Vuuren and Carter, 2014; O'Neill et al., 2015.

There is faith that environmental impacts can be managed effectively as technological development progresses.

The new scenario framework of RCPs and SSPs allows climate researchers to develop complex integrated scenarios that consider future changes in both climate and society, in order to systematically investigate the future consequences of climate change and of various mitigation and adaptation options (van Vuuren et al., 2014).

There is no direct link between RCPs and SSPs. However, achieving low greenhouse gas emissions pathways compatible with low RCPs (e.g. RCP2.6 and RCP4.5) is easier for some SSPs (e.g. SSP1 and SSP4) than for others (e.g. SSP5 and SSP3) (see Figure 1.2). Suggestions have been made for mapping the new scenario framework composed of RCPs and SSPs on to the earlier SRES storylines and emissions scenarios, as well as scenarios from other global environmental assessment studies (see last row of Table 1.6) (van Vuuren et al., 2012; O'Neill et al., 2014; van Vuuren and Carter, 2014).

1.2.3 Data coverage of indicators and scenarios

Most of the publications underpinning the indicators in this report use generally available emissions scenarios such as the 'old' SRES and the 'new' RCP scenarios, but there is inevitably variation in the choice and use of emissions scenarios and climate model runs in the studies underpinning individual indicators. Table 1.7 gives an overview of the data availability for all indicators and for other quantitative projections in this report including, among others, the emissions scenarios and climate models that were used. It also shows that only a limited number of impact, vulnerability and risk assessments have considered climate change along with other socio-economic developments. Further information on socio-economic scenarios for Europe is presented in Section 6.1.

Table 1.7 Data coverage of indicators and other quantitative projections

Section	Indicator/topic	Past trends (longest time series)	Projections	Emissions scenarios	Climate models	Socio-economic scenarios
3.2.2	Global and European temperature (*)	1850–2015	2080s	RCP4.5/8.5	RCM ensemble (EURO-CORDEX)	–
3.2.3	Heat extremes	1960–2015	2030s, 2080s	RCP4.5/8.5	GCM ensemble	–
3.2.4	Mean precipitation	1960–2015	2080s	RCP8.5	RCM ensemble (EURO-CORDEX)	–
3.2.5	Heavy precipitation	1960–2015	2080s	RCP8.5	RCM ensemble (EURO-CORDEX)	–
3.2.6	Wind storms	–	2080s	A1B	9 GCM and 11 RCM ensemble	–
3.2.7	Hail	1951–2010	–			
3.3.2	Arctic and Baltic sea ice (*)	*Arctic:* 1979–2016	Up to 2100	All RCPs	GCM ensemble	–
		Baltic: 1719–2016	–			
3.3.3	Greenland and Antarctic ice sheets	1992–2015	–			
3.3.4	Glaciers	1946–2014	Up to 2100	RCP4.5/8.5	14 GCM ensemble	–
3.3.5	Snow cover	1922–2015	Up to 2100	All RCPs	GCM ensemble	–
4.1.2	Ocean acidification	1988–2014	Up to 2100	All RCPs	GCM ensemble	–
4.1.3	Ocean heat content	1957–2013	–			
4.1.4	Sea surface temperature (*)	1870–2015	–			
4.1.5	Distribution shifts of marine species	1958–2014	–			
4.1.6	Ocean oxygen content	1906–2012	–			
4.2.2	Global and European sea level (*)	*Global:* 1880–2015	*Global:* 2081–2100	All RCPs, A1B	GCM ensemble	–
		European: 1970–2014	*European:* 2081–2100	RCP4.5	GCM ensemble	–
4.3.2	River flows	1963–2000	2080s	A1B	4 GCMs and 7 RCMs	–
4.3.3	River floods	1980–2010	2006–2035, 2036–2065, 2066–2095	RCP8.5	7 RCM ensemble	–
4.3.4	Meteorological and hydrological droughts	*Meteorological:* 1950–2012	*Meteorological:* 2050s, 2080s	RCP4.5/8.5	RCM ensemble	–
		Hydrological: 1963–2000	*Hydrological:* 2080s	A1B	12 GCM ensemble	Economy First
4.3.5	Water temperature	1911–2014	–			
4.4.2	Soil moisture	1951–2012	2030s	A1B	12 RCM ensemble	–
4.4.3	Phenology of plant and animal species	1982–2011	–			
4.4.4	Distribution shifts of plant and animal species	–	2050, 2100	A2, B1	HadCM3	SEDG, GRAS
4.4.5	Forest composition and distribution	–	2100	A1B	6 RCM ensemble	–
4.4.6	Forest fires	1980–2013	2080s	A1B	RACMO2 driven by ECHAM5	–
5.1.3	Economic losses from climate-related extremes (*)	1980–2013	–			
5.2.3	Floods and health	1991–2015	–			
5.2.4	Extreme temperatures and health	1987–2010	–			
5.2.5	Vector-borne diseases	Up to 2016	*Chikungunya:* 2020s, 2050s, 2080s	A1B, B1	COSMO-CLM	–
			West Nile Virus: 2025, 2050	A1B	CCSM3	–

Table 1.7 Data coverage of indicators and other quantitative projections (cont.)

Section	Indicator/topic	Past trends (longest time series)	Projections	Emissions scenarios	Climate models	Socio-economic scenarios
5.2.6	Water- and food-borne diseases	1982–2010	*Vibriosis:* 2050	–	–	–
5.3.2	Growing season for agricultural crops	1985–2014	–			
5.3.3	Agrophenology	1985–2014	–			
5.3.4	Water-limited crop yield	–	*Winter wheat:* 2030	RCP8.5	2 GCMs	–
			Crop mix: 2050s	A1B	12 GCM ensemble	–
			Wheat: 2060	RCP8.5	16 GCM ensemble	–
5.3.5	Crop water demand	1995–2015	2015–2045	RCP8.5	2 GCMs	–
5.4.2	Heating and cooling degree days	1951–2014	–			
Quantitative projections not presented in indicator format						
3.1.4	Changes in global and European temperature and precipitation		*Global:* 2081–2100	RCP2.6/8.5	GCM ensemble	–
			European: 2040s, 2080s	RCP2.6/8.5	GCM ensemble	–
4.4.7	Forest pests and diseases		2080s	A1B	2 GCMs	–
4.5.3	Climate change assessments of ecosystem services		2050s	A1B, A2, B1, B2	5 GCMs	We are the world, Should I stay or should I go
5.6.2	Tourism climatic index		2080s	A2	5 RCM ensemble (PRUDENCE)	–
6.1.1	Projected socio-economic developments		Up to 2100	–	–	SSP1–5
6.1.2	Projected changes in adaptive capacity		2020s, 2050s	–	–	We are the world, Icarus, Should I stay or should I go, Riders on the storm
6.2.2	Multi-sectoral hotspots		2 °C warming	RCP4.5/8.5	10 RCMs	–
6.2.3	Multi-hazard exposure		2020s, 2050s, 2080s	A1B	Different GCM-RCM combinations	–
6.2.4	An ecosystem service perspective		2050s	A1B, A2, B1, B2	5 GCMs	We are the world, Icarus
6.3	Projected costs of climate change in Europe		2080s	A1B, E1 (ENSEMBLES)	4 RCMs	–
6.6	Vulnerability to climate change in urban regions		2080s	A1B	12 RCM ensemble	–

Note: This table lists only quantitative projections of future changes in the form of graphs or maps. National or sub-national projections shown in boxes are not considered. A decade followed by 's' stands for the 30 years during which this decade is the centre (e.g. '2030s' refers to 2021–2050). Please see note below Table 1.2 for an explanation of the colour codes of indicator names. Indicators marked with an asterisk (*) are part of the EEA Core Set of Indicators (CSI) [8].

CCSM3, Community Climate System Model version 3; COSMO-CLM, Consortium for Small scale Modeling — Climate Limited-area Model; ECHAM5, fifth generation of the ECHAM general circulation model; GCM, general circulation model; HadCM3, Hadley Centre Coupled Model version 3; PRUDENCE, Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects; RACMO2, Regional Atmospheric Climate Model version 2; RCM, regional climate model.

[8] http://www.eea.europa.eu/data-and-maps/indicators#c5=&c0=10&b_start=0&c10=CSI.

1.3 Uncertainty in observations and projections

Many aspects of past and future climate change, its causes and its impacts are well known and undisputed by scientists (IPCC, 2013, 2014a, 2014b). Hence, there is substantial robust information available to inform climate change mitigation and adaptation policies. Nevertheless, data on observed and projected climate change and its impacts are always associated with some uncertainty. This section discusses the main sources of uncertainty that are relevant for this report, and how uncertainties are addressed and communicated, in particular in the 'Key messages'.

Note that the term 'uncertainty' is used by scientists to refer to partial, or imperfect, information (Sense about Science, 2013). Thus, the direction or the approximate magnitude of a phenomenon may be known, but the exact magnitude may not be known. For example, a scientific projection of the change in global mean temperature for a given emissions scenario may report a best estimate of 3 °C, with an uncertainty range of 2–4.5 °C. The uncertainty interval reflects the impossibility to forecast *exactly* what will happen. However, knowing that it is virtually certain that the Earth will continue to warm and that future warming will probably be within a certain range still provides highly relevant information to decision-makers concerned with climate change mitigation and adaptation.

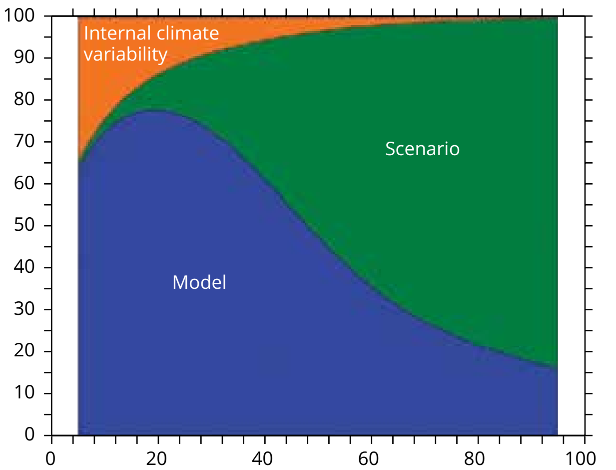
1.3.1 Sources of uncertainty

Uncertainties in indicators presented in this report arise primarily from the following sources. Some of them can, in principle, be reduced by further research, whereas others cannot.

- *Measurement errors* resulting from imperfect observational instruments (e.g. rain gauges) and/or data processing (e.g. algorithms for estimating surface temperature based on satellite data).
- *Aggregation errors* resulting from incomplete temporal and/or spatial data coverage. Most indicators presented in this report combine measurements from a limited number of locations (e.g. meteorological observation stations) and from discrete points in time to make aggregate statements on large regions and for whole time periods. Such aggregation introduces uncertainties, in particular when the measurement network is scarce and when the indicator exhibits large variations across space and/or time.
- *Natural variability* resulting from unpredictable natural processes within the climate system (internal climate variability; e.g. atmospheric and oceanic variability), influencing the climate system (e.g. future volcanic eruptions) and/or within climate-sensitive environmental and social systems (e.g. ecosystem dynamics).
- *Model limitations (of climate and climate impact models)* resulting from the limited resolution of models (e.g. hampering the explicit resolution of cloud physics), an incomplete understanding of individual Earth system components (e.g. dynamic ice sheet processes) or their interactions and feedbacks (e.g. climate–carbon cycle feedbacks), and/or an incomplete understanding of the environmental or social system under consideration (e.g. demographic development in flood risk zones). A parameter to describe a key uncertainty in global climate models is their climate sensitivity, which refers to the change in the annual global mean surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration, either at the time of doubling for a stylised concentration scenario (transient climate response) or in equilibrium (equilibrium climate sensitivity).
- *Future emissions trajectories (of greenhouse gases and aerosols)* determine the magnitude and rate of future climate change. Future emission levels depend on demographic, economic and technological development, as well as on international agreements for climate change mitigation (in particular under the UNFCCC).
- *Future development of non-climatic (socio-economic, demographic, technological and environmental) factors* determines how a given change in climate affects the environment and society.
- *Future changes in societal preferences and political priorities* determine the importance attached to a given climate impact (e.g. a local or regional loss of biodiversity).

The relevance of the various sources of uncertainty depends on the question to be answered. Their relative importance depends, among others, on the target system, the climate and non-climate factors the system is sensitive to, and the time horizon of the assessment. For example, uncertainty about future emissions levels of long-lived greenhouse gases becomes the dominant source of uncertainty for changes in global mean temperature on time scales of 50 years or more, but is of limited importance for short-term climate change projections (see Figure 1.3) (Hawkins and Sutton, 2009, 2011; Yip et al., 2011; Booth et al., 2013; Monier et al., 2014).

Figure 1.3 Relative contributions of three sources of uncertainty in model-based climate projections of global decadal mean surface temperature



Note: 'Model' refers to the climate model and 'scenario' refers to the emissions scenario.

Source: Adapted from Hawkins and Sutton, 2009. @ 2009 American Meteorological Society. Reproduced with permission.

Another source of uncertainty not explicitly mentioned in the list above is the downscaling of climate or climate impact projections. Most projections in this report cover all of Europe (i.e. EEA member and cooperating countries). Such a broad coverage necessarily limits the level of detail at which regional climatic, environmental and other features can be considered, and the spatial resolution at which projections can be presented. Decisions on the management of climate-sensitive resources at the national, regional and local levels typically require more detailed projections at a higher spatial resolution than can be presented in this report.

Some examples of how different kinds of uncertainties can influence the attribution of observed climate change to specific causes as well as climate change projections is given in Section 3.1. Further information on sources of uncertainty can be found in the uncertainty guidance of Climate-ADAPT ([9]).

1.3.2 Communicating uncertainty

The approach to describing the accuracy and robustness of data underpinning the indicators in this report is similar to that used in the 2012 report. It was inspired by the NUSAP ([10]) approach (Funtowicz and Ravetz, 1990) and by the considerable experience of the IPCC in communicating uncertainties (Mastrandrea et al., 2010). Over a period of more than 10 years, the IPCC has developed and refined a 'calibrated language' to express the confidence in and/or the likelihood of specific findings, which is consistently applied in IPCC reports. However, following the IPCC uncertainty guidance is not feasible in this report, because the small number of experts involved in its production prohibits quantitative expert assessments of confidence and uncertainty.

Unambiguity and clarity is particularly important in key messages, which summarise information from the underlying indicator or section. However, the very conciseness of key messages may prevent their robustness and uncertainty from being characterised in a nuanced way. Therefore, uncertainty communication focuses on key messages, but also involves the text underpinning them. In this report, uncertainty is addressed in particular by choosing carefully the type of statement and explaining the context of its validity, choosing the appropriate level of precision, and reporting the pedigree of a statement, including the main factors known to affect the confidence that can be had in a specific dataset or conclusion. These three elements are further explained below.

Appropriate choice of type of statement

Most indicator-related key messages in this report fall into one of the following categories:

- *observation* of a *climate* variable;
- *observation* of an *impact* variable (i.e. an environmental or social phenomenon that is sensitive to changes in climate);
- *detection* of a statistically significant *trend* (or change in trend) of a *climate* variable;
- *detection* of a significant *trend* (or change in trend) of an *impact* variable;
- *attribution* of an observed change in *climate* to anthropogenic factors (i.e. identifying anthropogenic actions, in particular greenhouse gas emissions, as the main cause of the observed change in climate);
- *attribution* of an observed *impact* to climate change (i.e. identifying an observed change in regional climate, for whatever reason, as the main cause of the observed regional impact);

([9]) http://climate-adapt.eea.europa.eu/uncertainty-guidance.
([10]) The Management of Uncertainty and Quality in Quantitative Information (http://www.nusap.net).

- *attribution* of an observed *impact* to *anthropogenic* climate change (i.e. identifying an observed change in regional climate as the main cause of an observed regional impact and also identifying anthropogenic greenhouse gas emissions as the main cause of the observed change in regional climate);
- model-based *projection* of a *climate* variable into the future;
- model-based *projection* of a climate-sensitive *impact* variable into the future;
- identification of *needs* for *adaptation*.

One type of statement that is not fully reflected in this list is model-based assessments of past changes in a climate or impact variable (e.g. climate re-analysis). Key messages are formulated so that it is clear what type of statement they make. For the sake of clarity, the combination of different types of statements in a single message is generally avoided. In this context, it is also important to carefully distinguish between the three different types of attribution statements (Hansen and Stone, 2015). Note that the type of statement supported by a particular dataset may depend on the spatial scale. For example, in the same dataset, a significant climate trend may be detectable at the continental scale (where year-to-year variability is low) but not in each region (where year-to-year variability is higher and regional factors may be important).

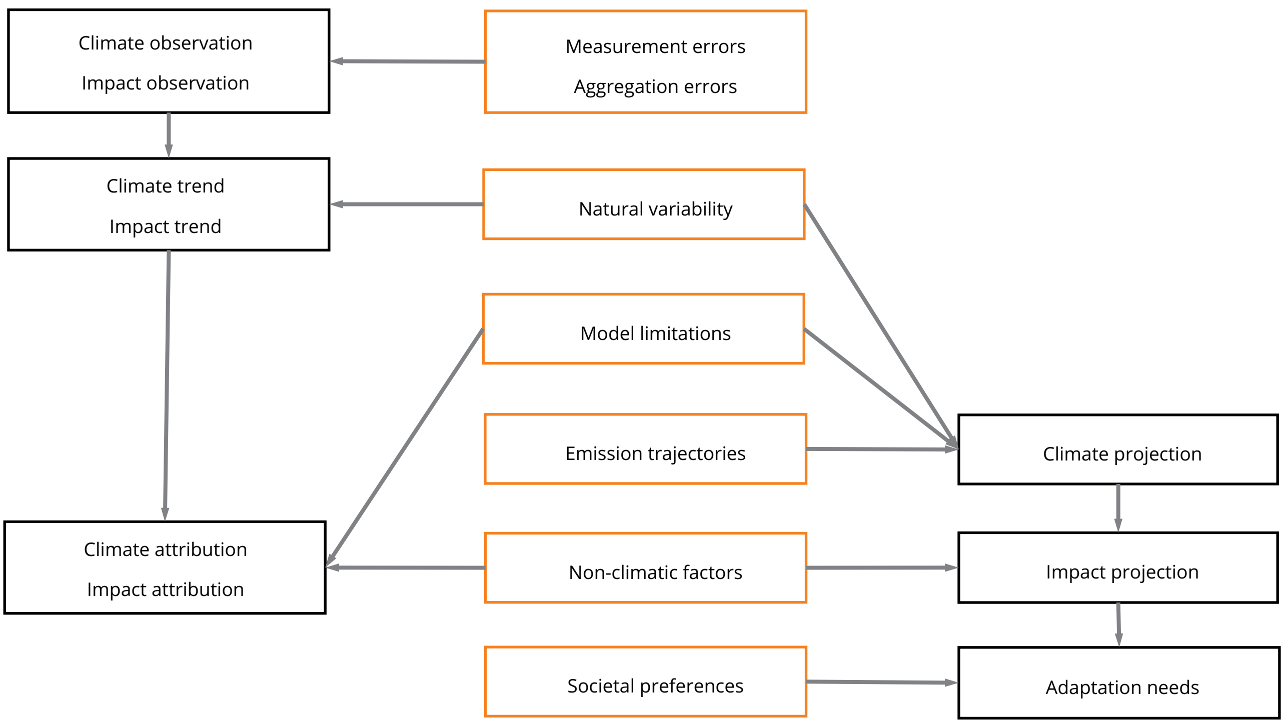
Different types of statements are subject to different sources of uncertainty (see Figure 1.4). The sources of uncertainty generally increase from observations and trends to attributions and projections, and from climate variables to climate impacts and possibly to adaptation needs. The term 'cascade of uncertainties' is used to represent that the magnitude of uncertainties in projections increases along the impact chain from greenhouse gas emissions to radiative forcing, global and regional climate change, and further to regional climate change impacts (see, for example, Ahmad et al., 2007).

Appropriate choice of the level of precision

The following levels of precision (or quantification) are distinguished in key messages (ordered here from least to most precise):

1. existence of effect (but the direction is ambiguous or unpredictable);

Figure 1.4 Influence of key sources of uncertainty on different types of statement



Note: This graphic shows how various sources of uncertainty (in orange) influence different types of statements (in black), with those on the left related to the past and those on the right related to the future.

Source: EEA.

2. direction of the change or trend;

3. order of magnitude of the change (e.g. indicated by a semi-quantitative verbal statement);

4. range or confidence interval;

5. single value (generally implying confidence in all significant digits).

As a general rule, key messages are formulated at the highest level of precision that is justified by the underlying data. Furthermore, related statements with different levels of precision (e.g. observation vs. projection) are clearly separated to indicate the precision of each individual statement.

Explicit information on the pedigree of information and uncertainty

Either the key message itself or the underlying text makes it explicit whether or not and how key sources of uncertainty have been considered in the underlying dataset. For example, a message on future climate change would indicate whether one or several emissions scenarios and one or several climate models were considered in producing the dataset.

1.3.3 Decision-making under uncertainty

The lack of perfect information is a common feature in all areas of science and policymaking. Therefore, uncertainty management is an integrated part of risk management. Decision-makers should be aware of the degree of uncertainty associated with specific data sources so that they can consider the range of plausible developments in their decisions, but uncertainties must not prevent decisions from being made (Sense about Science, 2013).

The importance of uncertainties about climate change and its impacts for a particular adaptation decision depends on factors such as the time horizon and reversibility of the decision, the relative importance of climate factors for the decision, and the costs of buffering the decision against uncertain developments. For example, when uncertainties are very large, it is often (but not always) prudent to focus on 'no/low regrets' and 'win–win' adaptation strategies that address adaptation to (uncertain) climate change jointly with other societal goals, thereby limiting the additional cost of the adaptation component.

A detailed discussion on adaptation decision-making under uncertainty or a review of the considerable body of academic and applied literature on this topic is beyond the scope of this report. Selected recent publications focus on robust adaptation decisions (Wilby and Dessai, 2010; Haasnoot et al., 2013), on decision-making approaches (Hallegatte et al., 2012), on adaptation assessment and decision-making (PROVIA, 2013), on economic assessment approaches (GIZ, 2013; OECD, 2015) and on practical adaptation examples from Europe (Capela Lourenço et al., 2014).

1.4 Definitions and frameworks for assessing vulnerability and risk

The terms 'vulnerability' and 'risk' are often used to describe the potential (adverse) effects of climate change on environmental, social and economic factors, as well as on systems. These terms are attractive, as they are intuitively understood by a large audience and rooted in the scientific communities that contribute to climate change assessments. The term 'vulnerable' is also used by the UNFCCC (UN, 1992) in the context of '(developing) countries [that] are particularly vulnerable to the adverse effects of climate change'. In general, use of these terms is unproblematic if they are applied in a rather generic, intuitive sense. However, conceptual models of vulnerability differ between scientific communities and are also changing over time. The resulting range of definitions can make the interpretation of certain statements difficult, in particular if the terms have been used quantitatively, and it may reduce the comparability across studies from different sources. The two most important concepts in the climate change context are the integrative vulnerability concept, as presented in the IPCC's Third and Fourth Assessment Reports (TAR and AR4), which is often described as 'outcome vulnerability' or 'end-point vulnerability', and the narrower vulnerability concept, as understood by the disaster risk community.

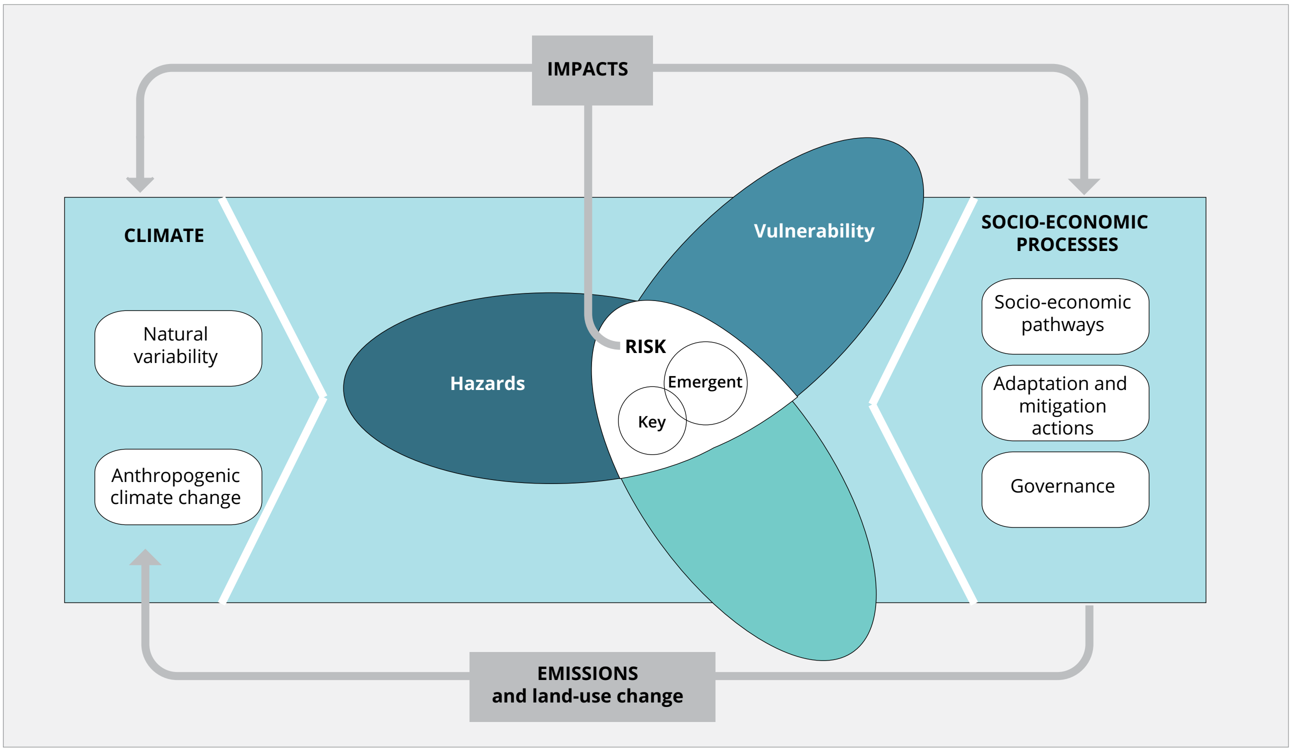
The IPCC defined vulnerability (to climate change) in its TAR and AR4 as '[...] a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity' (IPCC, 2007a). According to this definition, vulnerability (to climate change) is an integrated measure of the following three dimensions: exposure, sensitivity (which together determine the potential impacts of climate change) and adaptive capacity (i.e. the social and economic means to withstand climate change impacts). Vulnerability is, therefore, interpreted as the final outcome of an assessment that integrates biogeophysical and socio-economic factors. This concept has been applied in Europe by, for example, the CLIMSAVE project and for the assessment of urban areas (see Chapter 6).

Article 4.4 of the UNFCCC states that countries that are 'particularly vulnerable' to climate change should receive assistance for meeting the costs of adaptation. A sensible interpretation of this term requires consideration of the potential impacts as well as the adaptive capacity of countries, i.e. an integrated concept of vulnerability to climate change. However, such integration is highly sensitive to subjective preferences (Klein, 2009). Furthermore, the integration of climatic, environmental, economic and political factors into a single vulnerability score can obscure the key reasons why a particular country (or region, sector or population group) is more vulnerable than another, and thus compromise the development of effective adaptation and risk management measures. For example, increased flood risks may be caused by changes in extreme weather events, or by development in flood plains, or by a combination of these (and other) factors. The differentiation of factors behind observed or projected increases in climate-related risks can be facilitated by other conceptualisations of vulnerability and risk, such as those employed by the disaster risk community.

Standard applications of disaster risk assessment are primarily concerned with short-term (discrete) natural hazards, and assume that hazards are known and current vulnerabilities are static (Downing et al., 1999). The disaster risk approach distinguishes clearly between two determinants of risk to a system: exposure to a hazard (a potentially damaging physical event, phenomenon or human activity) and vulnerability (which denotes the relationship between the severity of the hazard and the degree of damage caused to an exposed element) (UN, 2004). An example of the recent application of this concept at the pan-European scale is presented in Section 6.2.

Additional definitions of vulnerability (and other terms) have been developed in a range of disciplines (e.g. ecology, epidemiology and social sciences). As a result, different terms have been used to describe similar concepts and the same term has been used to describe different concepts (O'Brien et al., 2007; Füssel, 2007; Birkmann and UNU-EHS Expert Working Group on Measuring Vulnerability, 2013, Chapter 23). For example, the indicators used to determine 'vulnerability' in the disaster risk context are often quite similar to those describing the 'sensitivity' of the system's components to climatic stimuli, and (integrated) vulnerability in the climate change context is sometimes used in a similar way to 'risk' in disaster risk assessment (Costa and Kropp, 2013). In addition, findings described as 'vulnerabilities' in some studies

Figure 1.5 An integrated framework for the risk of climate-related impacts



Source: IPCC, 2014a (Figure SPM.1). © 2014 Intergovernmental Panel on Climate Change. Reproduced with permission.

may be referred to as 'impacts' in others, and 'adaptive (or coping) capacity' in one setting may be described as 'social vulnerability' in another.

The IPCC partially integrated the different conceptualisations of vulnerability into its Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC, 2012), and further developed and adjusted these in the AR5 (IPCC, 2014a). The following points from the AR5's glossary are noteworthy (IPCC, 2014b, Annex II: Glossary): (1) 'vulnerability' is defined rather generally as the 'propensity or predisposition to be adversely affected'; (2) a similarly general definition is given for 'vulnerability index'; (3) the definition of 'outcome vulnerability' is similar to that for 'vulnerability' in the TAR and AR4; and (4) the definition of 'contextual vulnerability' is closer to the vulnerability concept applied in the social sciences and in ecology. The glossary also contains (for the first time) an explicit definition of 'risk', which 'results from the interaction of vulnerability, exposure and hazard' (see Figure 1.5). The definition also emphasises the partly subjective nature of risk (assessment), highlighting 'consequences where something of value is at stake [...], recognizing the diversity of values'. In summary, the predominant definition of vulnerability and risk in the IPCC AR5 is close to the use of these terms in the disaster risk community, but other vulnerability definitions are also recognised.

In line with the IPCC, the EEA accepts the existence of various definitions and interpretations of vulnerability and risk in climate change science and policy. The approach in this report is, therefore, not to choose one specific definition over another, but to use the terms from the underlying literature, and provide further explanation where needed.

The role of indicators in assessing vulnerability and risk

Indicator-based assessments of climate change vulnerability and risk are of particular interest to policymakers, as they are usually based on readily available (statistical) data and the results can be communicated effectively using graphical and map-based techniques. Results from contemporary indicator-based studies often follow the IPCC TAR/AR4 outcome-based definition of vulnerability (see above) and combine a range of individual indicators for each of the three components 'exposure', 'sensitivity' and 'adaptive capacity' into a single composite indicator of 'vulnerability' or 'risk' (Schröter et al., 2005; Yohe et al., 2006; Diffenbaugh et al., 2007; Dunford et al., 2015). The individual indicators are typically derived from physical models (e.g. key climate variables) or taken from statistically robust data sources (e.g. income, population, etc.).

However, composite indicators of vulnerability and risk have received scrutiny in several reviews, some of which have criticised the approaches because of methodological shortcomings (Barnett et al., 2008; Füssel, 2010; Hinkel, 2011; Tonmoy et al., 2014). Issues highlighted as problematic include the comparability or 'data normalisation' of individual indicators, statistical aggregation into a single composite indicator, and weighting of individual indicators (i.e. importance relative to one another). It has been argued that conceptualisations of vulnerability using composite indicators are often constructed without sufficient understanding of 'exposure', 'sensitivity' and 'adaptive capacity'; their influencing factors, interdependencies and non-linearities; spatial scale; and fundamental relationships to vulnerability. It has also been highlighted that underlying assumptions and interpretations of key terms (e.g. vulnerability, risk, etc.) are often not made explicit, and that related uncertainties are poorly communicated (if at all). In particular, generic indices of the vulnerability of countries (or regions) to climate change have been criticised as potentially misleading and inadequate in guiding climate adaptation investments, as they lack sector- or hazard-specific information.

Despite these shortcomings, composite indicators of vulnerability and risk remain attractive as synthesis (communication) tools that integrate information from multiple climatic and non-climatic stressors. They can provide an entry point for policymakers to discuss climate change adaptation needs, if they are used appropriately and if they are considered in conjunction with other information sources. It has been argued that sector-specific, region-specific and climate hazard-specific vulnerability indicators are more appropriate for decision-making than highly aggregated multi-sectoral indicators (Füssel, 2010; Preston et al., 2011). Note that all indicators based on sector-based assessments risk ignoring important cross-sectoral interactions. In order to ensure transparency, the approach in this report is to provide further explanation and clarification about underlying calculation methods and assumptions where composite indicators are presented (see, for example, Section 6.2).

2 Policy context

2.1 Global policy context

2.1.1 United Nations Framework Convention on Climate Change

The threat of climate change is being addressed globally by the United Nations Framework Convention on Climate Change (UNFCCC, 1992). Its long-term objective is 'to stabilise atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.'

Mitigation

In 1997, the Kyoto Protocol was adopted, which legally bound the participating developed countries to achieving greenhouse gas emissions reduction targets by 2008–2012, the first commitment period. A number of countries, as well as the EU, agreed to take on mitigation commitments until 2020 for a second commitment period running from 2013 to 2020 (UNFCCC, 2012).

In 2010, the international community agreed on the need to reduce emissions in order to prevent global temperature increases from exceeding 2 °C compared with pre-industrial levels ('Cancun agreements', UNFCCC, 2010). This would require global emissions to be cut by 40 to 70 % compared with 2010 by 2050 (Edenhofer et al., 2014).

At the Paris climate conference (COP21) in December 2015 (UNFCCC, 2015), 197 countries adopted the first-ever universal, legally binding global climate deal. The agreement is due to enter into force in 2020 or earlier, depending on the process of ratification. The Paris Agreement aims to be a bridge between today's policies and climate-neutrality before the end of the century, and, with regard to mitigation, the governments agreed:

- a long-term goal of keeping the increase in global average temperature to well below 2 °C compared with pre-industrial levels;
- to pursue efforts to limit the increase to 1.5 °C compared with pre-industrial levels, as this would significantly reduce risks and the impacts of climate change;
- on the need for global emissions to peak as soon as possible, recognising that this will take longer for developing countries;
- to undertake rapid reductions thereafter, in accordance with the best available science.

Before and during the Paris conference, countries submitted comprehensive national climate plans, outlining their intended nationally determined contributions (INDCs). These are not yet enough to keep global warming below a 2 °C increase (UNEP, 2015), but the agreement outlines the way to achieve this target. The EU contribution to the international agreement is detailed in the next section.

Adaptation

Even if the limit of a 2 °C increase (of the average global surface temperature) is adhered to, many places on Earth will experience a (much) higher temperature increase, and climate change will have many impacts across the globe. Adaptation to climate change has thus been recognised within the UNFCCC as an important policy pillar (with a primary focus on vulnerable developing countries), which is complementary to the mitigation of climate change. The current main agreed actions within the UNFCCC regarding adaptation are outlined below.

The UNFCCC requires all Parties to prepare and report 'National Communications' every three to five years. On climate change impacts, vulnerability and adaptation, the current guidance for developed countries includes reporting on actions within the country, on assistance provided to developing country Parties, and on research and systematic observation. The guidance on reporting, however, leaves much flexibility. EU Member States as well as the EU as a whole (prepared by the European Commission) have all reported their sixth National Communication (UNFCCC, 2016). However, there is limited quantitative and comparable (across

Europe) information in these reports on climate change impacts and vulnerability. These National Communications have been used as background material for this EEA indicator-based report.

The objective of the Nairobi Work Programme (UNFCCC, 2005) is to assist all countries, but in particular developing countries, in improving their understanding and assessment of impacts, vulnerability and adaptation to climate change, and in making decisions on practical adaptation actions and measures on a sound scientific, technical and socio-economic basis.

In 2009, developed countries pledged to provide new and additional resources of USD 30 billion for the period 2010–2012 in a Fast Start Finance programme, with balanced allocation between mitigation and adaptation, and USD 100 billion annually by 2020. The Cancun Agreements, adopted at the UN Climate Conference in Mexico (UNFCCC, 2010), established a Green Climate Fund, through which much of the funding will be channelled. Public and private finance provided by developed countries was estimated to be USD 62 billion in 2014, up from USD 52 billion in 2013 (OECD, 2015). The EU and its Member States provided EUR 7.34 billion in 'fast start finance' from public budgets and other development finance institutions from 2010 to 2012 and, in 2013 and 2014, these contributions were, respectively, EUR 9.5 billion and EUR 14.5 billion (EC, 2016a).

With regard to adaptation, governments agreed at the Paris COP21 (UNFCCC, 2015):

- to establish the adaptation goal of 'enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change';
- to strengthen societies' ability to deal with the impacts of climate change;
- to engage in national adaptation planning processes;
- to provide continued and enhanced international support for adaptation to developing countries.

The EU and developed countries outside the EU will continue to support climate action to reduce emissions and build resilience to climate change impacts in developing countries. Other countries are encouraged to provide or continue to provide such support voluntarily. Developed countries intend to continue their existing collective goal to provide USD 100 billion per year until 2025 when a new collective goal will be set.

2.1.2 Disaster risk reduction and sustainable development

The issue of climate change mitigation and adaptation has increasingly become an integrated part of economic analyses and is now a prominent element of risk assessments for public and private bodies. 'The Global Risks Report 2016' of the World Economic Forum (WEF, 2016) indicates that the most impactful risk for the years to come (i.e. the risk with the greatest potential damage) was found to be a failure of climate change mitigation and adaptation. This is the first time an environmental risk has topped the WEF ranking, ahead of weapons of mass destruction (second), water crises (third), large-scale involuntary migration (fourth) and a severe energy price shock (fifth). The number one risk in 2016 in terms of likelihood, meanwhile, is large-scale involuntary migration, followed by extreme weather events (second), a failure of climate change mitigation and adaptation (third), interstate conflict with regional consequences (fourth) and major natural catastrophes (fifth).

The Third UN World Conference on Disaster Risk Reduction (WCDRR), held in Sendai, Japan (14–18 March 2015) adopted the 'Sendai Framework for Disaster Risk Reduction 2015–2030' (UN, 2015). The framework is a voluntary, non-binding agreement. It includes four priorities for action:

- Priority 1: Understanding disaster risk.
- Priority 2: Strengthening disaster risk governance to manage disaster risk.
- Priority 3: Investing in disaster risk reduction for resilience.
- Priority 4: Enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation and reconstruction.

The framework includes seven targets intended to drive progress on protecting human beings and assets from extreme weather, and other natural and man-made hazards. These targets aim to reduce global disaster mortality, the number of affected people globally, direct disaster economic loss, disaster damage to critical infrastructure and disruption of basic services; to increase the number of countries with national and local disaster risk reduction strategies; to enhance international cooperation to developing countries; and to increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments. The framework acknowledges climate change as 'one of the drivers of disaster risk'.

In addition, the 2030 Agenda for Sustainable Development, agreed in 2015 (UN, 2016), has 17 overarching Sustainable Development Goals (SDG) and within each a range of targets ([11]). The following goals are most relevant regarding climate change adaptation (and also disaster risk reduction):

- Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
- Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
- Goal 13: Take urgent action to combat climate change and its impacts, acknowledging that the UNFCCC is the primary international, intergovernmental forum for negotiating the global response to climate change.
- Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
- Goal 15: Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss.

2.2 Mitigation at EU level

The EU climate change mitigation policy has targets for reducing its greenhouse gas emissions progressively up to 2050. Key relevant EU policies are the legally binding 2020 'climate and energy package' (included in EC, 2010), which comprises the EU Effort Sharing Decision (EU, 2009) and the revised EU emissions trading scheme; the 2030 'framework for climate and energy policies' (not yet adopted); and the 2050 low-carbon roadmap (EC, 2011).

The Effort Sharing Decision establishes binding annual greenhouse gas emissions targets for Member States for the period 2013–2020. These targets concern emissions from most of the sectors that are not included in the EU Emissions Trading System. The 2020 package is a set of binding legislation to ensure that the EU meets its climate and energy targets for 2020:

- 20 % cut in greenhouse gas emissions (from 1990 levels);
- 20 % of EU final energy consumption from renewables;
- 20 % improvement in energy efficiency compared with baseline.

The 2030 climate and energy framework proposes three key targets for 2030 (meeting at least these levels):

- 40 % cut in greenhouse gas emissions (from 1990 levels);
- 27 % of EU final energy consumption from renewables;
- 27 % improvement in energy efficiency compared with baseline.

These targets are defined to put the EU on track to achieving its transformation into a low-carbon economy, as detailed in the 2050 low-carbon roadmap, which aims to cut EU greenhouse gas emissions by 80 to 95 % by 2050.

The EU tracks its progress on cutting emissions through regular monitoring and reporting (EC, 2016b). All EU Member States are required to monitor their emissions under the EU's greenhouse gas monitoring mechanism, which sets the EU's own internal reporting rules on the basis of internationally (UNFCCC) agreed obligations. According to an EEA report, the EU is on track towards its 2020 climate targets (EEA, 2015b). The report also shows that, to achieve the EU's longer term goals for 2030 and 2050, new policies are required and more fundamental change is needed in the way the EU produces and uses energy in Europe.

2.3 Adaptation at EU level

The EU strategy on adaptation to climate change (EC, 2013a) aims to make Europe more climate-resilient. Taking a coherent approach by complementing the activities of Member States, it promotes adaptation action across the EU, ensuring that adaptation considerations are addressed in all relevant EU policies (mainstreaming), promoting greater coordination, coherence and information-sharing and supporting climate-resilient sustainable development. This section aims to provide information regarding the EU Adaptation Strategy and its implementation, including ongoing and planned actions beyond the detailed information that was provided in the sixth National Communication.

In 2013, the European Commission adopted the communication 'An EU Strategy on adaptation to climate change', which includes several elements

([11]) https://sustainabledevelopment.un.org/topics.

to support Member States in adaptation: providing guidance and funding, promoting knowledge generation and information-sharing, and enhancing resilience of key vulnerable sectors through mainstreaming. In addition, the 7th Environment Action Programme (EAP) to 2020, 'Living well, within the limits of our planet' (EU, 2013a), contains nine priority objectives, of which Objective 1, 'To protect, conserve and enhance the Union's natural capital', and Objective 2, 'To safeguard the Union's citizens from environment-related pressures and risks to health and well-being', are particularly relevant for climate change adaptation.

The EU and its Member States regularly submit — in line with their commitments under Article 4.1b of the Convention — information on adaptation actions through National Communications and other existing reports under the UNFCCC. The latest National Communication of the EU, as well as individual National Communications of its 28 Member States, can be found on the UNFCCC website (UNFCCC, 2016).

EU Adaptation Strategy — Objective 1: promoting action by Member States

All EU Member States are encouraged to adopt, implement and review comprehensive adaptation strategies.

- Full EU coverage: as of May 2016, 20 Member States (and three further EEA member countries) ([12]) have adopted adaptation strategies/action plans. Several Member States are in the process of either planning or reviewing their adaptation strategies and action plans based, inter alia, on the European Commission guidelines prepared for the formulation of adaptation strategies (EC, 2013b). For further information, see Section 2.4.

- Governance: the European Commission facilitates policy coordination and cooperates with Member States through regular meetings of a Working Group on Adaptation. Participants in this group are national contact points on adaptation appointed by the Member States.

- Monitoring: the European Commission proposed in 2015 an 'adaptation preparedness scoreboard', which identifies key indicators for assessing Member States' level of readiness and aims to review the steps in adaptation policymaking, comprising preparing the ground for adaptation, assessing risks and vulnerabilities, identifying adaptation options, implementing adaptation action, and monitoring and evaluation.

- In 2015, Member States provided reports on their adaptation activities within the EU climate monitoring and reporting system (the Monitoring Mechanism Regulation; EU, 2013b), including information on Member States' national adaptation planning and strategies, outlining their implemented or planned actions to facilitate adaptation to climate change. The information reported has been incorporated into the country pages of Climate-ADAPT ([13]) (see also Objective 2 below).

- Evaluation: in 2017–2018, the European Commission will assess whether action being taken in the Member States is sufficient and consider whether additional measures would be needed. In 2018, the Commission will report to the European Parliament and the Council on the evaluation of the EU Strategy on adaptation to climate change and propose its review if needed. The report will include information on progress by Member States, including an updated scoreboard, progress in mainstreaming (e.g. within EU policies and the use of EU funds), and new knowledge and demands.

- Action at local level: the Covenant of Mayors Initiative on Adaptation to Climate Change (Mayors Adapt) ([14]), which was recently merged with the Covenant of Mayors for Climate & Energy and Mayors Adapt ([15]), is an initiative whereby European cities sign up to contribute to a more climate-resilient Europe by developing local adaptation strategies and reviewing the outcomes on a biannual basis. More than 120 European cities or provinces have already committed, and the Commission is aiming to have at least 200 cities committed to the initiative by 2017.

- The LIFE Programme (EU, 2014) is the EU's financial instrument supporting environmental, nature conservation and climate action projects in the EU Member States. Yearly calls for proposals with adaptation-relevant priorities have been launched since 2014. Funding can be used for adaptation activities in vulnerable areas in Europe.

([12]) Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Lithuania, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the United Kingdom. In addition, Norway, Switzerland and Turkey have adopted adaptation strategies/action plans.
([13]) http://climate-adapt.eea.europa.eu/countries.
([14]) http://mayors-adapt.eu.
([15]) http://www.covenantofmayors.eu/index_en.html; https://ec.europa.eu/energy/en/news/cities-unite-energy-and-climate-action-new-integrated-covenant-mayors-launch.

EU Adaptation Strategy — Objective 2: better informed decision-making

The EU Adaptation Strategy promotes better informed decision-making by addressing gaps in knowledge about adaptation through various channels.

- Climate-ADAPT, the European Climate Adaptation Platform ([16]), aims to support Europe in adapting to climate change and helps users to access and share information on, for example, current and future vulnerability of regions and sectors, national and transnational adaptation strategies, case studies, potential adaptation options, and tools that support adaptation planning. Currently, it contains more than 1 500 adaptation resources in its database, as well as adaptation information relevant to all EU policy sectors, information on countries' adaptation policies and actions, and information on EU funding sources. The platform is continuously updated. In 2015, information on urban adaptation was improved in collaboration with the Mayors Adapt initiative. In addition, links with relevant other platforms including transnational, national and local adaptation portals are continuously improved. In the future, information from research projects and from climate services (including the Copernicus climate change service ([17])) will also be enhanced.

- Horizon 2020 ([18]), the EU Framework Programme for Research and Innovation, aims to dedicate 35 % of funds to climate-related research, including adaptation. The programme addresses knowledge gaps such as those identified in the EU Adaptation Strategy, including the development and testing of decision-making support tools, monitoring systems for adaptation, resilient infrastructures, and the integration of climate change adaptation in sectoral research (health, water, etc.) (see also Chapter 7).

- Currently the Copernicus climate change service, the EU programme on observations and climate services to support climate change policymaking, is under development with the operational service scheduled to start around 2018.

EU Adaptation Strategy — Objective 3: climate-proofing common EU action — promoting adaptation in key vulnerable sectors

- In the European Multiannual Financial Framework (2014–2020), the EU has agreed that at least 20 % of its budget for 2014–2020 — as much as EUR 80 billion — should be spent on climate change-related action, including in development cooperation programmes. In order to facilitate Member States' efforts in programming, principles and recommendations regarding the integration of adaptation into common EU funding instruments have been prepared ([19]). Climate change mitigation and adaptation actions receive more than EUR 114 billion from European Structural & Investment Funds (ESIFs), of which almost half — about EUR 56 billion — comes from the European Agricultural Fund for Rural Development. The European Regional Development Fund and the Cohesion Fund also make a significant contribution of about EUR 55 billion collectively. The allocated amounts cover 25 % of the overall ESIF budget, thus supporting the overall objective of allocating at least 20 % of the EU's overall budget for climate action (see above) (EC, 2015).

- Under the requirements of the Water Framework Directive (EC, 2000), Member States were due to present River Basin Management Plans by December 2015. These plans will be assessed by the European Commission and the results of the assessment will be published at the latest by the end of 2018. Climate change considerations and adaptation strategies will be looked at both in the plans and in the definition of the programmes of measures. The Floods Directive (EC, 2007) required Member States to carry out a preliminary assessment by 2011 to identify the river basins and associated coastal areas at risk of flooding. For such zones, Member States needed to draw up flood risk maps by 2013 and establish flood risk management plans focused on prevention, protection and preparedness, and report these by March 2016. Climate change should be taken into account. The European Commission will assess these plans and report on the results by the end of 2018 at the latest.

- One of the main objectives of the EU Common Agricultural Policy (CAP) 2014–2020 is to promote the sustainable management of natural resources and climate action. The CAP integrates environmental

([16]) http://climate-adapt.eea.europa.eu.
([17]) http://www.copernicus.eu; http://www.copernicus.eu/main/climate-change.
([18]) http://ec.europa.eu/programmes/horizon2020.
([19]) These principles and recommendations have been prepared for the European Maritime and Fisheries Fund, for programmes and investments of Cohesion Policy and for rural development programmes; see http://ec.europa.eu/clima/policies/adaptation/what/documentation_en.htm.

and climate change concerns by rewarding the introduction of practices that are beneficial for the environment and climate, by setting minimum targets for measures concerning environment and climate-related investments, and by promoting Member States' action towards the preservation of ecosystems and supporting a climate-resilient economy. Adaptations to the implementation and/or design of the CAP might occur as a follow-up to the mid-term report on implementation foreseen in 2017.

2.4 Adaptation at country level

This section provides a brief overview of adaptation actions undertaken at the level of individual EU Member States. It is based on the 2014 EEA report on national adaptation processes (EEA, 2014), reporting in 2015 by all 28 Member States under Article 15 of the Monitoring Mechanism Regulation, and the sixth UNFCCC National Communications of the EU Member States.

National adaptation strategies and plans, and monitoring, reporting and evaluation

To date, 23 European countries (20 EU Member States and three further EEA member countries) have adopted a national adaptation strategy (NAS) and 12 have developed a national adaptation plan (NAP) (see Map 2.1). More than half of European countries have made progress in identifying and assessing adaptation options.

Adaptation is most often implemented by applying 'soft' measures (e.g. providing information or mainstreaming). The water, agriculture and forestry sectors are reported to be the most advanced in terms of implementing portfolios of adaptation measures at all administration levels.

An increasing number of European countries are now taking action on monitoring, reporting and evaluation (MRE) of adaptation at national level (EEA, 2015a). So far, 14 countries have systems for monitoring, reporting and/or evaluation of adaptation in place or under development (see Map 2.1). Most countries have so far focused on monitoring and reporting activities. The evaluation of adaptation policies is often at an early stage because the implementation of adaptation has only just begun.

Across European countries, progress on adaptation strategies and plans varies considerably and the same is true for MRE of adaptation. Despite these differences, early insights from this dynamic field of practice can be valuable to countries with established approaches, as well as to those just beginning to consider MRE of adaptation. These experiences contribute to an essential information base for countries to learn from.

Success factors for and barriers to adaptation and knowledge gaps

Progress in adaptation depends on a number of success factors and their interconnection. For example, effective coordination among authorities supports the involvement of a wide range of stakeholders by ensuring the availability of consistent and reliable information, and by ensuring clarity with respect to roles and responsibilities.

Barriers to adaptation are not simply the inverse of success factors. A lack of resources (e.g. time, money and equipment) and uncertainties are viewed by European countries as the most important barriers. Uncertainties are a common feature across all levels of advancement in policymaking. Policymaking can benefit from embedding processes that focus on learning from experiences, reviewing progress and policy objectives, and encouraging innovative experimentation.

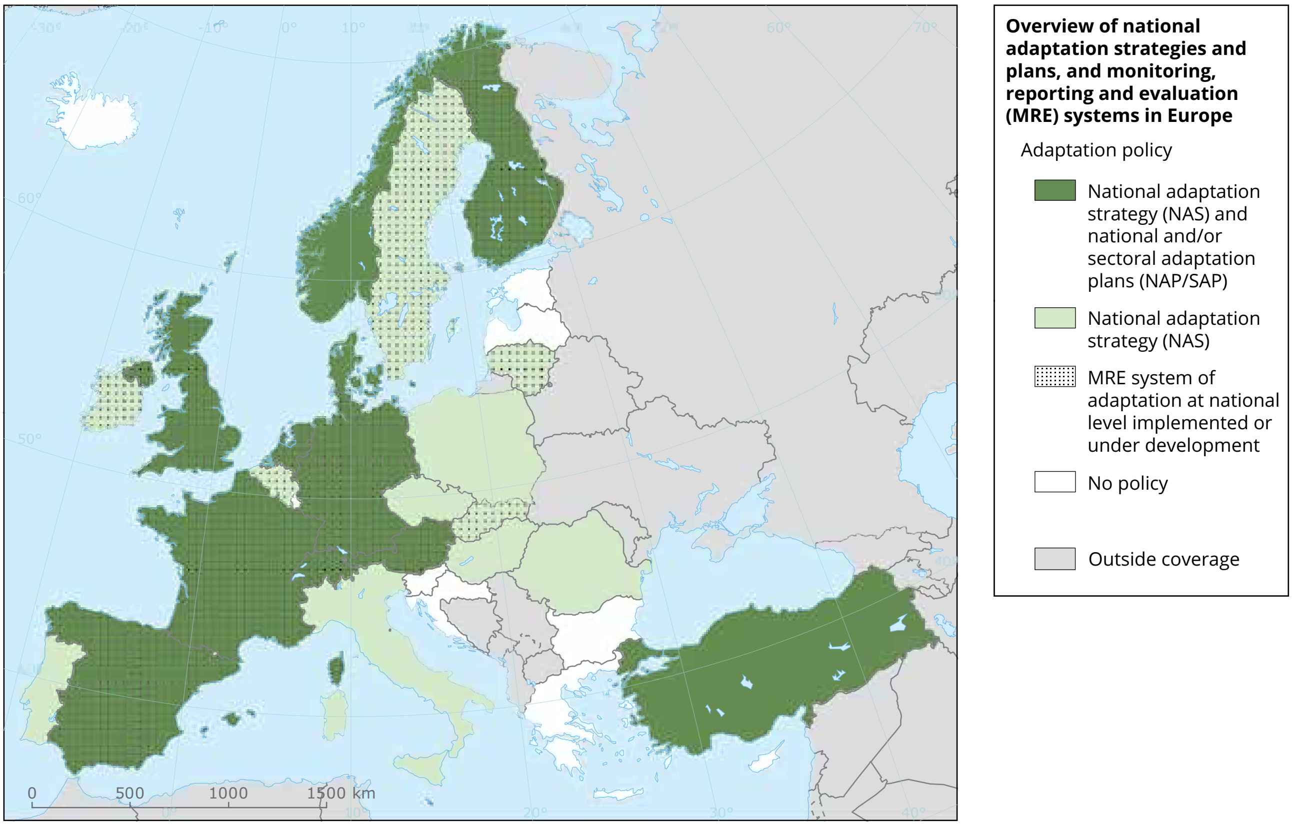
To further support adaptation in European countries, more information is needed on the costs and benefits of adaptation, as well as on the risks and uncertainties, vulnerabilities at local level, and the availability of data for monitoring and evaluation purposes (see also Chapter 7).

Transnational cooperation

Transnational cooperation in adaptation to climate change has increased with the recognition of the importance of adaptation as a cross-cutting policy area. Half of European countries report considering transnational cooperation in national adaptation policy processes. Transnational cooperation in adaptation has often been developed with the support of European funding instruments, and in the context of established cooperation forums such as European regional conventions.

Water management is an area that has a broad experience of transnational cooperation in the EU, and was the first area in which adaptation to climate change was considered, e.g. transboundary river basins or catchment management. Coastal area management is another common sector for transnational cooperation and where adaptation to climate change has been recognised as a transboundary issue, as well as biodiversity conservation and strategies, and risk management protocols for natural hazards.

Map 2.1 **Overview of national adaptation strategies and plans, and monitoring, reporting and evaluation (MRE) systems in Europe**



Source: Updated from EEA, 2014, 2015a.

The EU supports the development of regional strategies ([20]) that involve several countries and integrate the consideration of climate change impacts and adaptation, e.g. for the Baltic Sea region ([21]), the Danube region ([22]), the Adriatic and Ionian region ([23]), the Alpine region ([24]) and the international river basin district Rhine ([25]). Further information on macro-regional collaborations is provided in Section 2.5.

Valuable cooperation and exchange of experiences is also taking place within the Interest Group on 'Climate Change and Adaptation' (IG CCA) of the Network of European Environmental Protection Agencies.

([20]) http://ec.europa.eu/regional_policy/en/policy/cooperation/macro-regional-strategies.
([21]) http://www.baltadapt.eu.
([22]) http://www.danube-region.eu.
([23]) http://ec.europa.eu/regional_policy/en/policy/cooperation/macro-regional-strategies/adriatic-ionian.
([24]) http://ec.europa.eu/regional_policy/index.cfm/en/policy/cooperation/macro-regional-strategies/alpine.
([25]) http://www.iksr.org/en.

2.5 Adaptation in European macro-regions

There are a number of initiatives within European macro-regions that address and embed climate change adaptation. Specifically, those that are supported by legal and policy instruments are detailed below, per macro-region.

2.5.1 Arctic region

Arctic Council

The prime political body of the Arctic region is the Arctic Council ([26]), which is a high-level intergovernmental forum for cooperation, coordination and interaction among the Arctic states, with the involvement of the Arctic Indigenous communities and other Arctic inhabitants. Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden and the United States of America are Arctic Council Member States. Arctic organisations of indigenous peoples with an Arctic Indigenous constituency majority are permanent participants in the Arctic Council. The Standing Arctic Council Secretariat is located in Tromsø, Norway. The Council's activities are conducted in six working groups that deal with topics ranging from climate change to emergency response. Climate change has been addressed, in particular, by the Arctic Monitoring and Assessment Programme (AMAP), but, as climate change is a cross-cutting topic, other working groups also deal with this topic from their particular angle.

Other Arctic organisations

The members of The Nordic Council of Ministers are Denmark, Finland, Iceland, Norway, Sweden and the autonomous territories of the Åland Islands (Finland), the Faroe Islands (Denmark) and Greenland (Denmark). The Council's Arctic Co-operation Programme 2015–2017 addresses climate change as one of its focal areas (The Nordic Council, 2014).

The Barents Euro-Arctic Council (BEAC) is the forum for intergovernmental cooperation specifically for the Barents Region. The 'Action Plan on Climate Change for the Barents Co-operation' (BEAC, 2013) was adopted in 2013.

The Northern Forum includes sub-national or regional governments from eight northern countries and has a working group dedicated to water and climate change (Northern Forum, 2016).

EU Arctic policy

The EU Arctic policy (EEAS, 2014; European Parliament, 2014) has three main policy objectives:

- protecting and preserving the Arctic in cooperation with the people who live there;
- promoting the sustainable use of resources;
- international cooperation.

There is a proposal to further develop EU Arctic policy, including through supporting research and channelling knowledge to address environmental and climate change in the Arctic.

2.5.2 Baltic Sea region

Council of the Baltic Sea States

The Council of the Baltic Sea States (CBSS) is a political forum for regional intergovernmental cooperation working on three priority areas: regional identity, a safe and secure region, and a sustainable and prosperous region. The CBSS has a permanent international Secretariat located in Stockholm, Sweden. The Expert Group on Sustainable Development focuses in particular on climate change in the region (CBSS, 2016).

The CBSS, as leader of the EU Strategy for the Baltic Sea Region (EUSBSR) Horizontal Action Climate (see below), plays a central role in ensuring coherent joint policy development and capacity-building in this field across the whole region. In 2014, the CBSS initiated a policy process for strengthening dialogue, knowledge and information exchange across national and sectoral borders supporting the countries of the Baltic Sea region. The aim is to expand their national climate change adaptation strategies by establishing the Baltic Sea region-wide Climate Change Adaptation Stakeholder Platform (CBSS, 2014). This initiative also contributes directly to the implementation of the EU Climate Change Adaptation Strategy that stresses the need for closer cooperation between the EU Member States.

([26]) http://www.arctic-council.org/index.php/en.

Baltic Marine Environment Protection Commission

The Baltic Marine Environment Protection Commission (HELCOM) ([27]) is the governing body of the Convention on the Protection of the Marine Environment of the Baltic Sea Area (also known as the Helsinki Commission), which includes the following members: Denmark, Estonia, the European Union, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden.

Adaptation to climate change means adjustment and development of the necessary new measures to protect the Baltic Sea marine environment. In 2013, HELCOM countries decided to make the assessment of regional climate change and its implications on the Baltic Sea ecosystem a regular, indicator-based activity.

The European Union Strategy for the Baltic Sea Region

The European Union Strategy for the Baltic Sea Region (EUSBSR; EC, 2012) is the first comprehensive EU strategy to target a 'macro-region' in Europe. It aims to reinforce cooperation within the Baltic Sea region to promote more balanced development in the area, to contribute to major EU policies and to reinforce integration within the region. The EUSBSR includes programmes under EU Cohesion Policy, as well as European Neighbourhood and Partnership Instrument (ENPI) programmes and other financial instruments, e.g. the European Investment Bank. The European Council, the European Commission and the High Level Group on macro-regional strategies take the EUSBSR into account in policy initiatives, promote dialogue between stakeholders and contribute to reviewing and updating the Action Plan.

Climate change was a priority in the very first action plan of the EUSBSR in 2009 before it was incorporated in the Horizontal Action Sustainable Development for 2013–2015. The EUSBSR called for the development of a macro-regional approach to adaptation to climate change. In response, the EUSBSR flagship project 'Baltadapt' developed a 'Strategy for Adaptation to Climate Change in the Baltic Sea Region' and an accompanying Action Plan with recommended actions for transnational cooperation ([28]). Another outcome of the project was the climate adaptation information portal 'Baltic Window', which was integrated into Climate-ADAPT.

In the revised 2015 EUSBSR Action Plan, the continued importance of cooperation on climate change has been addressed by dedicating a Horizontal Action to climate change, Horizontal Action Climate, coordinated by the CBSS ([29]). It aims to reinforce cooperation in order to deal with several challenges by working together and promoting more balanced development in the area. The EUSBSR also contributes to major EU policies and reinforces integration within the area.

2.5.3 Mountain regions: the Pyrenees

Working Community of the Pyrenees and the Pyrenees Climate Change Observatory

The Working Community of the Pyrenees (CTP) ([30]) was established in 1983 with the aim of creating a permanent structure for cross-border cooperation in the Pyrenees region.

In 2010, the CTP created the Pyrenees Climate Change Observatory (OPCC) ([31]). The main objective of the OPCC is to monitor and gain a better understanding of climate change and to initiate studies and projects to identify actions to adapt to the effects of climate change in the Pyrenees region. The OPCC seeks to enhance the visibility of the Pyrenees in the fields of observation and adaptation to climate change. It also aims to integrate the Observatory into relevant European networks.

2.5.4 Mountain regions: the Alps

Alpine Convention

The Alpine Convention ([32]) is an international treaty that was signed in 1991 by the eight Alpine countries and by the EU, with eight protocols and two declarations dealing with the main key sectors. The Alpine Convention adopted a declaration on climate change in 2006 and a Climate Change Action Plan in 2009. The Alpine Convention issued special publications on the topic and has taken climate change into account in its activities and products, for example in the fourth 'Report of the State of the Alps' on sustainable tourism.

([27]) http://www.helcom.fi.
([28]) http://www.baltadapt.eu.
([29]) http://www.cbss.org/strategies/horizontal-action-climate.
([30]) https://www.ctp.org/index.php.
([31]) http://www.opcc-ctp.org/en/home.
([32]) http://www.alpconv.org/en/convention/default.html.

In the period 2013–2014, the Alpine Convention established a task force that developed the following guidelines for climate adaptation at the local level in the Alps:

- 'Guidelines on Local Adaptation to Climate Change for Water Management and Natural Hazards in the Alps (Alpine Convention, 2014b)' ([33]);

- 'Guidelines for Climate Change Adaptation at the Local Level in the Alps' (Alpine Convention, 2014a) ([34]).

In the period 2015–2016, relevant actions conducted by the Alpine Convention include supporting the establishment of a virtual alpine observatory. The Alpine Convention also endeavours to share and learn from reference documents, studies and good practice examples. The 'We are Alps' tour 2015 was dedicated to disseminating examples of innovative experiences related to the mitigation of and adaptation to climate change.

The Alpine Convention and the EEA are cooperating to improve the exchange of information and data and the interoperability of their information systems.

EU Strategy for the Alpine Region

The European Commission adopted, at the end of July 2015, a Communication and an Action Plan on the EU Strategy for the Alpine Region (EUSALP) ([35]). This strategy also addresses environmental objectives, such as the improvement of risk management and better management of climate change, including the prevention of major natural disasters.

International projects — often funded by European instruments such as the European Transnational Cooperation Alpine Space Programme and more recently the LIFE Programme — also provide a major contribution to the exchange of knowledge and experiences in the Alps.

The C3-Alps ([36]) project, co-funded by the Alpine Space Programme, has capitalised on the available knowledge about adaptation for the Alpine region. Its achievements include sustainable pilot adaptation activities in 12 regions across the Alps and a 'Climate Adaptation Platform for the Alps' ([37]). Initiated by C3-Alps, a permanent network of the national adaptation policymakers from all Alpine countries was established in 2012. Acting as an informal transnational cooperation structure, the network provides a platform for knowledge exchange and learning between countries.

2.5.5 Mountain regions: the Carpathians

Carpathian Convention

The Carpathian Convention ([38]) provides a framework for cooperation and multi-sectoral policy coordination, a platform for joint strategies for sustainable development, and a forum for dialogue between all stakeholders involved. It was signed in May 2003 by seven countries (the Czech Republic, Hungary, Poland, Romania, Serbia, Slovakia and Ukraine).

The Secretariat of the Carpathian Convention, located in the Vienna office of the United Nations Environment Programme (UNEP), supports the work of the Convention and assists in project development and implementation. Following the initiative by the European Parliament, studies on climate change and adaptation measures in the Carpathian region were performed. The outcomes of the three projects — CARPIVIA, CarpathCC and CARPATCLIM — raise awareness about the extent and impacts of climate change in various sectors in the region: forests, agriculture, water resources, grasslands, wetlands and tourism. The key findings of the projects are integrated into Climate-ADAPT. The Convention established a Working Group on Climate Change Adaptation, which will support policy proposals in line with the EU Strategy on Adaptation to Climate Change, and ensure proper follow-up to previous projects. Countries agreed to further contribute to Climate-ADAPT, providing data and information, under the coordination of the Secretariat. The aim is to create a specific section on the Carpathian area under the 'transnational regions' web page of Climate-ADAPT.

The 'Strategic Agenda on Adaptation to Climate Change in the Carpathian Region' was adopted at the Fourth Meeting of the Conference of the Parties to the Carpathian Convention (COP4) in 2014. The agenda

([33]) http://www.alpconv.org/en/organization/groups/WGWater/Documents/guidelines CC.pdf.
([34]) http://www.alpconv.org/en/ClimatePortal/Documents/GuidelinesCC.pdf.
([35]) http://www.alpine-region.eu.
([36]) http://www.c3alps.eu.
([37]) http://www.c3alps.eu/kip.
([38]) http://www.carpathianconvention.org.

includes recommendations for policy, institutional change and potential priority adaptation actions. It calls upon countries, local and regional authorities, and other stakeholders involved to formulate policies and design strategies to adapt to climate change and to mitigate its adverse effects. The Carpathian Convention Adaptation to Climate Change Working Group started to work on the development of an Action Plan, which will support the countries in developing common cooperation activities and projects under the new EU funding period 2014–2020.

2.5.6 Mediterranean region

Mediterranean Action Plan and Barcelona Convention

The Mediterranean Action Plan (MAP) ([39]) was adopted in 1975. The MAP is a regional cooperative effort involving 21 countries bordering the Mediterranean Sea, as well as the European Union. Through the MAP, countries aim to meet the challenges of protecting the marine and coastal environment and to achieve sustainable development.

In 1995, the 'Action Plan for the Protection of the Marine Environment and the Sustainable Development of the Coastal Areas of the Mediterranean' was adopted to replace the plan of 1975. At the same time, the 'Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean' (Barcelona Convention, 1995), an amended version of the 1976 Barcelona Convention, was adopted. The members of the Barcelona Convention are now Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, the European Union, France, Greece, Israel, Italy, Lebanon, Libya, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Syria, Tunisia and Turkey.

In 2009, the Barcelona Convention adopted the 'Marrakesh Declaration', which aimed 'to promote Mediterranean cooperation to combat the effects of climate change in the region' and 'to implement effective coordination to ensure the integration of climate change issues into development policies and ensure the strengthening of cooperation for the sharing of experience in the field of surveillance (early-warning systems) and the development and implementation of adaptation and risk-management strategies'.

A 'Regional Framework for Climate Change Adaptation in the Mediterranean' was endorsed at the 19th meeting of members of the Barcelona Convention (UNEP, 2016). The vision of the framework is that, by 2025, the marine and coastal areas of the Mediterranean countries and their communities have increased their resilience to the adverse impacts of climate variability and change, in the context of sustainable development. According to the framework, this will be achieved through common objectives, cooperation, solidarity, equity and participatory governance. Members are urged to translate the framework into actions and to take it into account and address it in their national and local integrated coastal zone management and climate change adaptation strategies and plans.

The Union for the Mediterranean, a multilateral partnership created in 2008 and consisting of the 28 EU Member States and 15 other Mediterranean partner countries, established a Climate Change Expert Group in 2014 ([40]). Its activities support the UNEP Framework for Climate Change Adaptation in the Mediterranean. The Expert Group acts as a regional dialogue platform, showcasing relevant initiatives, programmes and structures, including stakeholders, the private sector and various levels of governance, in both mitigation and adaptation.

([39]) http://www.unepmap.org/index.php-.
([40]) http://ufmsecretariat.org/ufm-climate-change-expert-group.

3 Changes in the climate system

This chapter describes observed and projected changes in key components of the climate system. Section 3.1 gives an overview of the human influence on the Earth's climate, primarily as a result of the emission of greenhouse gases. Section 3.2 presents several indicators of changes in the atmosphere, such as temperature and precipitation. Section 3.3 presents several indicators of changes in the cryosphere, such as ice and snow cover. The hydrosphere is another key component of the climate system. Changes in the ocean and its impacts on the marine environment are presented jointly in the following chapter in Section 4.1. Changes in freshwater systems are described in Section 4.3.

3.1 Human influence on the climate system

3.1.1 The climate system

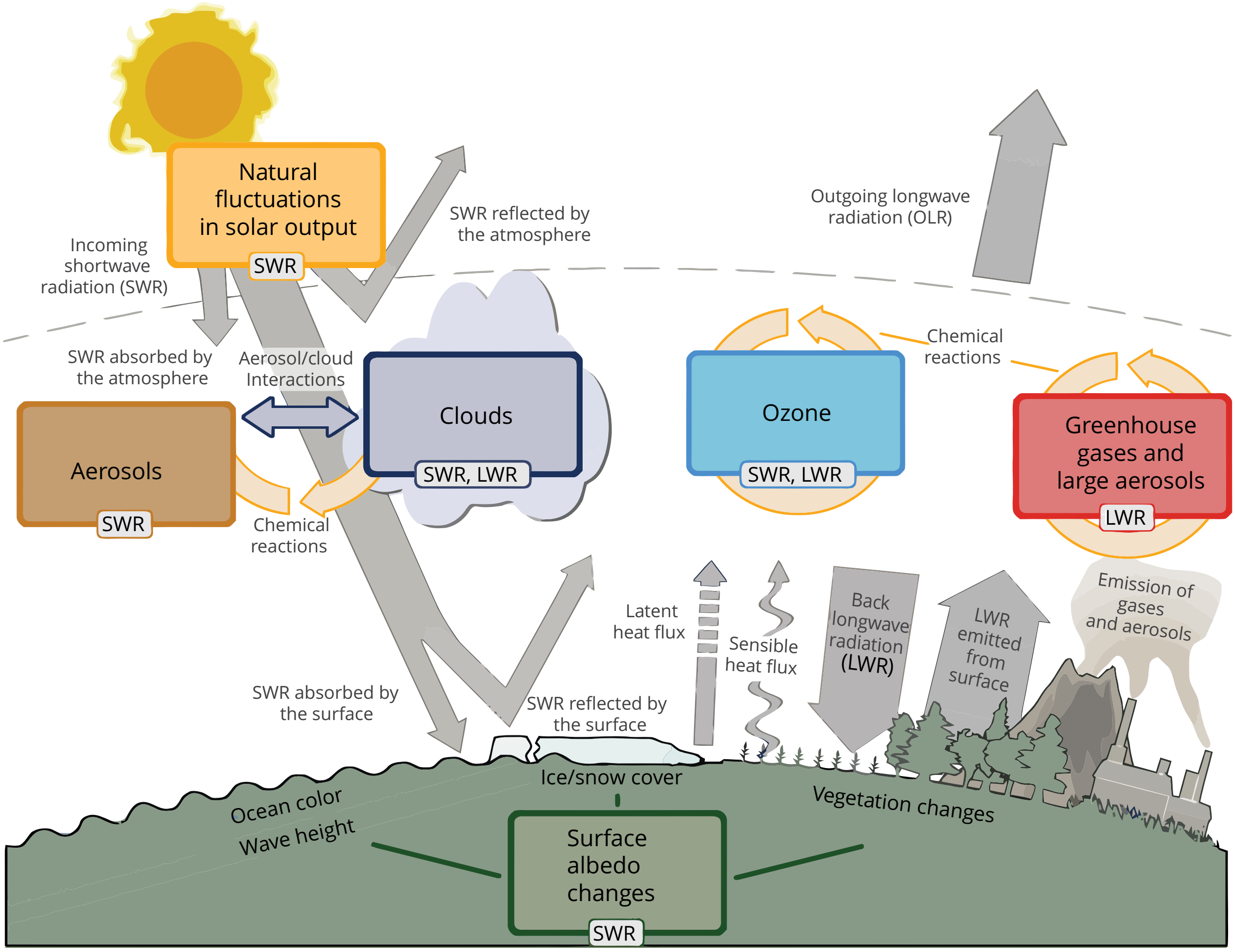
Climate is the statistical description (averages, trends, magnitude and variability) of the climate system over a long time period (usually at least 30 years). The climate system is a highly complex system that includes five major components: the atmosphere (see Section 3.2), the cryosphere (see Section 3.3), the hydrosphere, the upper lithosphere and the biosphere (see Chapter 4).

The Earth's climate system is powered by the incoming solar shortwave radiation (SWR), which is nearly in balance with the outgoing longwave radiation (LWR). Of the incoming solar SWR, about half is absorbed by the Earth's surface; the rest is reflected back to space or absorbed in the atmosphere (Figure 3.1). The energy absorbed by the Earth's surface warms it and is then emitted as LWR (terrestrial radiation) back to the atmosphere, where it is partly absorbed by certain radiatively active atmospheric constituents: water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), other greenhouse gases, clouds and (to a small extent) aerosols. These constituents also emit LWR in all directions and the component emitted downwards adds heat to the lower layers of the atmosphere and to the Earth's surface, further warming it. This is called the greenhouse effect (for details, see Cubasch et al., 2013).

Key messages

- The current average annual concentration of CO_2 in the atmosphere is close to 400 parts per million (ppm), which is the highest level for at least the last 800 000 years and about 40 % higher than the pre-industrial levels.
- Even if anthropogenic emissions of CO_2 and other greenhouse gases were to fall to zero in the very near future, the atmospheric residence time of greenhouse gases and the dynamics of the climate system would lead to further anthropogenic climate change for many decades, with rising temperatures, changing precipitation and drought patterns, more frequent and longer heat waves, and changes in other extreme climate events; sea levels would continue to increase for several centuries.
- The length and quality of meteorological records differs substantially across Europe and globally. Short records limit the detection of any long-term trends in extreme climate events. However, recent progress in extreme event attribution has provided increasing evidence that anthropogenic climate change has substantially increased the probability of various extreme weather events.
- The length, frequency and intensity of record-breaking temperature events is projected to increase on a global scale and within Europe. Furthermore, available climate projections agree that the frequency of heavy precipitation and droughts will increase in many areas in the 21st century.

Figure 3.1 The Earth's energy balance and the drivers of climate change



Note: The radiative balance between incoming SWR and outgoing LWR is influenced by global climate 'drivers'. Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (through fluctuations in the amount of incoming SWR). Human activity results in the emission of gases and aerosols, which modifies the amount of outgoing LWR. Surface albedo (reflection coefficient) is changed by changes in vegetation or land surface properties, snow or ice cover, and ocean colour. These changes are driven by natural seasonal and diurnal changes (e.g. snow cover), as well as human influence.

Source: Adapted from IPCC, 2013a (Figure 1.1). @ 2013 Intergovernmental Panel on Climate Change. Reproduced with permission.

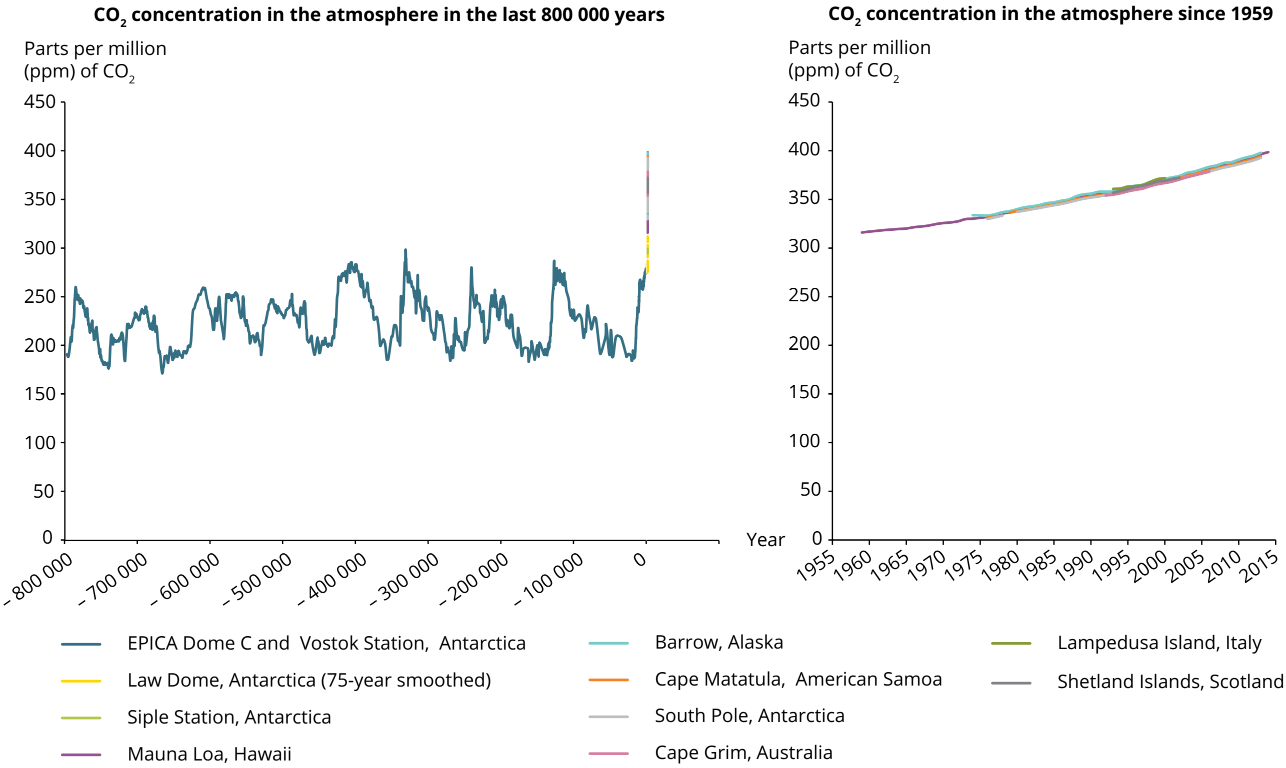
3.1.2 Drivers of climate change

Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) and that persists for an extended period, typically for at least a few decades or longer (IPCC, 2013a).

Climate change can be caused by natural external forcings (e.g. modulations of the solar cycles and volcanic activity) and by anthropogenic forcings (e.g. changes in the composition of the atmosphere or in land use). The main way through which humans are affecting the climate is by increasing the concentration of greenhouse gases in the atmosphere. This is a result of emissions caused by the burning of fossil fuels (for electricity production, transport, industry, commercial and residential activities), deforestation, agricultural practices, and land-use, and forest management practices. The current average annual concentration of CO_2, the most important anthropogenic greenhouse gas, is close to 400 parts per million (ppm), which is the highest level it has been over at least the last 800 000 years and about 40 % higher than the levels in the pre-industrial period of the mid-18th century (Figure 3.2). Since the start of the industrial era at the beginning of the 19th century, the overall effect of human activities on climate has greatly exceeded the effects on climate due to known changes in natural processes (e.g. changes in solar SWR) on comparable time scales.

In addition to long-term climate change, the climate is varying as a result of natural internal processes, such as El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO).

Figure 3.2 Atmospheric CO_2 concentrations for the last 800 000 years and since 1959



Note: The CO_2 concentration until 1955 is estimated from ice-core or deep-sea sediment data. Concentrations from 1959 are obtained from instrumental measurements from eight different measurement stations.

Source: Luthi et al., 2008; US EPA, 2015.

3.1.3 Observed climate change and its attribution to specific causes

Since the 1850s, almost the entire land and sea surface has warmed, although not uniformly, as land areas show more warming than oceans. According to the World Meteorological Organization (WMO), 2015 was the warmest year on record, which 'broke all previous records by a strikingly wide margin' (WMO, 2016). The total increase in global average land and ocean near-surface temperature in 2015 was around 1 °C compared with the pre-industrial period (see Section 3.2.2 for details). Increased temperatures have led to the melting of the Greenland ice sheet, Arctic sea ice, mountain glaciers and snow cover, which are all declining rapidly (see Section 3.3 for details). Observations also show increases in ocean heat content in the deeper ocean (i.e. between 700 and 2 000 m and below 3 000 m) and increases in sea level (see Sections 4.1 and 4.2 for details). Changes in global precipitation since 1900 display both positive and negative trends, but there are many areas that lack robust long-term measurements (IPCC, 2013a).

In Europe, 2014 and 2015 were the warmest years on record (EURO4M, 2016) (see Section 3.2.2).

Furthermore, reconstructions show that summer temperatures in Europe in recent decades are the warmest for at least 2 000 years, and that they lie significantly outside the range of natural variability (Luterbacher et al., 2016). Several independent analyses have concluded that, in relation to the 2014 Europe temperature record, 98 % of the temperature increase can be attributed to anthropogenic climate change, which made this record 35–80 times more likely (EURO4M, 2015; Kam et al., 2015).

Observations of climate variables are made from measurements taken *in situ* (land and sea surface, atmosphere and deep ocean), as well as remote measurements made by satellites, lidars and radars. Global-scale observations date back to the mid-19th century, with independent, comprehensive and sustained datasets available since the 1950s.

Globally and within Europe, some regions have shorter data records than others and, even within Europe, not all data from weather stations are shared freely (Map 3.1). As a result, there are large data gaps, even in interpolated datasets (Donat et al., 2013; Zwiers et al., 2013). In regions where many stations with long records are available to all users, assessments can be more detailed than in regions with a small number of stations or with short records. Limited data availability is particularly detrimental for the detection of long-term climate trends in extreme events (see Section 3.1.5). Increased data sharing by meteorological services would improve the accuracy of regional climate change assessments, including understanding of past and future climate and weather extremes.

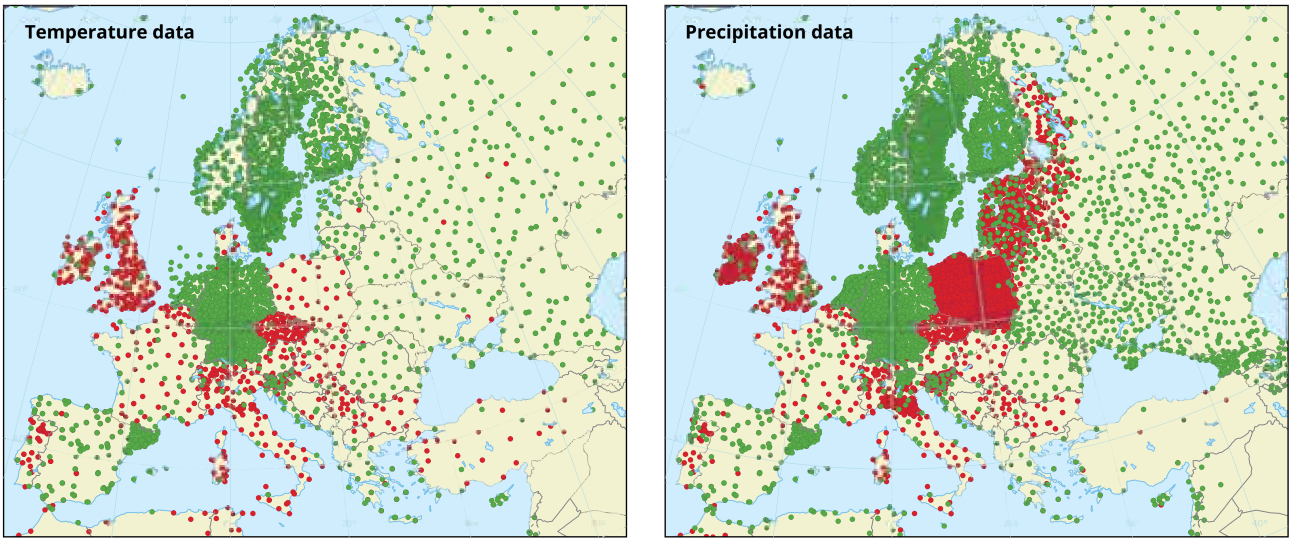
There is strong evidence that observed changes in many climate variables, including extremes, can be attributed to anthropogenic climate change (Hegerl and Zwiers, 2011; Bindoff et al., 2013; Trenberth et al., 2015; Stott et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2016). The IPCC AR5 concluded that 'It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century' (IPCC, 2013b). Furthermore, anthropogenic forcings are very likely to be the main cause of the decline in Arctic sea ice, and likely to be the cause of decreases in the Greenland ice sheet and glaciers worldwide in recent decades. Anthropogenic forcings have also influenced the global water cycle in different ways, including increases in record-breaking rainfall events (Lehmann et al., 2015).

3.1.4 Future climate change

Even if anthropogenic emissions of greenhouse gases were to fall to zero in the very near future, the dynamics of the climate system and the atmospheric residence time of greenhouse gases (typically decades to centuries) mean that past human activities will influence the climate for many decades to come. This will affect other components of the climate system, leading to hotter and more frequent heat extremes, the melting of snow and ice, increasing sea levels and changing precipitation patterns, including precipitation extremes.

Projections of precipitation and temperature from general circulation models (GCMs) are generally the basis for the assessment of climate change, but they do not provide detailed information on climate change impacts at regional or local scales (see Box 3.1). Map 3.2 depicts the spatial patterns of changes in near-surface temperature and precipitation using the multi-model mean of at least 30 GCMs for the period 2081–2100 relative to 1986–2005 under the RCP2.6 scenario (low emissions scenario) and RCP8.5 scenario (high emissions scenario) (see Section 1.2 for details). The two scenarios show warming and changes in precipitation across the globe, both of which are much

Map 3.1 Location of stations with temperature and precipitation data



Location of stations

- Downloadable data
- Non-downloadable data

0 500 1 000 1 500 km

Note: This map shows stations available in the European Climate Assessment & Dataset (ECA&D) (with different lengths of records) for daily mean temperature and daily precipitation amount. Green dots represent downloadable data and red dots represent additional non-downloadable data that have been used for producing gridded datasets.

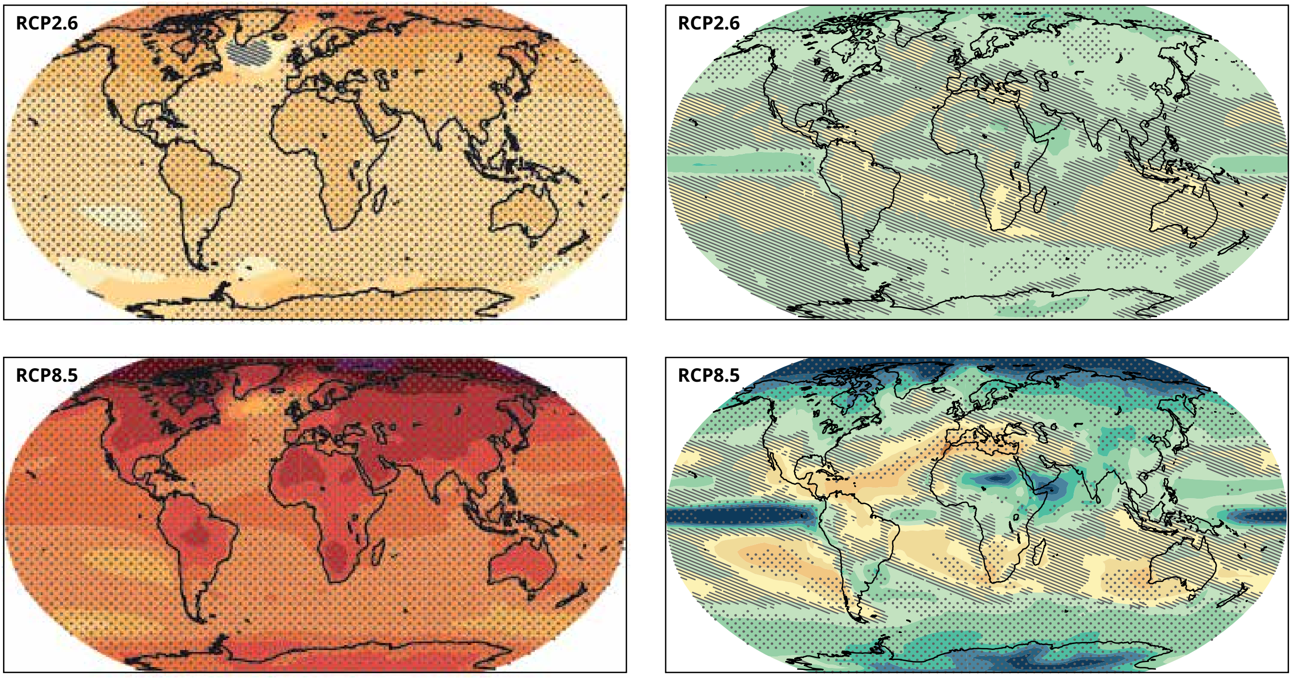
Source: Adapted from van der Schrier et al., 2013.

more intense for RCP8.5 than for RCP2.6. The warming is particularly strong at high latitudes. Increasing precipitation is projected for high-latitude regions and the equatorial Pacific, whereas decreasing precipitation is projected for many sub-tropical and mid-latitude regions, including the Mediterranean.

GCMs provide guidance on the range of possible futures for each scenario. For example, Figure 3.4 depicts key aspects of future climate change in Europe for two future periods and two scenarios. Key uncertainties (see Section 1.4 for further explanation) are depicted by showing the results for two RCP scenarios (RCP2.6 and RCP8.5) and for several GCMs separately.

All models and both scenarios show that Europe will become warmer in the 21st century. For the 2040s, both scenarios (RCP2.6 and RCP8.5) show similar changes in precipitation, and the differences are mainly the result of model uncertainties. However, in the 2080s, the difference between both scenarios increases. Almost all climate models agree that northern Europe (top of Figure 3.4) will become wetter, in particular under the RCP8.5 scenario. Under the RCP8.5 scenario, all models agree that southern Europe will become drier in the 2080s (bottom of Figure 3.4). However, under the RCP2.6 scenario, the GCMs do not agree on the direction of changes in both future periods.

Map 3.2 Projected changes in global average surface temperature and precipitation



Changes in global average surface temperature (left) and precipitation (right) in 2081–2100 relative to 1986–2005 under RCP2.6 (upper panel) and RCP8.5 (lower panel)

°C: –2 – 1.5 – 1 – 0.5 0 0.5 1 1.5 2 3 4 5 7 9 11

%: – 50 – 40 – 30 – 20 – 10 0 10 20 30 40 50

Regions where the multi–model mean signal is less than 1 standard deviation of internal variability

Regions where the multi–model mean signal is greater than 2 standard deviations of internal variability and where 90 % of models agree on the sign of change

Note: Hatching indicates regions where the multi-model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean signal is greater than two standard deviations of internal variability and where 90 % of models agree on the direction of change.

Source: IPCC, 2013b (Figure SPM.8.a/b). © 2013 Intergovernmental Panel on Climate Change. Reproduced with permission.

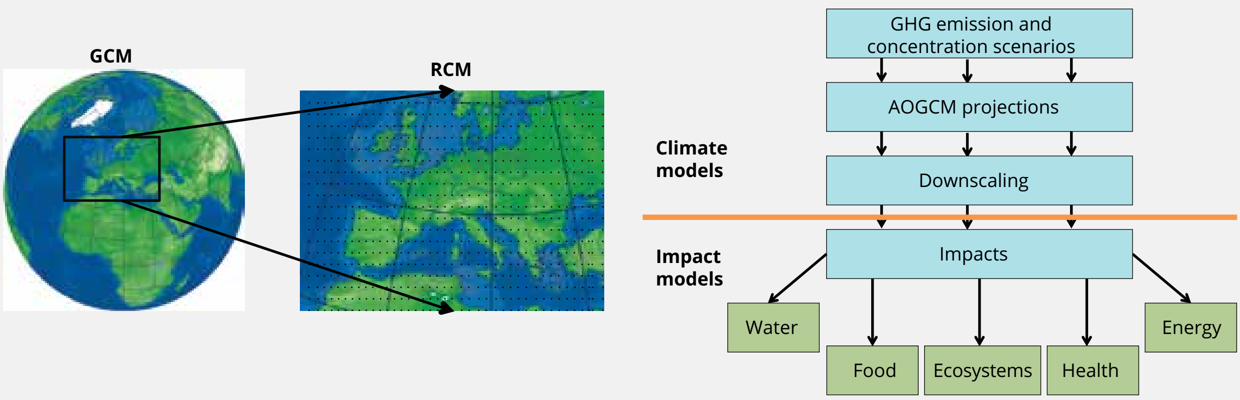
Box 3.1 Projecting climate change with models

Climate models, often termed general circulation models (GCMs), are numerical models that simulate the climate system at the global scale based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for its known properties (IPCC, 2013a) (Figure 3.3). Climate models are the most advanced tools available for modelling the state of the climate system and simulating its response to changes in atmospheric concentrations of greenhouse gases and aerosols. Models differ in their complexity, in the number of spatial dimensions and in the complexity of describing physical, chemical or biological processes. Climate models are evolving towards Earth system models (ESMs), which include a representation of the carbon cycle, an interactive calculation of atmospheric CO_2 or compatible emissions, and other climatic components (e.g. atmospheric chemistry, ice sheets, dynamic vegetation and the nitrogen cycle). The simulations of future climate depend highly on boundary conditions, which are not sufficiently known for the future, and hence the results are highly uncertain. Most global climate change studies and assessments (including IPCC AR5) have been using GCMs from CMIP5. These models simulate atmospheric processes at a horizontal resolution of between 50 and 250 km and with 30 to 80 vertical layers, and the ocean processes at a horizontal resolution of between 20 and 150 km and with up to 40 vertical layers.

For more detailed regional climate impact assessments, regional climate models (RCMs) have been used. RCMs are limited in area but can provide information on the climate in higher spatial resolution than GCMs. RCMs typically have a horizontal resolution of between 2 and 50 km, which allows for a better representation of topographic features (e.g. mountain ranges) and of regional-scale climate processes. As a result, they can provide more detailed projections of changes in regional precipitation patterns, weather extremes and other climate events. The World Climate Research Programme CORDEX (Jones et al., 2011) has developed a set of high-resolution downscaled climate data based upon the CMIP5 experiments with various domains for different regions of the world, including Europe. The EURO-CORDEX study (Jacob et al., 2014; Kotlarski et al., 2014) has used combinations of five different GCMs and seven different RCMs over the European region (approximate 27 °N–72 °N, 22 °W–45 °E), at a horizontal resolution of 12.5 km and representing the time period from 1951 to 2100.

As models differ in their use of numerical methods, the description of physical processes and the characterisation of climate variability, their simulations of past and current climate show deviations from the observed climate. Furthermore, different models provide somewhat different climate projections when forced with the same emissions scenario (see Section 1.3). Nevertheless, the scientific community is confident that climate models provide credible quantitative estimates of future climate change, as these models are based on fundamental physical laws and are able to reproduce the key features of observed climate change. These projections are usually presented as a multi-model ensemble, in order to represent the spread of possible future climate change.

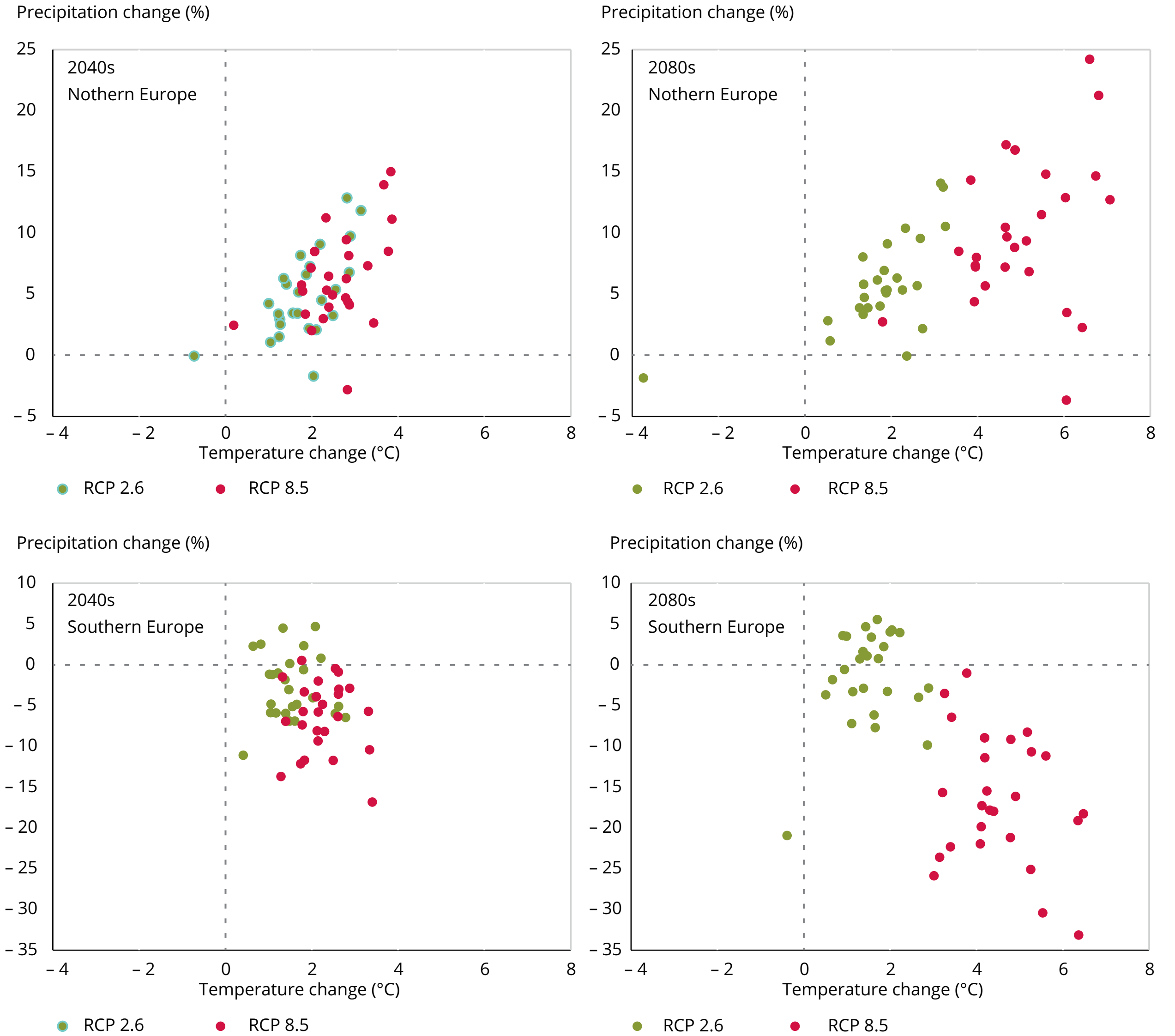
Figure 3.3 Components needed for modelling climate change and its impacts



Note: AOGCM, atmosphere–ocean general circulation model; GHG, greenhouse gas.

Source: EEA.

Figure 3.4 Projected changes in annual temperature and precipitation for northern Europe and southern Europe and for two time periods



Note: Projected changes in annual temperature and precipitation for northern and southern Europe for two time periods, relative to 1961–1990. Each point is from a global model projection in the CMIP5 dataset (as used in the IPCC AR5) using either a high (RCP8.5: red circles) or low (RCP2.6: green circles) forcing scenario. Only models in the CMIP5 that had projections for both scenarios were used.

Source: UK Met Office.

3.1.5 Weather- and climate-related extreme events

Climate change is expected to lead to changes in the frequency and strength of many types of extreme weather and climate events (IPCC, 2012). Extreme events (e.g. severe heat waves, extreme rainfall, droughts, etc.) are rare by definition, which means that there are fewer data available to analyse past changes in their frequency or intensity. This makes extreme weather more difficult to analyse, understand and project. Rare extreme events tend to have the highest impact and cause the greatest damage to natural and managed systems and to human well-being (see Chapters 5 and 6).

Observed changes in extremes and their attribution to climate change

Since 1950, the number, magnitude and duration of several weather extremes have changed globally and in Europe, and there is strong evidence that these observed changes have generally been caused by human activities. For example, about 75 % of the present-day moderate daily hot extremes over land globally can be attributed to human influence, and this fraction increases non-linearly with further warming (Fischer and Knutti, 2015). Furthermore, record-breaking rainfall events have significantly increased since 1980, and this increase is consistent with rising temperatures (Lehmann et al., 2015). Characteristics such as the likelihood and magnitude of individual climate and weather extremes (such as the heat waves in 2003 in central Europe and in 2010 in eastern Europe) have also been attributed to anthropogenic climate change (e.g. Stott et al., 2004; Pall et al., 2011; Herring et al., 2014; Christidis et al., 2015).

Future changes in extremes

Confidence in projecting changes in the direction and magnitude of climate extremes depends on the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models. Regional climate models with very high resolution (1–2 km grid spacing) and with explicit representation of convection processes, which are typically used for weather forecasting, have recently been used for the first time for regional-scale climate change studies. Such models are particularly beneficial for studying precipitation changes on daily and sub-daily time scales, which in turn improves the accuracy of assessing heavy precipitation, flash floods, hail and other extreme events (Kendon et al., 2014; Montesarchio et al., 2014; Ban et al., 2015) (see Section 3.2 for more details).

The length, frequency and/or intensity of record-breaking temperature events is projected to increase over most land areas globally and in Europe. Furthermore, available climate projections agree that the frequency of heavy precipitation events and/or the proportion of total rainfall from heavy precipitation events will increase in the 21st century over many areas of the globe (IPCC, 2013a).

3.1.6 Tipping elements in the climate system

Anthropogenic climate change may trigger abrupt and/or irreversible changes in large-scale climate systems and processes, such as polar ice sheets, ocean circulations, carbon reservoirs and various non-linear feedback processes (Lenton et al., 2008; Good et al., 2011; Hansen et al., 2016) (see, for example, Sections 3.2, 3.3 and 4.1). These risks are known, among others, as large-scale singularities or tipping elements in the climate system. A comprehensive review is available in a recent research report (Good et al., 2014). While the risk of tipping elements is a key reason for mitigating climate change, their assessment is beyond the scope of this report.

3.2 Atmosphere

Key messages

- Three different long-term observational records show that the global average annual near-surface (land and ocean) temperature in the decade 2006–2015 was 0.83 to 0.89 °C higher than the pre-industrial average. The year 2015 was the warmest on record globally, at approximately 1 °C above the pre-industrial level.
- European land areas in the decade between 2006 and 2015 have warmed by around 1.5 °C since the pre-industrial age. The years 2014 and 2015 were jointly the warmest years on record in Europe.
- Further global warming between 0.3 and 4.8 °C is projected for the 21st century, depending on the emissions scenario. The annual average land temperature across Europe is projected to continue increasing faster than global average temperature.
- Since 2003, Europe has experienced several extreme summer heat waves (2003, 2006, 2007, 2010, 2014 and 2015). Such heat waves are projected to occur as often as every two years in the second half of the 21st century under a high emissions scenario (RCP8.5). The impacts will be particularly strong in southern Europe.
- Precipitation changes across Europe show more spatial and temporal variability than temperature changes. Annual precipitation has increased in most of northern Europe, in particular in winter, and has decreased in most of southern Europe, in particular in summer. Heavy precipitation events have increased in northern and north-eastern Europe since the 1960s whereas different indices show diverging trends for south-western and southern Europe. Heavy precipitation events are projected to become more frequent in most parts of Europe.
- Observations of wind storm location, frequency and intensity have shown considerable variability across Europe during the 20th century. However, most studies agree that the risk of severe winter storms, and possibly of severe autumn storms will increase in the future for the North Atlantic, as well as for northern, north-western and central Europe.
- Hail is responsible for significant damage to crops, vehicles, buildings and other infrastructure. Despite improvements in data availability, trends and projections of hail events are still subject to large uncertainties owing to a lack of direct observation and inadequate microphysical schemes in numerical weather prediction and climate models.

3.2.1 Overview

Relevance

Changes in atmospheric composition affect atmospheric climate variables, in particular temperature, precipitation and wind speed, which in turn affect almost all natural and human-managed systems, as well as human health and well-being. In fact, climate change is often equated with atmospheric changes, and changes in other climate system components, such as the hydrosphere and the cryosphere, are often considered effects of atmospheric changes. It is therefore not surprising that global mean surface temperature is specifically mentioned as a proxy for the magnitude of global climate change in Article 2 of the UNFCCC (UN, 1992), and that the political discussion on global climate policy often focuses on the most appropriate value for constraining its increase (see Chapter 2 for further details).

While changes in annual or seasonal averages of atmospheric climate variables are easier to monitor and report, changes in extreme weather events (e.g. heat waves, heavy precipitation, wind storms and hail), which generally have the highest impact and cause the greatest damage to humans and natural systems, are more difficult to detect.

Selection of indicators

The following are six indicators that describe past trends and projected changes in the most dynamic component of the Earth's climate system: the atmosphere.

- *Global and European temperature* consists of two parts. Global mean surface temperature is the key climate variable to track anthropogenic climate change. It is also the only climate variable for which a political target exists. The average European land temperature gives a clear signal of climate change in Europe that is relevant for assessing the impacts of climate change, and for informing adaptation planning.

- *Heat extremes* can have severe impacts on society, and they are the most deadly climatic hazard in Europe.
- *Mean precipitation* is a key climate variable with major importance for all ecosystems and social systems.
- *Heavy precipitation* can cause floods, with considerable impacts on social-economic sectors and ecosystem services.
- *Wind storms* are a significant weather hazard that can cause considerable damage in various parts of Europe.
- *Hail* is responsible for significant damage to buildings, crops, vehicles and infrastructure in affected regions. However, the local nature of hail makes it difficult to monitor and to detect trends using classical observational networks.

Meteorological droughts are discussed jointly with hydrological droughts in Section 4.3.4.

Data quality and data needs

The presented atmospheric climate variables, with the exception of hail, are a subset of the Essential Climate Variables (ECVs) defined through the Global Climate Observing System (GCOS) (see Section 7.1.1). Spatial and temporal coverage of the observed climate variables varies significantly across the globe; it is generally best over Europe and North America.

Regular instrumental measurements of temperature and precipitation started around 1850; since then monthly information about global temperature and precipitation have become available. A dense network of stations across the globe, and particularly in Europe, now provide regular monitoring of key atmospheric climate variables, using standardised measurements, quality control and homogeneity procedures at European level. However, even where sufficient data are available, several problems can limit their use for analysis. These problems are mainly connected with 1) limitations of distributing data in high spatial and temporal resolution by many countries, 2) unavailability of data in easy-to-use digital format, and 3) lack of data homogeneity.

In November 2014, the European Commission signed a Delegation Agreement with ECMWF (European Centre for Medium-Range Weather Forecasts) for the implementation of the Copernicus Climate Change Service (C3S). The C3S will provide access to information for monitoring and predicting climate change and will, therefore, help to support adaptation and mitigation. It benefits from a sustained network of in situ and satellite-based observations, reanalysis of the Earth's climate, and modelling scenarios based on a variety of climate projections (see Section 7.1.2).

3.2.2 Global and European temperature

Key messages

- According to three different observational records of global average annual near-surface (land and ocean) temperature, the last decade (2006–2015) was 0.83 to 0.89 °C warmer than the pre-industrial average, which makes it the warmest decade on record. Of the 16 warmest years on record, 15 have occurred since 2000. The year 2015 was the warmest on record, around 1 °C warmer than the pre-industrial level, followed by 2014.
- The average annual temperature for the European land area for the last decade (2006–2015) was around 1.5 °C above the pre-industrial level, which makes it the warmest decade on record. Moreover, 2014 and 2015 were jointly the warmest years in Europe since instrumental records began.
- Climate models project further increases in global average temperature over the 21st century (for the period 2081–2100 relative to 1986–2005) of between 0.3 and 1.7 °C for the lowest emissions scenario (RCP2.6) and between 2.6 and 4.8 °C for the highest emissions scenario (RCP8.5).
- All UNFCCC member countries have agreed on the long-term goal of keeping the increase in global average temperature to well below 2 °C compared with pre-industrial levels and have agreed to aim to limit the increase to 1.5 °C. For the three highest of the four RCPs, global average temperature increase is projected to exceed 2 °C compared with pre-industrial levels by 2050.
- Annual average land temperature over Europe is projected to increase by the end of this century (2071–2100 relative to 1971–2000) in the range of 1 to 4.5 °C under RCP4.5 and 2.5 to 5.5 °C under RCP8.5, which is more than the projected global average increase. The strongest warming is projected across north-eastern Europe and Scandinavia in winter and southern Europe in summer.

Relevance

This indicator shows absolute changes in average annual and decadal near-surface temperature for the globe and for a region covering Europe ([41]). Near-surface air temperature gives one of the clearest and most consistent signals of global and regional climate change. It has been measured for many decades or even centuries in some locations. Observational networks across the globe, and especially in Europe, provide regular monitoring of temperature using standardised measurements, quality control and homogeneity procedures.

Global mean surface temperature is specifically mentioned as a proxy for the magnitude of global climate change in Article 2 of the UNFCCC (UN, 1992), and the political discussion on global climate policy often focuses on the most appropriate value for constraining its increase. The agreement adopted at the UNFCCC COP21 in Paris in December 2015 sets out a global action plan to limit the increase in global average temperature to well below 2 °C, with the aim to limit the increase to 1.5 °C, compared with pre-industrial levels (see Chapter 2 for further details).

Changes in air temperature also influence other components of the climate system, such as sea level and the intensity and frequency of floods and droughts. Furthermore, temperature has a direct impact on many natural and managed systems, such as biota and crop productivity, and on human health and well-being.

([41]) In the context of this section, Europe is defined as the area between 35 and 70 ° North and – 25 and 45 ° East.

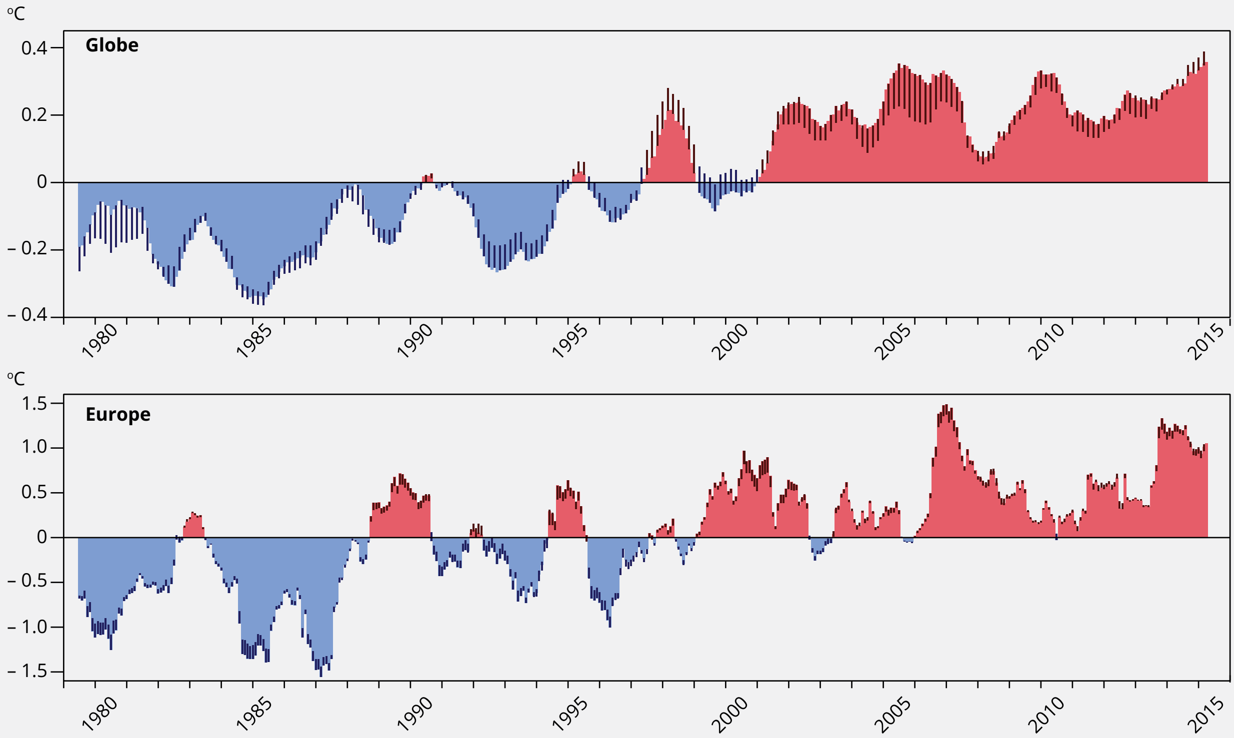
Box 3.2 Climate reanalysis

Reanalysis is the name given to the use of a modern data assimilation system to analyse comprehensive sets of observations that extend back in time over multiple decades. It employs a model of the atmosphere, ocean or coupled climate system to spread observational information in space and time, and from one variable to another. Reanalysis produces gap-free global datasets for numerous climate variables, at higher spatial or temporal resolution than is usually provided by directly analysing a single type of observation. This makes the datasets valuable for studying short-term climatic processes and extreme events. The value of the information provided for longer term trends depends on the quality and changes over time of the global observing system, on the realism of the assimilating model, and on how well observations are combined with background information from the model, which takes into account the varying biases and random errors of both the observations and the background information.

Smoothed time series of global and European average surface air temperatures are presented in Figure 3.5, starting from 1979, a year that followed a significant upgrade of the observing system. Differences from the 1981–2010 average are shown for the ERA-Interim reanalysis (Dee et al., 2011). Uncertainty bars show the spread of values provided by ERA-Interim, the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al., 2015), HadCRUT4 (Morice et al., 2012) and US National Oceanic and Atmospheric Administration (NOAA) Global Temp (Karl et al., 2015) datasets that combine monthly temperature data from land stations with measurements of sea-surface temperature. All datasets indicate that global temperature has risen since the 1970s to reach values that are the highest on record.

Shorter-period fluctuations in global values are more uncertain. This is largely because the effects of sea ice changes are better represented in the reanalyses and because sea-surface temperature analyses differ. The datasets agree quite well across Europe, where average temperatures were high from mid-2006 to mid-2007 and have recently been high for a prolonged spell since 2014.

Figure 3.5 Global and European average surface air temperatures from 1979 to 2015



Note: Running 12-month averages from the ERA-Interim reanalysis are shown, with solid red and blue shading indicating when temperature is above and below, respectively, the average for 1981–2010. The short, darker bars provide an indication of the uncertainty in the estimates provided by different datasets.

Source: Copernicus Climate Change Service, ECMWF ([42]).

([42]) For further details on the time series and maps, see http://climate.copernicus.eu/resources/data-analysis/average-surface-air-temperature-analysis.

Past trends: global temperature

Records of global average temperature show long-term warming trends since the end of the 19th century, which have been most rapid since the 1970s. Three independent analyses of global average temperature using near-surface observation records — HadCRUT4 (Morice et al., 2012), NOAA Global Temp (Karl et al., 2015) and GISTEMP by the NASA Goddard Institute for Space Studies (Hansen et al., 2010; GISTEMP team, 2016) — show similar amounts of warming. They show warming compared with pre-industrial temperatures (using the earliest observations from the period 1850–1900 as a proxy) of between 0.83 and 0.89 °C for the decade 2006–2015 (Figure 3.6). This magnitude of warming corresponds to almost half of the 2 °C warming that is compatible with the global climate stabilisation target of the EU and the ultimate objective of the UNFCCC (UNFCCC, 2009). Similar estimations of warming have also been obtained through 'climate reanalysis' (Box 3.2). The year 2015 was the warmest on record according to different near-surface temperature observational analyses, with temperatures around 1 °C above pre-industrial levels (WMO, 2016). The year 2014 was the second warmest on record. Note that such statements are always associated with some uncertainty, primarily because of spatial and temporal gaps in the data record and different interpolation methods (Blunden and Arndt, 2015).

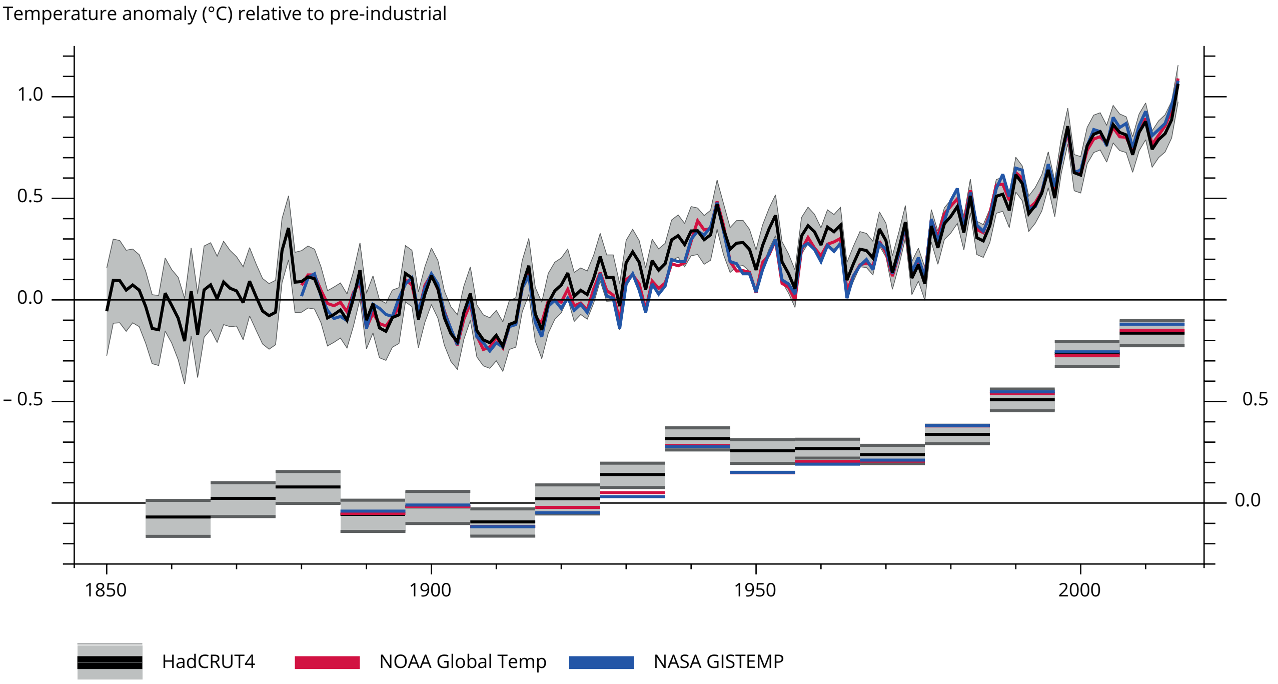
Furthermore, the annual temperature anomalies are also strongly influenced by climate variability due to natural forcings (volcanic eruptions and solar activity) and by internal variability within the climate system (e.g. multi-annual climate fluctuations such as the ENSO, which influence the rate of heat uptake by the oceans) (IPCC, 2013). Global ocean heat content has been increasing continuously since the 1950s up to at least 2 000 m, without showing any slow-down (see Section 4.1). Furthermore, a recent study that uses new datasets of the sea surface temperature and more sophisticated interpolation methods for data-sparse regions such as the Arctic suggests that the increase in global average temperature since 1998 was higher than the increase in the observed near-surface temperature as used for the IPCC AR5 (Karl et al., 2015; Fyfe et al., 2016). Changing the start and end years also has an effect on the rate of change, but this is less than the impact of newly available data and methods for interpolation (Karl et al., 2015).

Past trends: European temperature

The average annual temperature over European land areas increased by 1.45 to 1.59 °C in 2006–2015 relative to the pre-industrial period; this increase is larger than the increase in global average temperature. This makes it the warmest decade on record (Figure 3.7). The grey shading in Figure 3.7 shows the 95 % confidence interval, which reflects uncertainties owing to areas without observation stations, inhomogeneities in measurements and biases as a result of urbanisation (van der Schrier et al., 2013). The years 2014 and 2015 were jointly the warmest calendar years in Europe since instrumental records began, and anthropogenic climate change made these record temperatures 35–80 times more likely (EURO4M, 2015; Kam et al., 2015). Moreover, climate reconstructions show that summer temperatures in Europe in the last three decades (1986–2015) have been the warmest for at least 2 000 years, and that they lie significantly outside the range of natural variability (Luterbacher et al., 2016).

All of Europe has warmed significantly since the 1960s (Map 3.3). The strongest warming has been observed over the Iberian Peninsula, particularly in summer, and across central and north-eastern Europe. Winter warming has been strongest over Scandinavia.

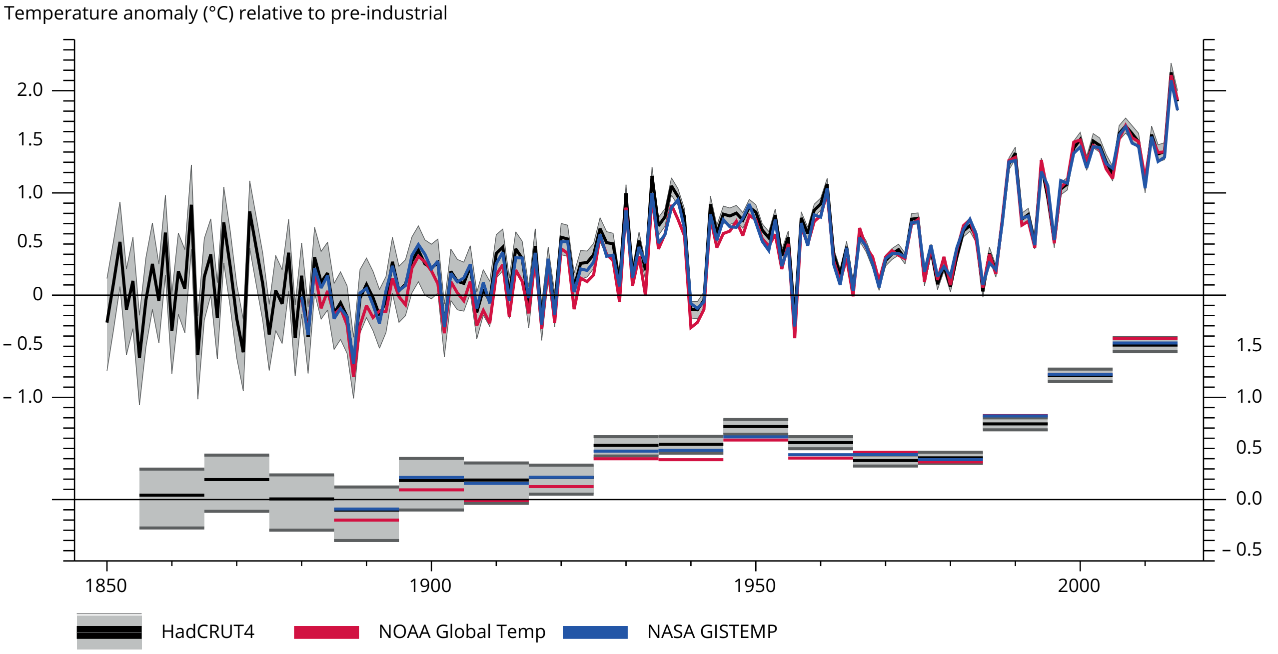
Figure 3.6 Global average near-surface temperatures between 1850 and 2015 relative to the pre-industrial period



Note: Three sources of data are used for the mean annual change (upper panel) and mean decadal (10-year) change (lower panel) relative to the pre-industrial period. The uncertainty ranges (values between 2.5 and 97.5 percentiles) for the HadCRUT4 dataset are represented by grey shading.

Source: EEA and UK Met Office, based on HadCRUT4 (Morice et al., 2012), NOAA Global Temp (Karl et al., 2015) and GISTEMP (Hansen et al., 2010).

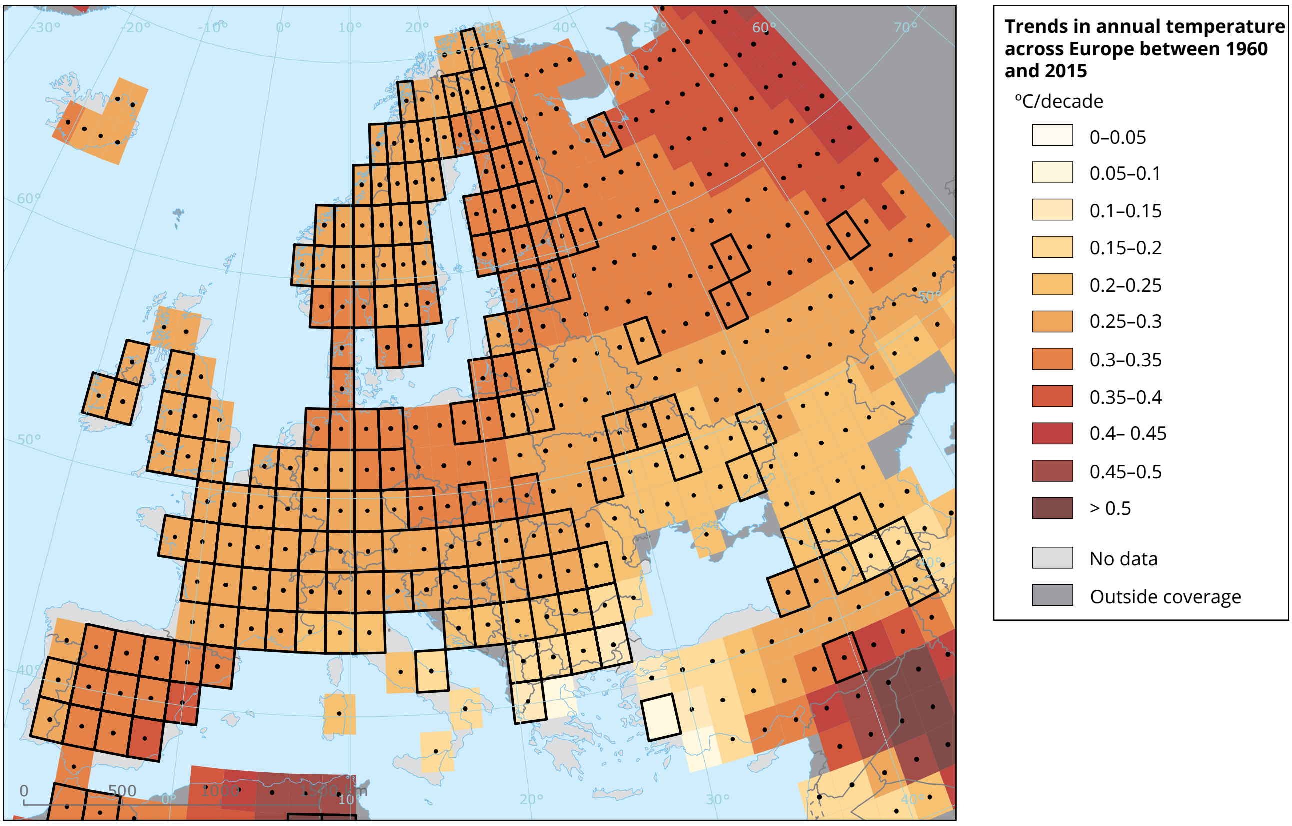
Figure 3.7 European average temperatures between 1850 and 2015 over land areas relative to the pre-industrial period



Note: The datasets, pre-industrial periods and techniques are the same as those used in Figure 3.6.

Source: EEA and UK Met Office, based on HadCRUT4 (Morice et al., 2012), NOAA Global Temp (Karl et al., 2015) and GISTEMP (Hansen et al., 2010).

Map 3.3 Trends in annual temperature across Europe between 1960 and 2015



Note: Grid boxes outlined with solid black lines contain at least three stations and so are likely to be more representative of the grid box than those that are not outlined. Significance (at the 5 % level) of the long-term trend is shown by a black dot (which is the case for almost all grid boxes in this map).

Source: EEA and UK Met Office, based on the E-OBS dataset (updated from Haylock et al., 2008).

Projections: global temperature

The global average temperature will continue to increase throughout this century as a result of projected further increases in greenhouse gas concentrations (see Sections 1.2 and 3.1). The CMIP5 climate projections summarised in the IPCC AR5 project that global temperature will increase by mid-century (2046–2065 relative to 1986–2005) by 0.4–1.6 °C for RCP2.6, 0.9–2.0 °C for RCP4.5, 0.8–1.8 °C for RCP6.0 and 1.4–2.6 °C for RCP8.5; the warming projections for the end of the century (2081–2100) are 0.3–1.7 °C for RCP2.6, 1.1–2.6 °C for RCP4.5, 1.4–3.1 °C for RCP6.0 and 2.6–4.8 °C for RCP8.5. All projections show greater warming over land than over the oceans. Projected warming is strongest in the Arctic at about twice the global average. These patterns are consistent with the observations during the latter part of the 20th century (Collins et al., 2013).

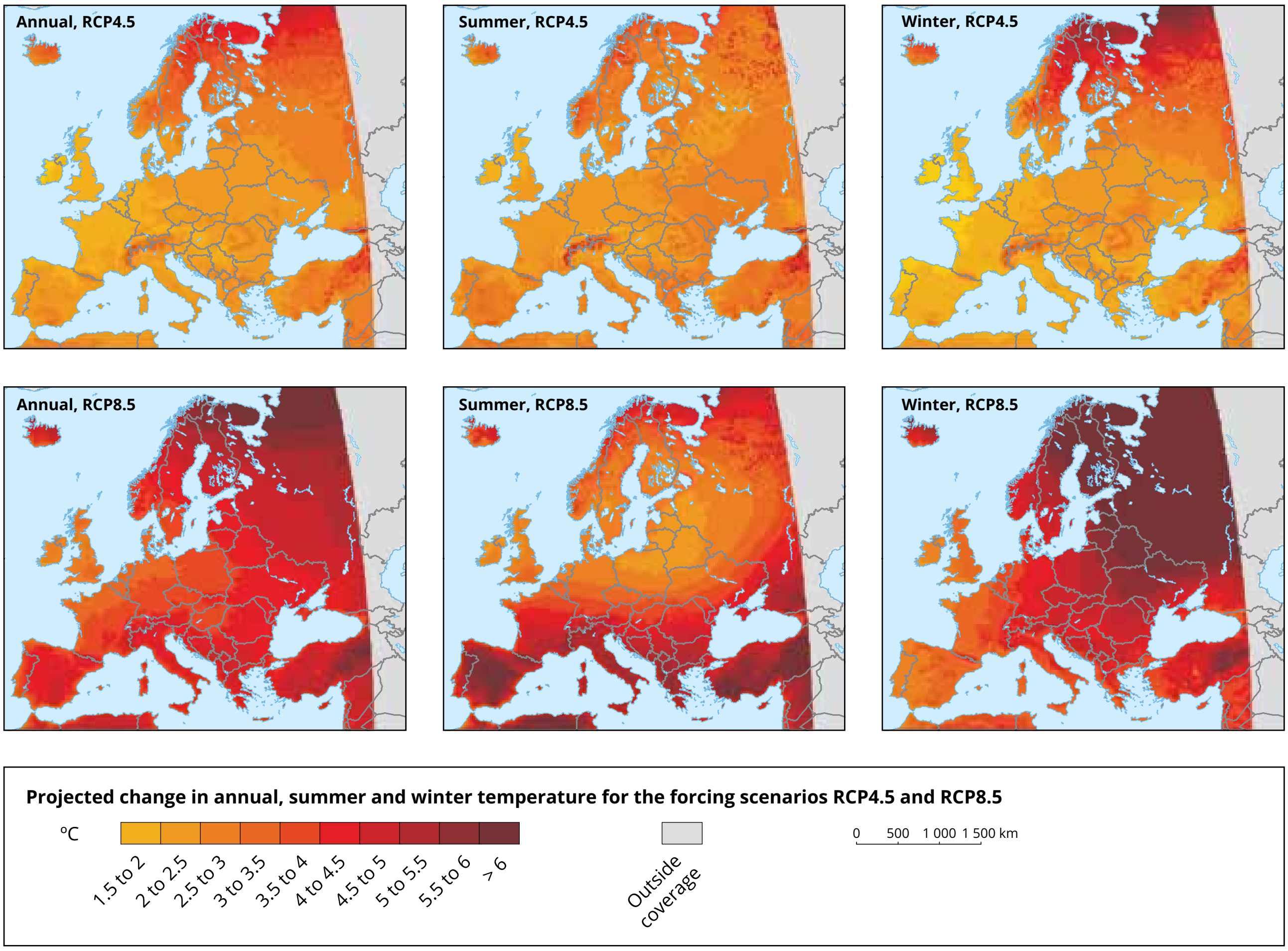
The UNFCCC target of limiting global average warming to less than 2.0 °C above pre-industrial levels is projected to be exceeded between 2042 and 2050 by the three highest of the four RCP scenarios (Vautard et al., 2014). The lowest, RCP2.6, implies a strong reduction in greenhouse gas emissions over this century and negligible or even negative emissions at the end of the century (Moss et al., 2010).

Several studies have projected climate change beyond 2100 based on the so-called extended concentration pathways (ECPs; see Section 1.2. The central estimates (i.e. average across models) for global mean temperature increase by 2200, relative to pre-industrial levels, are between 1.3 °C for ECP2.6 and 7.1 °C for ECP8.5 (Meinshausen et al., 2011; Collins et al., 2013).

Projections: European temperature

Temperatures across Europe are projected to continue increasing throughout this century. Projections from the EURO-CORDEX initiative suggest that European land areas will warm faster on average than global land areas (Jacob et al., 2014). According to the multi-model ensemble mean, European land areas are projected to warm in the range of 1 to 4.5 °C for the RCP4.5 scenario and in the range of 2.5 to 5.5 °C for RCP8.5 over the 21st century (2071–2100 compared with 1971–2000) (Map 3.4). The strongest warming is projected over north-eastern Europe and Scandinavia in winter and over southern Europe in summer.

Map 3.4 Projected changes in mean annual, summer and winter temperature for the forcing scenarios RCP4.5 and RCP8.5



Note: This map shows projected changes in mean annual (left), summer (middle) and winter (right) near-surface air temperature (°C) in the period 2071–2100 compared with the baseline period 1971–2000 for the forcing scenarios RCP4.5 (top) and RCP8.5 (bottom). Model simulations are based on the multi-model ensemble average of many different combined GCM–RCM simulations from the EURO-CORDEX initiative.

Source: EURO-CORDEX (Jacob et al., 2014).

3.2.3 *Heat extremes*

Key messages

- The number of warm days (those exceeding the 90th percentile threshold of a baseline period) have almost doubled since 1960 across the European land area.
- Europe has experienced several extreme heat waves since 2000 (2003, 2006, 2007, 2010, 2014 and 2015). Under a high emissions scenario (RCP8.5), very extreme heat waves as strong as these or even stronger are projected to occur as often as every two years in the second half of the 21st century. The impacts will be particularly strong in southern Europe.

Relevance

The increase in the global surface temperature is expected to affect the frequency and intensity of extreme events, such as heat extremes (Fischer and Schär, 2010; Stott et al., 2011; Russo et al., 2014). The severity of a heat wave depends on a number of factors, including its duration, its relative intensity (how much hotter than normal) and its absolute intensity.

Heat extremes are often associated with droughts because dry soil reduces evaporative cooling and thus increases the magnitude of a heat wave (Mueller and Seneviratne, 2012). On the other hand, heat extremes can increase the frequency and intensity of heavy precipitation events (including hailstorms), because warmer air can hold a greater quantity of water (Kendon et al., 2014).

Heat extremes also have strong direct impacts on human health and well-being, as well as on society (e.g. through decreased labour productivity), ecosystems (e.g. through forest fires) and agriculture. In particular, heat waves exacerbated by the urban heat island effect and air pollution can have devastating impacts on human health in urban areas.

Past trends

Observational data show a continued increase in heat extremes over land in the period 1997–2012) (Seneviratne et al., 2014). At the global scale, warm days and nights, as well as heat waves, have become more frequent in recent decades. The increase in maximum daily temperatures has generally been faster than the increase in annual average temperature (IPCC, 2013). In Europe, since the 1950s, large areas have experienced intense and long heat waves, with notable impacts on human health and socio-economic systems (García-Herrera et al., 2010; Russo et al., 2015). As a result, 500-year-old temperature records were broken over 65 % of Europe in the period 2003–2010 alone (Barriopedro et al., 2011).

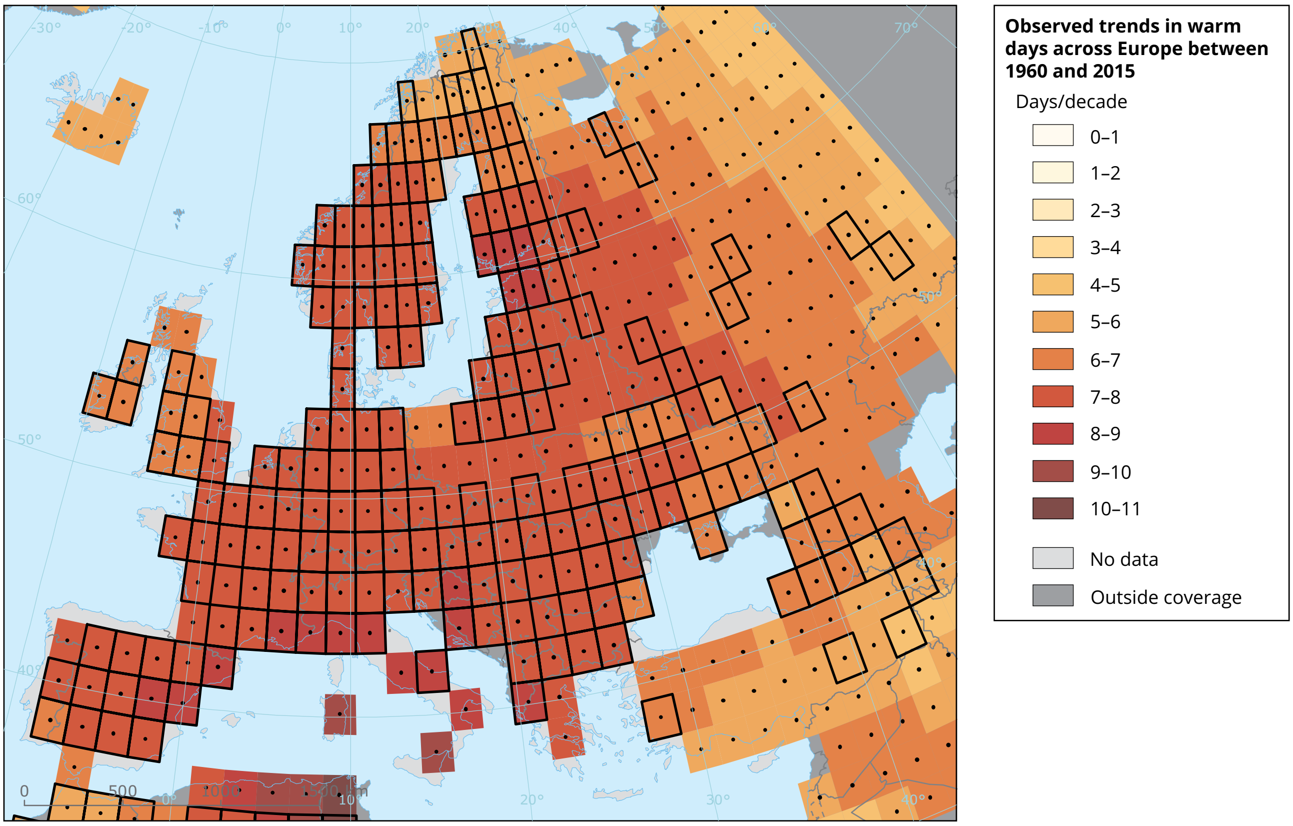
Indices for extreme temperatures, including the annual maximum value of daily maximum temperature (Tx_x), have shown significant upwards trends across Europe since the 1950s (Donat, Alexander, Yang, Durre, Vose, and Caesar, 2013). The number of unusually warm days (Tx90p) has increased by up to 10 days per decade since 1960 in most of southern Europe and Scandinavia (Map 3.5). Based on the daily Heat Wave Magnitude Index (HWMId), Europe has experienced 11 intense and long heat waves between 1950 and 2015, most of which occurred after 2000 (in 2003, 2006, 2007, 2010, 2014 and 2015) (Russo et al., 2015). The most severe heat waves have been characterised by the persistence of extremely high night-time temperatures (Russo et al., 2015). A substantial fraction of the probability of recent extreme events can be attributed to human-induced climate change, and it is likely that, for temperature extremes occurring over previous decades, a fraction of their probability was attributable to anthropogenic influences (King et al., 2016).

Projections

Periods with extreme high temperatures are projected to become more frequent and to last longer across Europe during this century (Fischer and Schär, 2010; Russo et al., 2014; Schoetter et al., 2014). Projections based on a multi-model ensemble agree on increases in heat wave frequency and magnitude for most European regions during the 21st century under all RCP scenarios. Extreme summer heat waves, such as the ones experienced in different parts of Europe in 2003 and 2010, will become much more common in the future. Under the RCP8.5 scenario, very extreme heat waves ([43])

([43]) To assess changes in heat waves, the HWMI has been used. The HWMI is defined based on the magnitude and length of heat waves in a year, where heat waves are periods of at least three consecutive days with a maximum temperature above the threshold for the reference period 1981–2010. For details, including the definition of very extreme heat waves, see Russo et al., 2014.

Map 3.5 **Observed trends in warm days across Europe between 1960 and 2015**

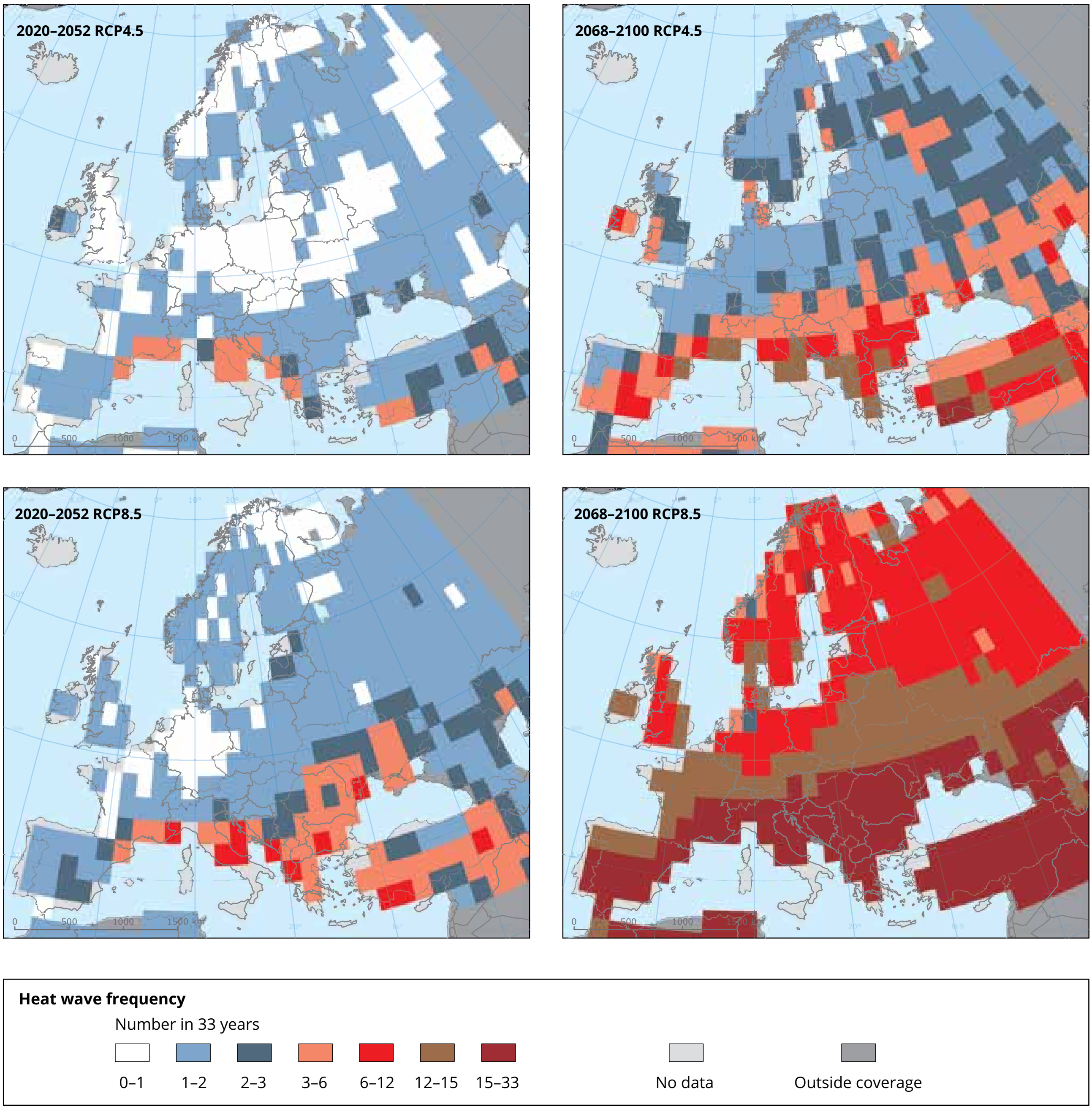


Note: Warm days are defined as being above the 90th percentile of the daily maximum temperature centred on a five-day window for a reference period. Grid boxes outlined with solid black lines contain at least three stations and thus trends are more robust. High confidence in the long-term trend (at the 5 % level) is shown by a black dot (which is the case for all grid boxes in this map). The reference period is 1971–2000.

Source: EEA and UK Met Office, based on HadEX2 (updated from Donat, Alexander, Yang, Durre, Vose, Dunn et al., 2013).

(much stronger than either the 2003 or the 2010 heat waves) are projected to occur as often as every two years in the second half of the 21st century (Map 3.6). The projected frequency of heat waves is greatest in southern and south-eastern Europe (Russo et al., 2014). According to a different analysis, at the end of the 21st century, 90 % of the summers in southern, central and north-western Europe will be warmer than any summer in the period 1920–2014 under the RCP8.5 scenario (Lehner et al., 2016). The most severe health risks are projected for low-altitude river basins in southern Europe and for the Mediterranean coasts, where many densely populated urban centres are located (Fischer and Schär, 2010).

Map 3.6 **Number of very extreme heat waves in future climates under two different emissions scenarios**



Note: Very extreme heat waves are defined as having a HWMI above 8. For comparison, the 2003 western European heat wave had an average HWMI of around 3, and the 2010 eastern European heat wave had an average HWMI of around 5. The upper maps show the median number of very extreme heat waves in a multi-model ensemble of GCMs of the near future (2020–2052) and the latter half of the century (2068–2100) under the RCP4.5 scenario. The lower maps are for the same time periods but under RCP8.5.

Source: Adapted from Russo et al., 2014.

3.2.4 Mean precipitation

Key messages

- Annual precipitation since 1960 shows an increasing trend of up to 70 mm per decade in north-eastern and north-western Europe, and a decrease of up to 90 mm per decade in some parts of southern Europe. At mid-latitudes no significant changes in annual precipitation have been observed. Mean summer precipitation has significantly decreased by up to 20 mm per decade in most of southern Europe, while significant increases of up to 18 mm per decade have been recorded in parts of northern Europe.
- Projected changes in precipitation vary substantially across regions and seasons. Annual precipitation is generally projected to increase in northern Europe and to decrease in southern Europe. The projected decrease in southern Europe is strongest in the summer.

Relevance

Precipitation plays a vital role in all environmental systems and social sectors, including natural ecosystems, agriculture, water supply, energy production and tourism. Daily precipitation has been recorded systematically in most of Europe since the 1950s. However, despite the length of precipitation records, a climate change signal cannot be detected with certainty in all European regions owing to the high spatial and temporal variability of precipitation. Difficulties in detecting trends can also arise from the small sampling area of rain gauges, calibration errors in instrumentation and erroneous measurements during snow or gales (e.g. Hofstra et al., 2009).

Past trends

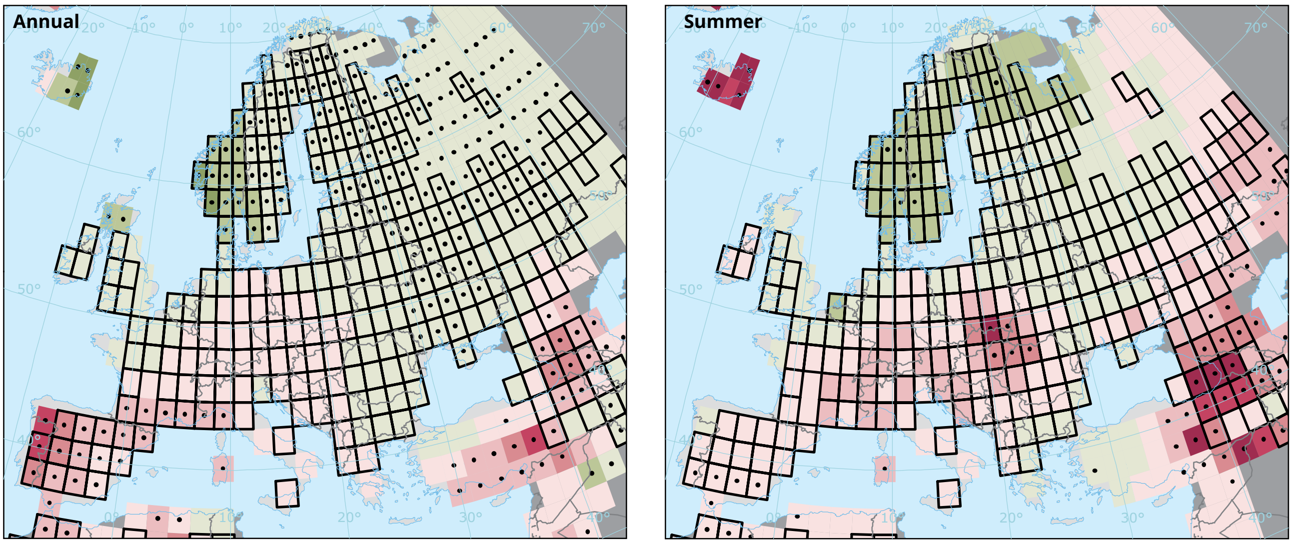
According to the E-OBS dataset (Haylock et al., 2008), average annual precipitation across Europe shows no significant changes since 1960. However, significant changes have been observed at sub-continental scales. Most precipitation studies show a tendency towards wetter conditions in the northern hemisphere throughout the 20th century, but the changes are less spatially coherent than temperature change. The majority of Scandinavia and the Baltic states have observed an increase in annual precipitation of greater than 17 mm per decade, which is as high as 70 mm per decade in western Norway (Map 3.7, left). Winter precipitation (December to February) tends to decrease in limited areas in southern Europe, and significant increases (up to 70 mm per decade) have been recorded in most of northern Europe (Maraun, 2013). In contrast, annual precipitation has decreased by up to 90 mm per decade in the Iberian Peninsula, in particular in central Portugal. Mean summer (June to August) precipitation has significantly decreased by up to 20 mm per decade in most of southern Europe, while significant increases (up to 18 mm per decade) have been recorded in parts of northern Europe (Map 3.7, right) (van den Besselaar et al., 2013; Casanueva et al., 2014).

Changes in large-scale circulation patterns (synoptic atmospheric circulation) play a key role in the observed changes in precipitation (Casanueva et al., 2014; Fleig et al., 2015). It is not clear if the relatively minor land-use changes in Europe since the 1950s have influenced observed precipitation trends (Taylor, 2015).

Projections

For a high emissions scenario (RCP8.5), the models (ensemble mean) project a statistically significant increase in annual precipitation in large parts of central and northern Europe (of up to about 30 %) and a decrease in southern Europe (of up to 40 %) from 1971–2000 to 2071–2100 (Map 3.8, left); in summer, the precipitation decrease extends northwards (Map 3.8, right) (Jacob et al., 2014). A zone with small changes that are not significant (but are, however, partially robust in the direction of the change), shows where the precipitation pattern (as presented in the ensemble mean) changes the direction of the change. For a medium emissions scenario (RCP4.5), the magnitude of change is smaller, but the pattern is very similar to the pattern for the RCP8.5 scenario. The range of projected changes in precipitation from the multi-model ensemble are generally the same between RCP4.5 and RCP8.5, or larger in RCP8.5, especially at the end of the century (Jacob et al., 2014).

Map 3.7 Observed trends in annual and summer precipitation across Europe between 1960 and 2015



Trends in annual (left) and summer (right) precipitation across Europe between 1960 and 2015

Annual precipitation (mm/decade): – 80 – 60 – 40 – 20 0 20 40 60 80

0 500 1 000 1 500 km

Summer precipitation (mm/decade): – 20 – 15 – 10 – 5 0 5 10 15 20

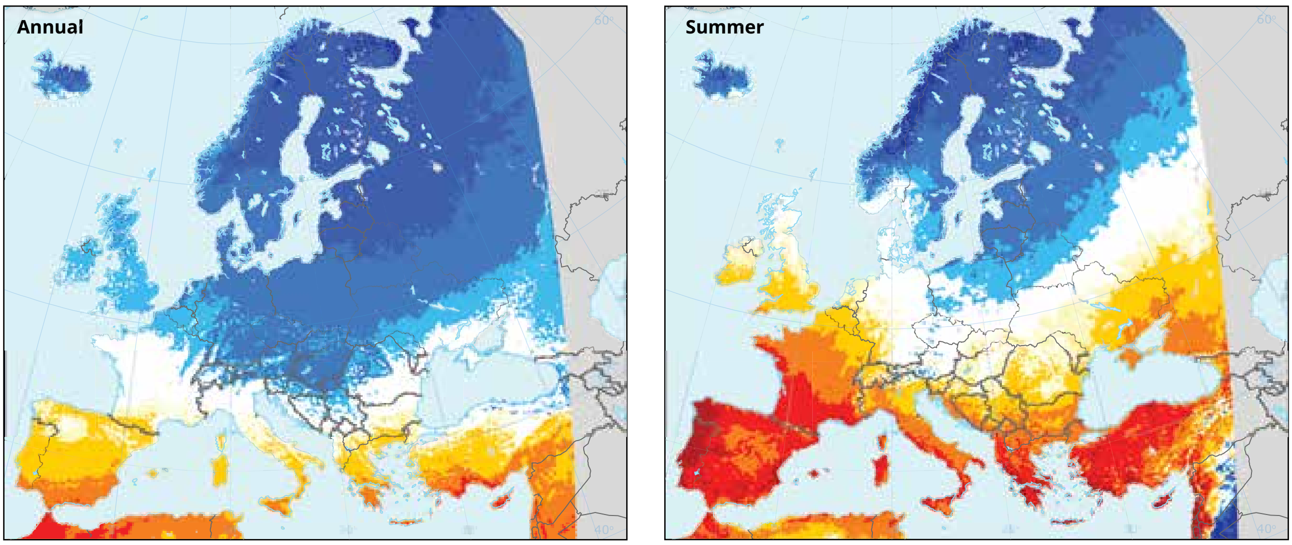
No data

Outside coverage

Note: Boxes that have a thick outline contain at least three stations. Black dots represent high confidence in the long-term trend in that box (at the 5 % level).

Source: EEA and UK Met Office, based on the E-OBS dataset (updated from Haylock et al., 2008).

Map 3.8 Projected change in annual and summer precipitation



Projected change in annual (left) and summer (right) precipitation

%: – 40 – 30 – 20 – 10 – 5 5 10 20 30

Outside coverage

0 500 1 000 1 500 km

Note: This map shows projected changes in annual (left) and summer (right) precipitation (%) in the period 2071–2100 compared with the baseline period 1971–2000 for the forcing scenario RCP8.5. Model simulations are based on the multi-model ensemble average of many different RCM simulations from the EURO-CORDEX initiative.

Source: EURO-CORDEX (Jacob et al., 2014).

3.2.5 Heavy precipitation

Key messages

- The intensity of heavy precipitation events in summer and winter have increased in northern and north-eastern Europe since the 1960s. Different indices show diverging trends for south-western and southern Europe.
- Heavy precipitation events are likely to become more frequent in most parts of Europe. The projected changes are strongest in Scandinavia and eastern Europe in winter.

Relevance

Changes in the frequency and magnitude of heavy precipitation events can have considerable impacts on society, including agriculture, industry and ecosystem services. An assessment of past trends and future projections of heavy precipitation is therefore essential for advising policy decisions on mitigation and adaptation to climate change. The risks posed by heavy precipitation hazards, such as flooding events (including cloud burst and flash floods) are also influenced by non-climatic factors, such as population density, floodplain development and land-use changes. Hence, estimates of future changes in such risks need to consider changes in both climatic and non-climatic factors.

To accurately assess trends in heavy precipitation at local scales, high-resolution datasets are required. These climatological datasets are compiled from the observation networks from countries and additional data from regional observations networks. As some countries do not share all of their datasets, the spatial and temporal coverage of the European dataset, and consequently the accuracy of past trends, varies across Europe (see Section 3.1).

Past trends

The majority of observation-based studies that investigate trends in extreme rainfall intensity are based on data recorded at the daily time scale. An index for the maximum annual precipitation over five consecutive days (Rx5d) shows significant increases up to 5 mm per decade over northern and north-western Europe in winters and up to 4 mm in summers (Map 3.9, left) (Donat, Alexander, Yang, Durre, Vose, Dunn et al., 2013). The same index shows decreases of more than 5 mm per decade in south-western Europe in winter and between 2 and 3 mm in summer (Map 3.9, right). The smaller trends in central and south-eastern Europe are not statistically significant. The increase in northern and north-eastern Europe is a consequence of the observed shift polewards of the North Atlantic storm track and weakening of Mediterranean storms (Hov et al., 2013).

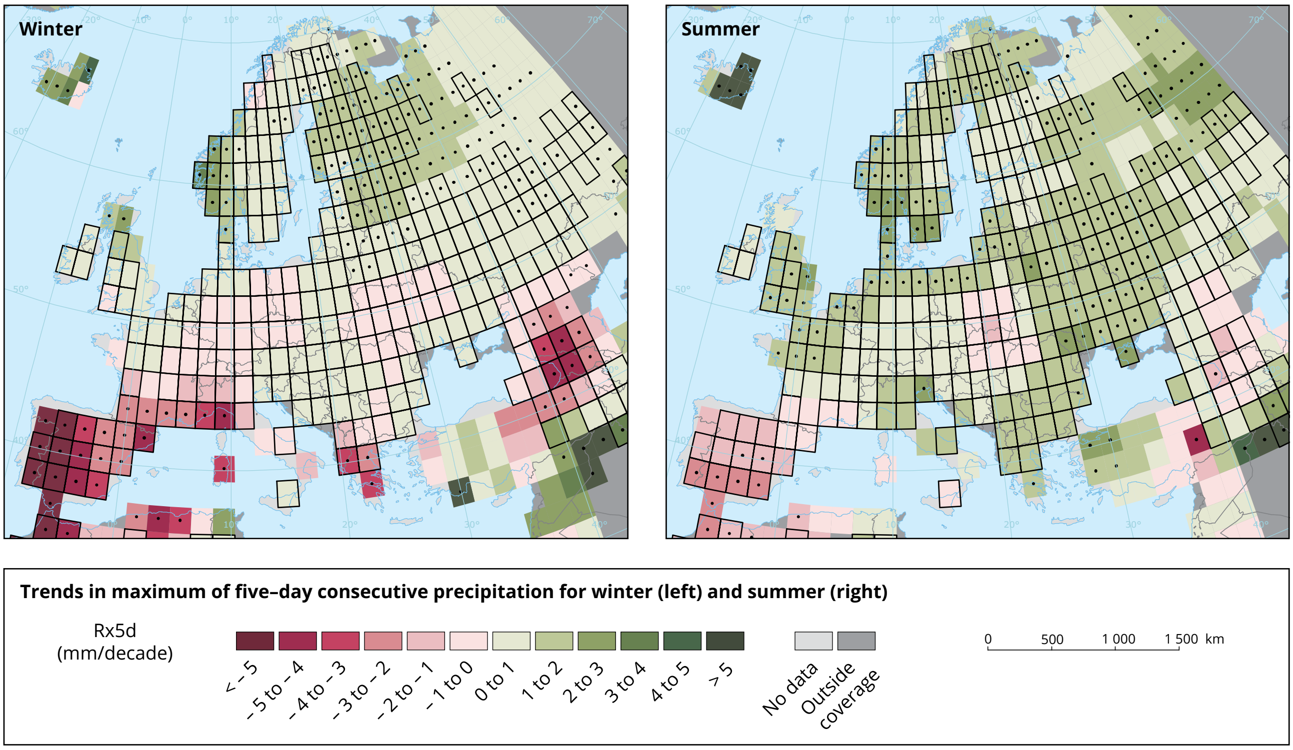
A wider literature review suggests that heavy precipitation events have become more intense and more frequent in Europe on average, but there are important differences across regions, seasons, time periods, heavy precipitation indices and underlying datasets (Zolina et al., 2010; van den Besselaar et al., 2013; Gallant et al., 2013; Donat, Alexander, Yang, Durre, Vose, Dunn et al., 2013; Fischer et al., 2014; Casanueva et al., 2014). Studies generally agree that heavy precipitation has become more intense in northern and north-eastern Europe since the 1950s, even though not all changes are statistically significant. Different studies and indices show diverging trends for south-western and southern Europe.

Records of daily mean precipitation are often insufficient to study trends and changes in heavy precipitation. The damage associated with heavy precipitation often originates from sub-daily localised heavy precipitation events, which can lead to costly flash floods. Owing to limited data availability, only a limited number of studies have focused on large regional scale assessments of sub-daily precipitation (Hartmann et al., 2013). A recent review study concludes that extreme sub-daily precipitation events have generally increased in Europe, even in regions with decreases in mean rainfall, but there is large variability across regions, seasons and event durations (Westra et al., 2014).

Projections

Global warming is projected to lead to a higher intensity of precipitation and longer dry periods in Europe (IPCC, 2012; Hov et al., 2013). Projections show an increase in heavy daily precipitation in most parts of Europe in winter, by up to 35 % during the 21st century. Heavy precipitation in winter is projected to increase over most of Europe, with increases of up to 30 % in north-eastern Europe (Map 3.10, left). In summer, an increase is also projected in most parts of Europe, but

Map 3.9 **Observed trends in maximum annual five-day consecutive precipitation across Europe in winter and summer between 1960 and 2015**



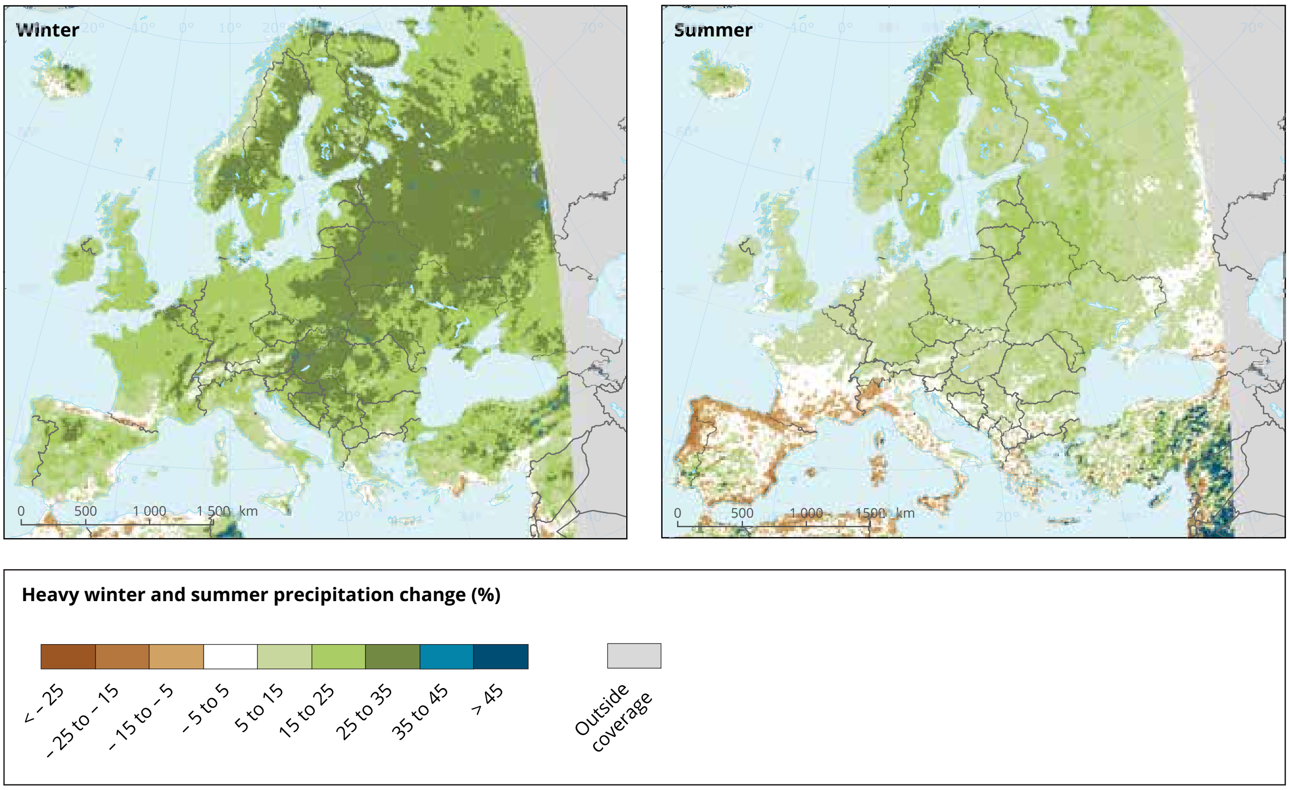
Note: This map shows observed trends in maximum annual five-day consecutive precipitation across Europe in winter (left) and summer (right) between 1960 and 2015. Boxes with an outline contain at least three stations. Black dots show trends that are statistically significant (at the 5 % level).

Source: EEA and UK Met Office, based on HadEX2 (updated from Donat, Alexander, Yang, Durre, Vose, Dunn et al., 2013).

decreases are projected for some regions in southern and south-western Europe (Map 3.10, right) (Jacob et al., 2014). Similar patterns were found for other heavy precipitation indices (Rajczak et al., 2013; Sillmann et al., 2013; Giorgi, Coppola and Raffaele, 2014).

The continued increase in the spatial and temporal resolution of global and regional climate models has generally improved the representation of extreme precipitation and increased confidence in model-based projections (Kopparla et al., 2013; Giorgi, Coppola, Raffaele et al., 2014; Montesarchio et al., 2014). However, regional climate models with spatial resolutions of between 10 and 30 km typically used in climate change studies are still too coarse to explicitly represent sub-daily localised heavy precipitation events (Chan et al., 2014; Ban et al., 2015). Evidence from high-resolution climate models suggests that the intensity of sub-daily extreme rainfall is likely to increase in the future, whereby an increase of (theoretically estimated) ~ 7 % per °C appears most likely in many regions (Westra et al., 2014). A very high-resolution model (typically 1–5 km) used for weather forecasts with explicit convection has recently been used for a climate change experiment for a region in the United Kingdom. This study projects intensification of short-duration heavy rain in the summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding (Kendon et al., 2014; Ban et al., 2015; Lehmann et al., 2015).

Map 3.10 Projected changes in heavy precipitation in winter and summer



Note: This map shows projected changes in heavy daily precipitation (%) in winter and summer for 2071–2100, compared with the baseline period 1971–2000, for the RCP8.5 scenario based on the ensemble mean of different RCMs nested in different GCMs.

Source: EURO-CORDEX (Jacob et al., 2014).

3.2.6 Wind storms

Key messages

- Storm location, frequency and intensity have shown considerable decadal variability across Europe over the past century, such that no significant long-term trends are apparent.
- Recent studies on changes in winter storm tracks generally project an extension eastwards of the North Atlantic storm track towards central Europe and the British Isles.
- Climate change simulations show diverging projections on changes in the number of winter storms across Europe. However, most studies agree that the risk of severe winter storms, and possibly of severe autumn storms, will increase for the North Atlantic and northern, north-western and central Europe over the 21st century.

Relevance

Wind storms are atmospheric disturbances that are defined by strong sustained wind. They can range from relatively small and localised events to large features covering a substantial part of the continent. Large storms in Europe are extra-tropical cyclones; they develop from low-pressure weather systems that capture their energy from the temperature contrast between the sub-tropical and polar air masses that meet in the Atlantic Ocean. In northern and north-western Europe, severe cyclones can occur all year. In central Europe, severe cyclones occur mainly between November and February, but weaker cyclones can also occur in other seasons.

Wind storms can lead to structural damage, flooding and storm surges (see Sections 4.2, 4.3 and 5.1), which may be caused either by the wind itself, in particular short gusts, or by accompanying heavy precipitation. These events can have large impacts on human health and on vulnerable systems, such as forests, as well as transport and energy infrastructures. According to Munich RE's natural catastrophe loss database (NatCatSERVICE) (Munich RE, 2015), storms were the costliest natural hazard (in terms of insured losses) in Europe between 1980 and 2013; they ranked fourth in terms of the number of human casualties (see Section 5.1). The European regions most strongly affected were north-western, western and northern Europe, in particular regions close to the coast (Outten and Esau, 2013; Osinski et al., 2015).

Studies of storm activity have increased in recent years as a result of improved observational datasets, the development of algorithms for the identification and quantification of these phenomena, and improved understanding of the causation of extreme weather events. In addition, high-resolution GCM simulations for both present-day climate and climate change scenarios are increasingly becoming available. Nevertheless, there are still considerable uncertainties in the historical records and in our understanding of the processes influencing current storm activity and how these may be affected by climate change (Ulbrich et al., 2009; Nikulin et al., 2011; Krueger et al., 2013; Outten and Esau, 2013; Feser et al., 2014; Pfahl, 2014; Osinski et al., 2015).

Past trends

Studies of past changes in extra-tropical storms have used a variety of methods, making it difficult to compare the results of different studies or to assess if there is any underlying trend in climate change. Storm location and intensity in Europe has shown considerable variation over the past century, but northern hemisphere storm tracks and intensity have likely shifted northwards since at least 1970 (Ulbrich et al., 2009; Hov et al., 2013).

Wind data at the local or regional levels can show a series of decreases and increases continuing over several decades. Long records of wind speed for various regions across Europe indicate that storm intensity (i.e. storminess) has not significantly changed over the past 200 years. Available studies of storminess in north-western Europe indicate relatively high levels during the 1880s, followed by below-average conditions between the 1930s and 1960s, a pronounced increase in storminess until the mid-1990s, and average or below-average activity afterwards. Somewhat similar patterns were observed in other parts of Europe (Matulla et al., 2007; Feser et al., 2014).

There is low confidence in the robustness of reanalysis results for extreme wind speeds before the middle of the 20th century (Hartmann et al., 2013; Feser et al., 2014). A single reanalysis study for the period

1871–2008 suggests an increasing trend in storminess across western, central and northern Europe, with storminess in the North Sea and the Baltic Sea region reaching its highest values towards the end of the 20th century (Donat, Renggli et al., 2011). Other studies have produced evidence that both conflicts and agrees with this result (Wang et al., 2011, 2014; Brönnimann et al., 2012; Krueger et al., 2013).

Projections

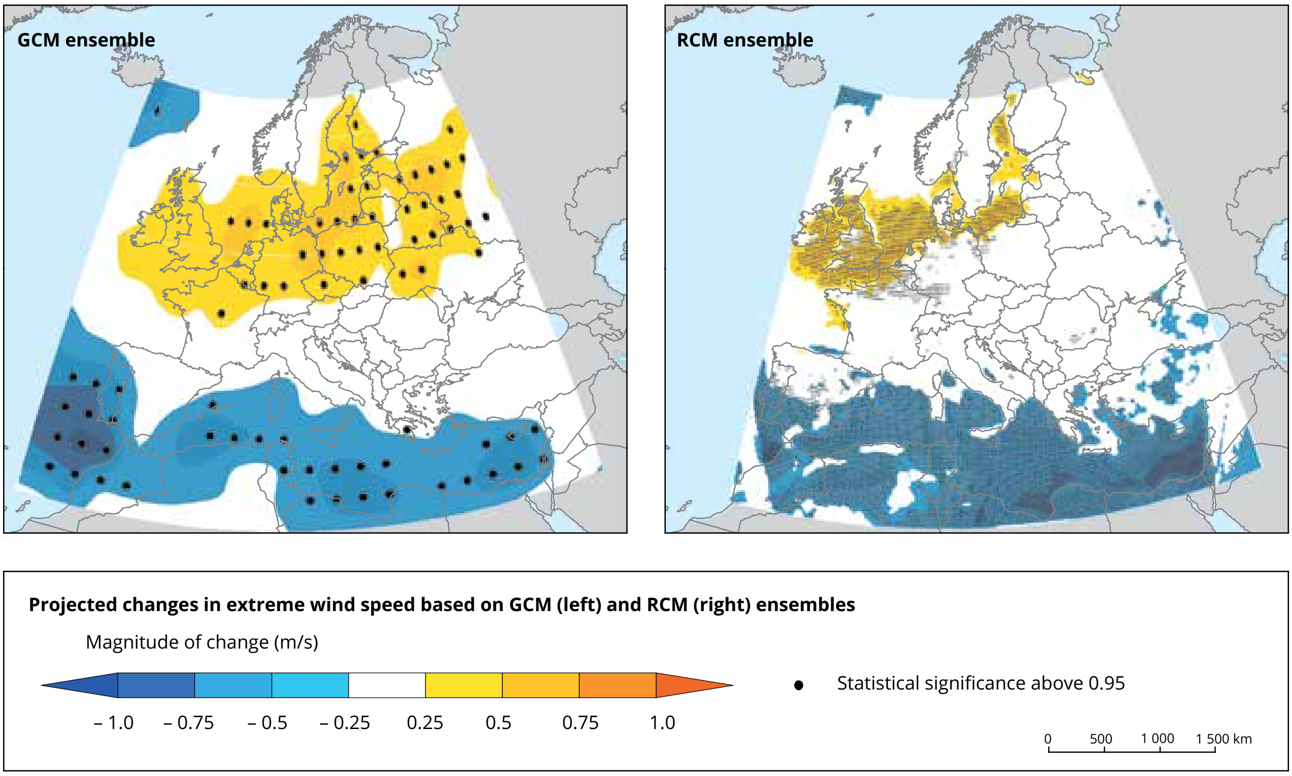
The simulation of extra-tropical cyclones in climate models remains a scientific challenge in spite of recent significant progress in modelling techniques. Earlier model studies showed shifts both polewards (Gastineau and Soden, 2009) and towards the equator (McDonald, 2011; Scaife et al., 2011) in the Atlantic storm track. The latter could double the predicted increase in winter rainfall over western and central Europe compared with other climate projections. Recent simulations based on CMIP5 data project an extension eastwards of the North Atlantic storm track towards central Europe and the British Isles (Zappa et al., 2013).

Modelling studies show diverging results on changes in the number of storms across Europe, but they generally agree on increases in the strongest, most damaging storms in most European regions. A study using a multi-model ensemble projects a small increase in the wind speed of the strongest winter storms over northern parts of central and western Europe, and a decrease in southern Europe (Map 3.11) (Donat, Leckebusch et al., 2011). The associated change in mean potential economic loss varied between – 7 % in the Iberian Peninsula and + 25 % in Germany.

A comprehensive review study covering the North Atlantic and northern, north-western and central Europe shows large agreement that the intensity of winter storms will increase in all these regions over the 21st century (Feser et al., 2014). Another recent study focusing on central Europe concluded that models consistently projected an increased frequency and intensity of severe storms over central Europe. Under SRES A1B conditions, increases in frequency towards the end of the 21st century range between − 11 % and + 44 %, with an ensemble average of 21 % (Pardowitz, 2015). The intensity of storms affecting central Europe once a year was found to increase by about + 30 %, with individual models projecting changes between − 28 % and up to + 96 %. These results are largely consistent with those of a recent study based on the GCM projections underlying the IPCC AR5 (Zappa et al., 2013). One recent study with a single, very high-resolution (~ 25 km) GCM indicates that the frequency and intensity in Europe of severe autumn storms originating in the tropical Atlantic will increase in a warmer future climate as will the area affected (Baatsen et al., 2015). However, this result cannot be considered robust, as it has not yet been confirmed by other studies.

In summary, the risk of severe winter storms, and possibly of severe autumn storms, is projected to increase in many regions in Europe, in particular for the North Atlantic and northern, north-western and central Europe.

Map 3.11 Projected changes in extreme wind speed based on GCM and RCM ensembles



Note: This map shows the ensemble mean of changes in extreme wind speed (defined as the 98th percentile of daily maximum wind speed) for A1B (2071–2100) relative to 1961–2000. Left: based on nine GCMs. Right: based on 11 RCMs. Coloured areas indicate the magnitude of change (unit: m/s) and statistical significance at the 5 % level is shown by black dots.

Source: Adapted from Donat, Leckebusch et al., 2011. Reproduced with permission.

3.2.7 Hail

Key messages

- Hail events are among the most costly weather-related extreme events in several European regions, causing substantial damage to crops, vehicles, buildings and other infrastructure.
- The number of hail events is highest in mountainous areas and pre-Alpine regions. Since 1951, increasing hail trends have been noted in southern France and Austria, and decreasing (but not statistically significant) trends have been noted in parts of eastern Europe.
- Future projections of hail events are subject to large uncertainties, because small-scale hail events cannot be directly represented in global and regional climate models. However, model-based studies for central Europe show some agreement that hailstorm frequency will increase in this region.

Relevance

Hailstorms are most common in mid-latitudes with high surface temperature and humidity, as these conditions promote the required instability associated with strong thunderstorms and the temperature in the upper atmosphere is sufficiently low to support ice formation. The occurrence of hail over Europe is not uniform over space and time (Punge and Kunz, 2016). Most hail events occur in summer or nearby mountain areas where convective energy and trigger mechanisms for convection are highest (Punge et al., 2014).

Hail is responsible for significant damage. For example, three hailstorm events in Germany in July and August 2013 caused around EUR 4.2 billion of combined damages to buildings, crops, vehicles, solar panels, greenhouses and other infrastructure (Munich RE, 2014).

Past trends

Trends in days with hail have been calculated using surface-based observations, but are unreliable owing to the limited number of stations and the stochastic nature of hailstorms (Punge and Kunz, 2016). Trends in hail observations are sometimes analysed using reports of damage as a proxy (e.g. insurance claims), although damage is also a function of the vulnerability of the impacted area to damage. Several European regions show an increase in the convective conditions that can potentially form hail. In some areas (such as south-west Germany), an increase in damage days is observed (Kunz et al., 2009). However, these changes are not uniform across Europe, with large regional differences mostly related to topography.

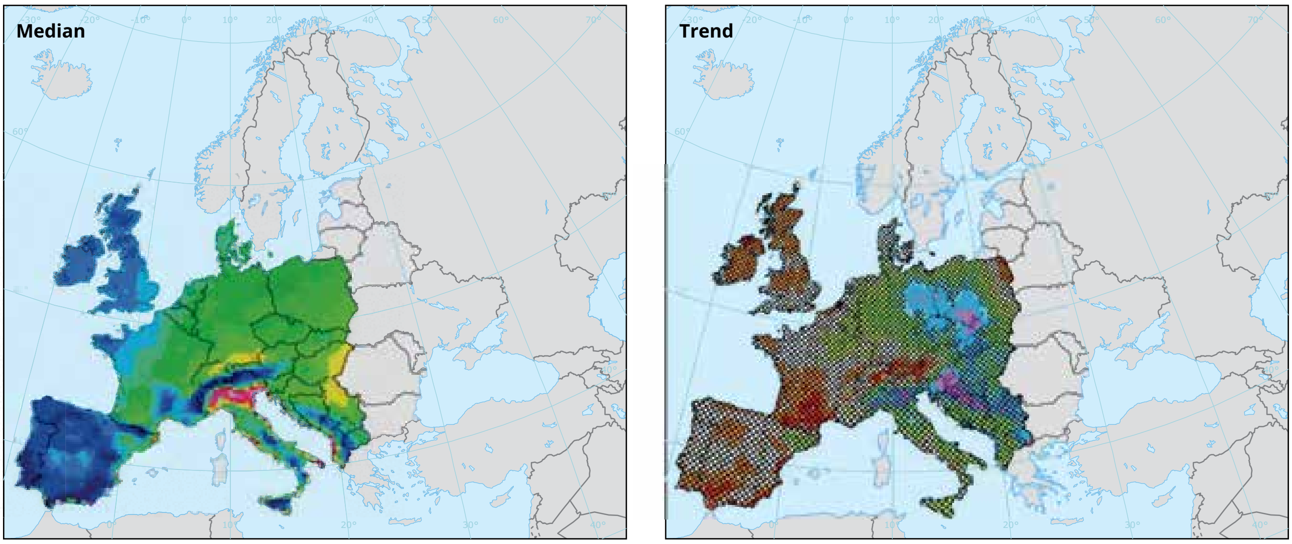
A study of hailstorm frequencies over the period 1978–2009 in Germany and eastern Europe shows general increases in convective available potential energy (CAPE) and increases in evaporation, which have been attributed to rising temperatures, but the changes in these weather variables do not necessary modify the numbers and intensities of severe convective storms (Mohr and Kunz, 2013; Punge and Kunz, 2016). The atmosphere has become more unstable, and thus more suitable for hail, especially in southern and central Europe, where the temperature increase in summer has been particularly large (Mohr, Kunz, and Geyer, 2015).

Recently, European hail climatology for the period 1951–2010 was analysed using a combination of various meteorological parameters relevant for thunderstorms and hail (Mohr, Kunz, and Geyer, 2015). This has been expressed as the potential hail index (PHI), which quantifies the atmospheric potential for hailstorms. The climatology shows the highest values of the mean PHI for the areas north and south of the Alps, the eastern Adriatic coast and parts of eastern Europe (Map 3.12, left). Increasing hail trends (with a PHI over 3 in the period 1951–2010) are found in southern France and Spain, and decreasing trends (with a PHI lower than –5 in the period 1951–2010) in eastern Europe (Map 3.12, right). However, trends are not significant (at the 5 % significance level) in most grid boxes.

Projections

Much of the published work relevant to future hail projections is based upon developing the relationships between large-scale atmospheric environments and small-scale severe weather events, such as severe thunderstorms, hailstorms and tornadoes. Available projections suggest increases in CAPE, which result in conditions that favour severe thunderstorms becoming more frequent, and decreases in wind shear, which reduces the likelihood of hailstorms (Brooks, 2013).

Map 3.12 Observed annual median and trend of the mean PHI over the period 1951–2010



Observed annual median (left) and trend (right) of the mean Potential Hail Index (PHI) over the period 1951–2010

PHI 0 2.5 5 7.5 10 12.5 15 17.5 20 22.5 25

25 27.5 30 32.5 35 37.5 40 42.5 45 47.5 50

Outside coverage

PHI – 13 – 11 – 9 – 7 – 5 – 3 – 1 1 3 5 7

Not statistically significant at the 5 % level

0 500 1 000 1 500 km

Note: Trends that are not significant at the 5 % level are cross-hatched. Significant trends are found only for values below a PHI of – 5 over the period.

Source: Based on the logistic hail model (Mohr, Kunz, and Geyer, 2015) and reanalysis data from NCEP-NCAR (Kalnay et al., 1996).

Different RCMs have been used for assessing changes in hailstorms at the national and sub-national scales. A statistically significant downwards trend for hailstones with diameters between 21 and 50 mm was projected for the United Kingdom (Sanderson et al., 2015). An increase in hailstorm frequency between 7 and 15 % for the period 2031–2045 compared with 1971–2000 was projected for south-west Germany based on large-scale weather patterns (Kapsch et al., 2012). Using the PHI and an ensemble of seven RCMs, an increase in hail probability over most areas of Germany was projected for the period 2021–2050 compared with 1971–2000 (Mohr, Kunz, and Keuler, 2015). The projected changes are largest in southern Germany (values of almost 7 PHI). However, the results are subject to large uncertainties, mainly owing to low spatial resolution and convective parametrisation schemes in regional climate models (Fischer et al., 2014). Improving the convective parametrisation schemes and increasing the spatial resolution of models would improve the accuracy of future hail projections.

3.3 Cryosphere

Key messages

- Consistent with a warming climate, observations confirm the decrease of snow cover, the shrinking of glaciers, increased melting of the large polar ice sheets in Greenland and Antarctica, and the declining area and thinning of Arctic sea ice.
- Further reductions of the cryosphere are projected in the future. The projected changes vary across regions and indicators, and there are large uncertainties in some of the projections.
- The melting of ice and snow and the thawing of permafrost cause positive feedback loops that can accelerate climate change further.
- Changes in the cryosphere affect global sea level, many species, ecosystems and their services, freshwater supply, river navigation, irrigation and power generation. The projected changes could increase natural hazards and the risk of damage to infrastructure. At the same time, they could create new opportunities for navigation and the exploitation of natural resources in the Arctic region.

3.3.1 Overview

Relevance

The cryosphere includes all permanent or seasonal snow and ice on land, in the seas, rivers and lakes, and in the ground (permafrost). It is the second largest component of the climate system, after the oceans, with regard to mass and heat capacity. Because of its importance, the cryosphere features prominently in climate change literature (AMAP, 2011; Barry and Gan, 2011; Olsen et al., 2012; Vaughan et al., 2013; Key et al., 2015). The concern for the long-term and irreversible changes in the cryosphere is receiving increasing international attention (ICCI, 2015). Recent scientific work has focused in particular on the Greenland and Antarctic ice sheets (Shepherd et al., 2012; Joughin et al., 2014; Noël et al., 2014), as the fate of the ice sheets has major implications for long-term sea level rise. In addition, melting of the Greenland ice sheet can influence the Atlantic meridional overturning circulation and thereby create a feedback that can critically influence long-term changes in the climate system (Blaschek et al., 2014). Another important part of the cryosphere is the Arctic permafrost, as thawing of permafrost can lead to major positive feedback processes, accelerating climate change (Parmentier et al., 2015; Schuur et al., 2015).

The scientific publications that have been published since the previous CCIV report (EEA, 2012) confirm the general patterns of change, but have provided new data on the melting of the Greenland and Antarctic ice sheets, suggesting that the mass loss may accelerate and that there is a risk of irreversible processes at relatively low levels of air temperature increase. This would imply a higher rise in sea level than previously assumed.

Snow and ice are important for the global climate system (see Section 3.1). Much of the sunlight that hits these surfaces is reflected back into space instead of warming the Earth. As the melting of snow and ice leads to expansions of darker surfaces such as water or ground, more heat is absorbed. These positive ice-temperature feedback processes are already accelerating the loss of sea ice in summer and autumn, which has resulted in higher winter near-surface air temperatures in the Arctic (Screen and Simmonds, 2010).

Ice and snow are important for many ecosystems. Some species spend their entire life cycle in areas dominated by the cryosphere, whereas others are adapted to temporary snow and ice. Observed changes in the cryosphere are already affecting species interactions and entire ecosystems (Post et al., 2009).

The cryosphere plays an important role in water management. Two-thirds of the world's freshwater resources are frozen. Seasonal melting releases water during the warm season, thereby supporting water supplies and hydropower. The cryosphere is also closely linked to sea level. The melting of glaciers and of the large ice sheets in Greenland and Antarctica is already contributing significantly to global sea level rise, and this contribution is expected to increase in the future.

Changes in the cryosphere have social and economic consequences by affecting sea ice and the distribution of permafrost on land. Such changes affect transport routes, building technology, tourism and recreation, and opportunities to exploit natural resources. Furthermore, thawing of permafrost can contribute to climate change through release of CO_2 and CH_4 from Arctic permafrost areas (Hollesen et al., 2015; Schuur et al., 2015).

Selection of indicators

The cryosphere provides easily observable signs of climate change over a wide range of time scales, from millennia to seasonal variations within a year. This section presents indicators that cover the following components of the cryosphere:

- *Arctic and Baltic sea ice:* sea ice covers large areas. It reflects light more than open sea and has impacts on ocean circulation, which transports heat from the equator to the poles. Sea ice and its variations also affect navigation and the exploitation of natural resources.
- *Greenland and Antarctic ice sheets:* the continental ice sheets of Greenland and the Antarctic influence the global climate in many ways. First of all, they have important effects on global sea level. Furthermore, they modify ocean temperatures and circulation, vegetation and land-surface albedo.
- *Glaciers:* glaciers and ice caps influence sea level, river flow and freshwater supply, ecosystems and many human activities.
- *Snow cover:* snow covers a large area, but has a relatively small volume. Its reflection of light is important for climatic conditions, it insulates the soil in winter and is an important source of temporary water storage.

Information on changes in permafrost is not presented as an indicator. In the past 15–25 years for which data are available, European permafrost has shown a general warming trend, and the depth of seasonal thaw has increased at several European permafrost sites (Harris et al., 2009; EEA, 2012). Substantial near-surface permafrost degradation is projected over much of the permafrost area, which is expected to increase the risk of rock falls, debris flows, ground subsidence and impacts on biodiversity (Shaefer et al., 2012). Efforts to improve and systematise the monitoring of permafrost are being pursued (Biskaborn et al., 2015).

Data quality and data needs

Data on the cryosphere vary significantly with regard to availability and quality. Snow and ice cover have been monitored globally since satellite measurements started in the 1970s. Improved technology allows for more detailed observations and observations of a higher resolution. High-quality long-term data are also available on glaciers throughout Europe. Direct historical area-wide data on the Greenland and Antarctic ice sheets cover about 20 years, but reconstructions give a 200 000-year perspective.

Continuous efforts are being made to improve knowledge of the cryosphere. Scenarios for the future development of key components of the cryosphere have recently become available from the CMIP5 project, which has provided climate change projections for the IPCC AR5 (see Section 3.1). Owing to their economic importance, considerable efforts have also been devoted to improving real-time monitoring of snow cover and sea ice.

3.3.2 *Arctic and Baltic sea ice*

Key messages

- The extent and volume of the Arctic sea ice has declined rapidly since global data became available, especially in summer. Over the period 1979–2015, the Arctic has lost, on average, 42 000 km² of sea ice per year in winter and 89 000 km² per year by the end of summer.
- The nine lowest Arctic sea ice minima since records began in 1979 have been the September ice cover in each of the last nine years (2007–2015); the record low Arctic sea ice cover in September 2012 was roughly half the average minimum extent of 1981–2010. The annual maximum ice cover in March 2015 and March 2016 were the lowest on record, and the ice is also getting thinner.
- The maximum sea ice extent in the Baltic Sea shows a decreasing trend since about 1800. The decrease appears to have accelerated since the 1980s, but the interannual variability is large.
- Arctic sea ice is projected to continue to shrink and thin. For high greenhouse gas emissions scenarios, a nearly ice-free Arctic Ocean in September is likely before mid-century. There will still be substantial ice in winter.
- Baltic Sea ice, in particular the extent of the maximal cover, is projected to continue to shrink.

Relevance

Observed changes in the extent of Arctic sea ice provide evidence of global warming. Reduced polar sea ice will speed up global warming further (Hudson, 2011) and several studies have also suggested causal links between the sea ice decline and summer precipitation in Europe, the Mediterranean and East Asia (Simmonds and Govekar, 2014; Vihma, 2014). Reduced Arctic ice cover may also lead to increases in heavy snowfall in Europe during early winter (Liu et al., 2012).

The projected loss of sea ice may offer new economic opportunities for oil and gas exploration, shipping, tourism and some types of fisheries Most of these activities would increase the pressure on, and the risks to, the Arctic environment.

Past trends

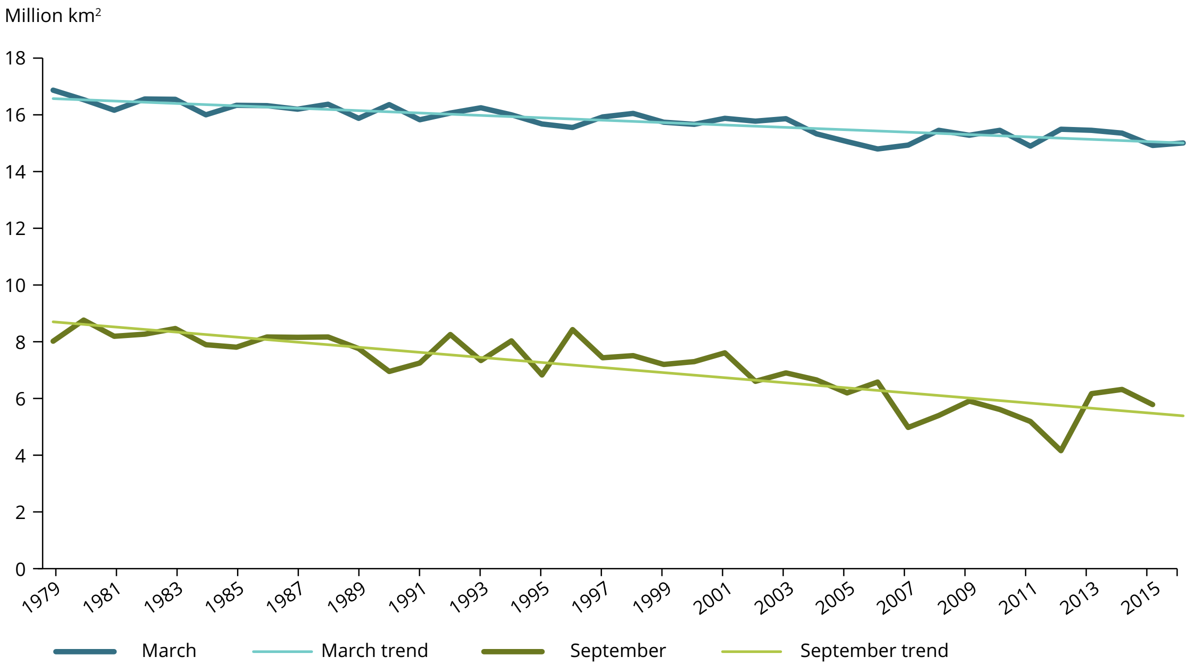
In the period 1979–2015, the sea ice extent in the Arctic decreased by 42 000 km² per year in winter (measured in March) and by 89 000 km² per year in summer (measured in September) (Figure 3.8), which, based on historical records, is likely unprecedented since the 14th century (Halfar et al., 2013). The maximum sea ice extent in March 2015 and March 2016 were the lowest on record. Arctic sea ice loss is driven by a combination of warmer ocean waters and a warmer atmosphere, including an earlier onset of summer surface melt (Collins et al., 2013). In contrast, Antarctic sea ice has reached record high levels in recent years, but the expansion of the Antarctic sea ice has been less than half of the loss of Arctic sea ice (Parkinson, 2014).

Changes in Arctic sea ice may trigger complex feedback processes. Warming and a longer melt season result in increased solar heat uptake by the ocean, which delays the autumn refreeze (Stammerjohn et al., 2012). However, a warmer atmosphere means that there are more clouds and, in summer, these reflect sunlight, thus representing a negative feedback mechanism. Even so, some evidence suggests that winter regrowth of ice is inhibited by the warmer ocean surface (Jackson et al., 2012). Thinner winter ice leads to more heat loss from the ocean and a warmer atmosphere, and hence thicker cloud cover, which inhibits the escape of heat to space (Palm et al., 2010), which is a positive feedback mechanism.

The minimum Arctic sea ice cover at the end of the melt season in September 2012 broke all previously observed records. All years since 2002 have been below the average for 1981–2010 (Figure 3.8). Comparison of recent sea ice coverage with older ship and aircraft observations suggests that summer sea ice coverage may have halved since the 1950s (Meier et al., 2007). Since more reliable satellite observations started in 1979, summer ice has shrunk by 10 % per decade (Comiso et al., 2008; Killie and Lavergne, 2011). Between 1979 and 2011, the reduction of sea ice has significantly reduced albedo, corresponding to an additional 6.4 ± 0.9 W/m² of solar energy input into the Arctic Ocean region since 1979. Averaged over the globe, this albedo decrease corresponds to a forcing that is 25 % of that due to the change in CO_2 during this period (Pistone et al., 2014).

The Arctic sea ice is also getting thinner and younger, as less sea ice survives the summer to grow into

Figure 3.8 **Arctic sea ice extent**



Note: Trend lines and observation points for March (the month of maximum sea ice extent) and September (the month of minimum sea ice extent) are indicated. This figure does not reflect the reduction of sea ice thickness, which has also been declining over the same period.

Source: EUMETSAT Satellite Application Facility on Ocean and Sea Ice (OSI SAF) and CryoClim. Data delivered through Copernicus Marine Environment Monitoring Service.

thicker multi-year floes (Comiso, 2012). A recent analysis has found that annual mean ice thickness has decreased from 3.59 m in 1975 to 1.25 m in 2012, i.e. a 65 % reduction in less than 40 years (Lindsay and Schweiger, 2015). This supports findings from calculations of sea ice volume from satellites and an earlier estimate by the Pan Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) ([44]), which suggests that the mean monthly sea ice volume has decreased by about 3 000 km³/decade since 1979 (Schweiger et al., 2011, updated with PIOMAS data available online).

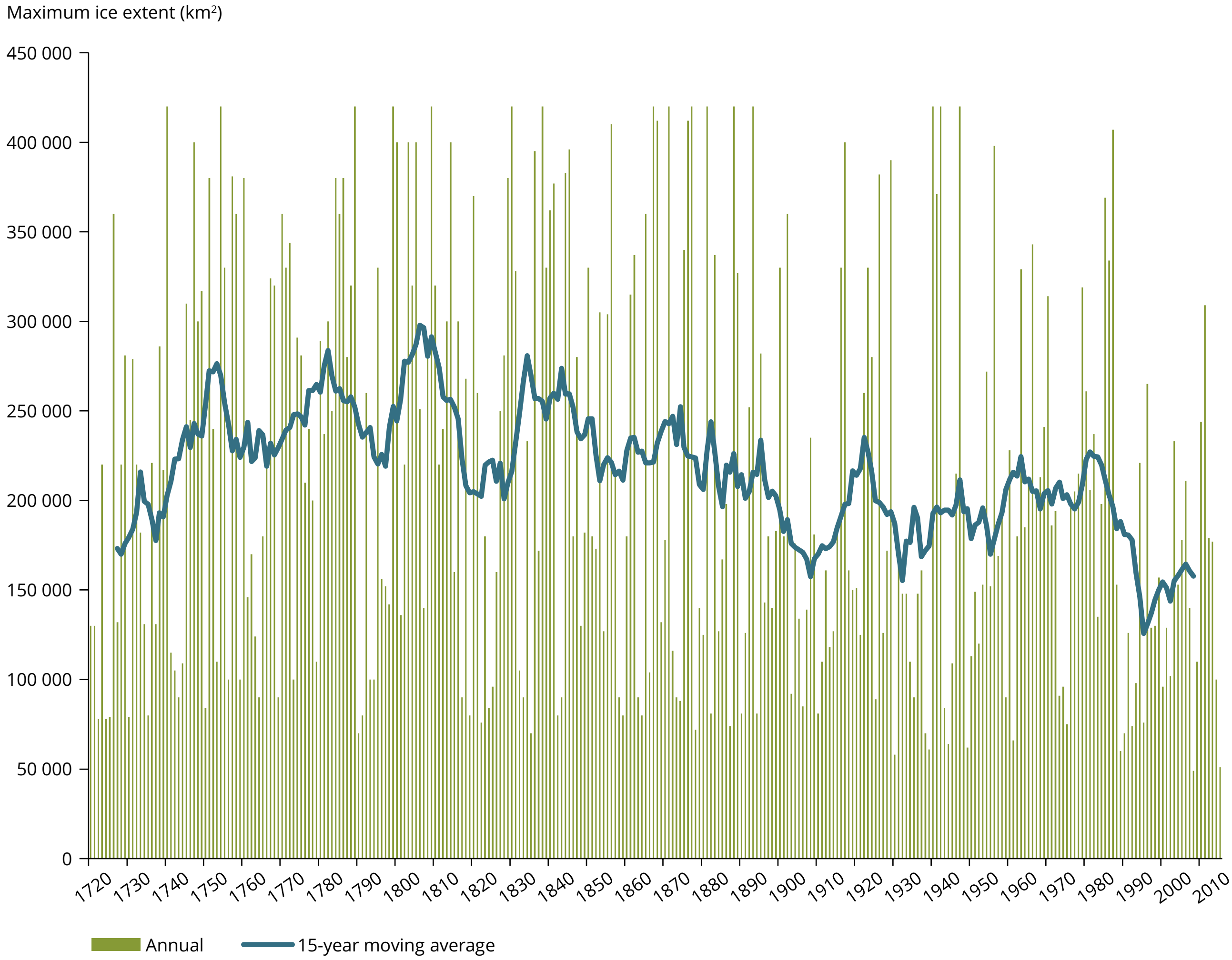
Information on sea ice extent in the Baltic Sea goes back to 1720. The maximum sea ice extent has displayed a decreasing trend most of the time since about 1800 (Figure 3.9). The decrease in sea ice extent appears to have accelerated since the 1980s, but large interannual variability makes it difficult to demonstrate this statistically (Haapala et al., 2015). The frequency of mild ice winters, defined as having a maximum ice cover of less than 130 000 km², has, however, increased from seven in 30 years in the period 1950–1979 to 15 in the period 1986–2015. The frequency of severe ice winters, defined as having a maximum ice cover of at least 270 000 km², has decreased from six to four during the same periods.

Projections

Improving the ability to track the observed rapid summer-time melting of Arctic sea ice has been a challenge for modelling (Stroeve et al., 2012), but observations fall well within the model range in recent modelling studies (Hezel et al., 2014). All model projections agree that Arctic sea ice will continue to shrink and thin. For high greenhouse gas emissions scenarios, a nearly ice-free Arctic Ocean in September is likely to occur before mid-century (Figure 3.10) (Massonnet et al., 2012; Stroeve et al., 2012; Wang and Overland, 2012; Collins et al., 2013; Overland and Wang, 2013). An extension beyond 2100 suggests that, for the highest emissions scenario (RCP8.5), the Arctic could become ice-free year-round before the end of the 22nd century; on the other hand, a recovery of Arctic sea ice could become apparent in the 22nd century if stringent

([44]) http://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly.

Figure 3.9 Maximum extent of ice cover in the Baltic Sea



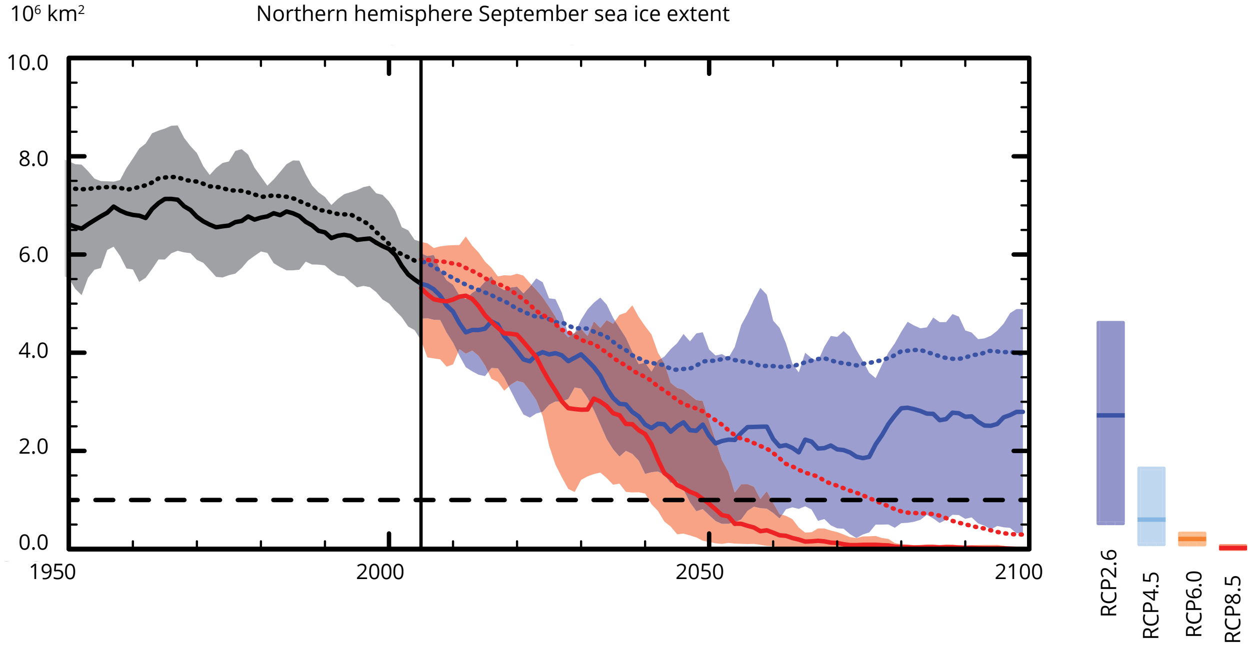
Note: This figure shows the maximum extent of ice cover in the Baltic Sea in the winters of 1719/1720–2015/2016 and the 15-year moving average.

Source: Jouni Vainio, Finnish Meteorological Institute (updated from Seinä and Palosuo, 1996; Seinä et al., 2001).

policies to reduce global greenhouse gas emissions, and eventually concentrations, are successfully implemented (Hezel et al., 2014).

Projections of Baltic Sea ice extent under different emissions scenarios suggest that the maximal ice cover and ice thickness will continue to shrink significantly over the 21st century. The best estimate of the decrease in maximum ice extent from a model ensemble is 6 400 km^2/decade for a medium emissions scenario (RCP4.5) and 10 900 km^2/decade for a high emissions scenario (RCP8.5); for the latter scenario, largely ice-free conditions are projected by the end of the century (Luomaranta et al., 2014).

Figure 3.10 Projected changes in northern hemisphere September sea ice extent



Note: This figure shows changes in northern hemisphere September sea ice extent as simulated by CMIP5 models over the 21st century under different emissions scenarios (RCPs). Sea ice extent is defined as the total ocean area in which sea ice concentration exceeds 15 % and is calculated on the original model grids. The solid lines show the five-year running means under the emissions scenarios RCP2.6 (blue) and RCP8.5 (red), based on those models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea ice, with the shading denoting the uncertainty range. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars (right). For completeness, the CMIP5 multi-model mean for RCP2.6 and RCP8.5 is indicated with dotted lines. The black dashed line represents nearly ice-free conditions.

Source: Adapted from IPCC, 2013b (Figure SPM-7(b)).

3.3.3 Greenland and Antarctic ice sheets

Key messages

- The Greenland and Antarctic ice sheets are the largest bodies of ice in the world and play an important role in the global climate system. Both ice sheets have been losing large amounts of ice at an increasing rate since 1992.
- The cumulative ice loss from Greenland from 1992 to 2015 was 3 600 Gt and contributed to global sea level rise by approximately 10 mm; the corresponding figure for Antarctica is 1 500 Gt, which corresponds to approximately a 5 mm global sea level rise since 1992.
- Model projections suggest further declines of the polar ice sheets in the future, but the uncertainties are large. The melting of the polar ice sheets is estimated to contribute up to 50 cm of global sea level rise during the 21st century. Very long-term projections (until the year 3000) suggest potential sea level rise of several metres with continued melting of the ice sheets.

Relevance

The Greenland and Antarctic ice sheets are important in the global climate system. This indicator documents recent change in the ice sheets and discusses the consequences of projections. Note that the land-based, permanent Antarctic ice sheet should not be confused with Antarctic sea ice, which covers the ocean and strongly changes with the seasons. Together, the Antarctic and Greenland ice sheets contain more than 99 % of the freshwater ice on Earth. The change in the amount of ice in the ice sheets, known as the 'mass balance', is an important indicator that can document loss of ice. An increased rate of mass loss results in a faster rise in the global mean sea level (see also Section 4.2.2). A net mass loss of 362.5 billion tonnes corresponds to a 1 mm sea level equivalent (Hanna et al., 2013). Owing to gravitational forces, the melting of the Antarctic ice sheet contributes relatively more to sea level rise in the northern hemisphere than the melting of the Greenland ice sheet. In addition, melt water from the ice sheets reduces the salinity of the surrounding ocean, with potential feedback to the climate system (Blaschek et al., 2014). An upper layer of fresher water may reduce the formation of dense deep water, one of the mechanisms driving global ocean circulation. Recent freshening in the vicinity of Greenland has contributed to changes that may weaken the Atlantic meridional overturning circulation, with cooler winters and summers around the North Atlantic a potential consequence, but uncertainties are still significant (Yang et al., 2016).

Past trends

The mass balance of the polar ice sheets is affected by numerous factors, including changes in precipitation patterns over the ice sheets, snowfall, changes in the snowline, summer melting of snow, changes in ice sheet albedo, changes in the extent of supraglacial lakes, submarine melting of the floating ice shelves at the tongue of marine outlet glaciers, and icebergs breaking off of glaciers (Box et al., 2012; Howat et al., 2013; Vavrus, 2013; Benning et al., 2014). The changing balance between ice accumulation, on the one hand, and melting and sublimation of ice and snow, submarine melting and calving, on the other hand, determines the future development of the ice sheets. Both ice sheets have lost significant amounts of ice since 2005 (Figure 3.11).

Several different methods have been used to monitor the mass balance of the Greenland ice sheet. The overall conclusion of all available studies is that Greenland is losing mass (Figure 3.11). Average ice loss increased from 34 (uncertainty interval: – 6 to 74) billion tonnes per year over the period 1992–2001 to 215 (157 to 274) billion tonnes per year over the period 2002–2011. In 2012, an exceptional loss estimated at more than 500 billion tonnes was recorded. From 1992 to 2012, the contribution to the global sea level has been estimated to have been approximately 8.0 mm (6.6 to 9.4 mm) (Clark et al., 2015). In 2013–2015, the net loss of ice was slower than in 2012, with a total of approximately 280 billion tonnes net loss over the period (DMI et al., 2015).

In Greenland, the area subject to summer melt has increased significantly over recent decades (Fettweis et al., 2011; Vaughan et al., 2013). The increased melting has been attributed to changes in general circulation in summer, creating warmer conditions over Greenland (Fettweis, Hanna et al., 2013). Ice core data suggest that large-scale melting events such as the one observed in 2012 have occurred once every few hundred years on average, with previous ones in 1889 and in the 12th century. It is not currently possible to tell whether the frequency of these rare extensive melt events has changed (Nghiem et al., 2012; Tedesco et al., 2013). Another important process that may accelerate the loss of ice from the ice sheets is enhanced submarine melting of glaciers terminating in the sea. Its importance may be greater than previously assumed. The process has been documented for both the Greenland and the Antarctic ice sheets (Wouters et al., 2015).

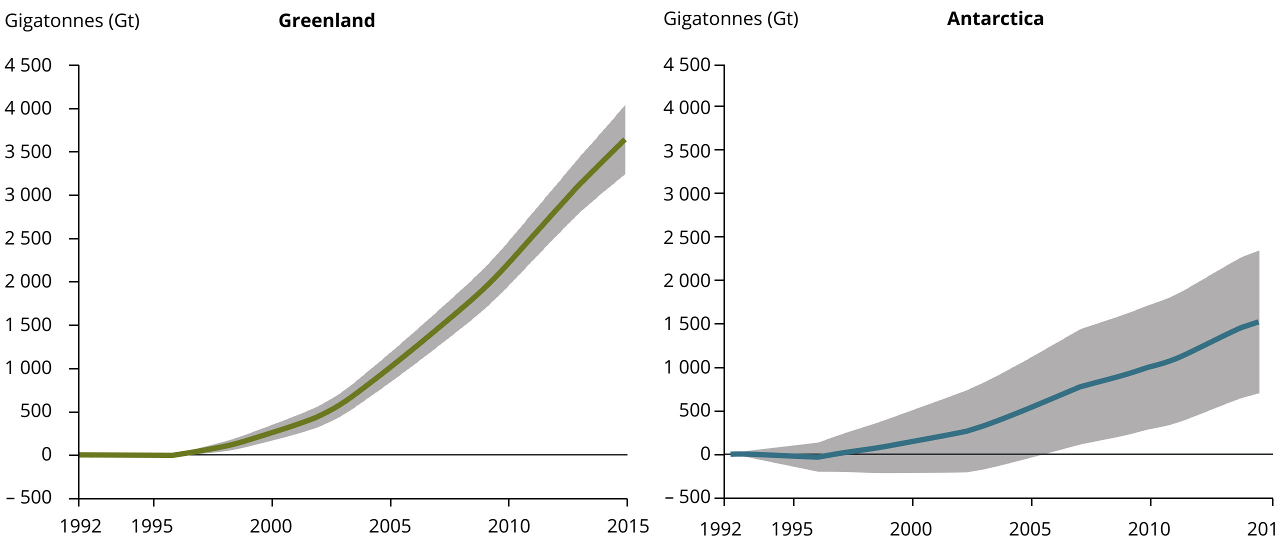
East Antarctica had a slightly positive mass balance of + 14 (– 29 to + 57) billion tonnes per year over the period 1992–2011, but, overall, the Antarctic ice sheet has lost on average approximately 70 billion tonnes of ice per year, as West Antarctica and the Antarctic Peninsula have lost 65 (39 to 91) and 20 (6 to 34) billion tonnes per year, respectively. The floating ice shelves have also become thinner (Paolo et al., 2015). From 1992 to 2015, the ice loss of the Antarctic ice sheet has contributed approximately 5 mm (2 to 7 mm) to the global sea level (Clark et al., 2015). All in all, the ice sheets have contributed to about one-third of the total sea level rise since the 1990s (Shepherd et al., 2012; Barletta et al., 2013; Vaughan et al., 2013; Helm et al., 2014). A recent study of Antarctica suggests, however, that the snow accumulation has exceeded the mass loss from ice discharge, leading to the equivalent of an annual 0.23 mm sea level depletion between 2003 and 2008 (Zwally et al., 2015).

Projections

All recent studies indicate that the mass loss of the Greenland ice sheet will increase the global sea level, with greater radiative forcing leading to greater sea level rise. Recent studies suggest an upper bound of 16 cm of sea level rise from the Greenland ice sheet during the 21st century for a high emissions scenario and somewhat lower values for lower emissions scenarios (Church et al., 2013; Fürst et al., 2015). One recent study estimated that the Greenland ice sheet contribution until the year 3000 will be 1.4, 2.6 and 4.2 m for the emissions scenarios SRES B1, A1B and A2 (with stabilised greenhouse concentrations after 2100), respectively (Goelzer et al., 2012; Church et al., 2013).

On multi-millennial time scales, the Greenland ice sheet shows threshold behaviour due to different feedback mechanisms. If a temperature above the threshold is maintained for an extended period, the melting of the Greenland ice sheet could self-amplify, which would eventually result in near-complete ice loss (equivalent to a sea level rise of about 7 m). Coupled climate–ice sheet models with a fixed topography (that do not consider the feedback between surface mass balance and the height of the ice sheet) estimate that the global mean surface air temperature threshold above which the Greenland ice will completely melt lies between 2 and 4 °C above pre-industrial levels (Rae et al., 2012; Church et al., 2013; Fettweis, Franco et al., 2013; Vizcaino et al., 2015). In contrast, a study modelling

Figure 3.11 Cumulative ice mass loss from Greenland and Antarctica



Note: The figure shows the cumulative ice mass loss from Greenland and Antarctica derived as annual averages from more than 100 assessments. The uncertainty interval is estimated from the 90 % confidence intervals (5 to 95 %) of the individual studies.

Source: Shepherd et al., 2015, updated from 2012.

the ice sheet dynamically suggests that the threshold could be as low as about 1 °C above pre-industrial levels (Robinson et al., 2012). The complete loss of the Greenland ice sheet is not inevitable because it has a long time scale. Complete melting would take tens of millennia if near the threshold and a millennium or more for temperatures a few degrees above the threshold (Robinson et al., 2012; Church et al., 2013; Applegate et al., 2015).

The uncertainties around future ice discharge from Antarctica, and the associated sea level rise, are larger than for Greenland. However, mass loss of the Antarctic ice sheet has a greater impact on the sea level in the northern hemisphere than a comparable loss of the Greenland ice sheet, owing to gravitational forces. A comprehensive analysis applying various climate, ocean and ice sheet models estimates that the additional ice loss for the 21st century is 7 cm (90 % range: 0–23 cm) of global sea level equivalent for a low emissions scenario (RCP2.6) and 9 cm (90 % range: 1–37 cm) for a high emissions scenario (RCP8.5) (Levermann et al., 2014). By 2100, the rise of global sea level will be clearly influenced by the development of the Antarctic ice sheet. A recent study suggests that the Antarctic ice sheet has the potential to contribute more than a metre to sea level rise by 2100 and more than 15 metres by 2500, if emissions continue unabated (DeConto and Pollard, 2016).

Several studies that were published after the release of the IPCC AR5 suggest that melting of the West Antarctic Ice Sheet (WAIS) has been accelerating recently and that a WAIS collapse is already inevitable and irreversible. There are also indications of instability in some parts of the much larger East Antarctic Ice Sheet. These new results suggest that the global mean sea level contribution from Antarctica alone could be several metres on a time scale of a few centuries to a millennium (Favier et al., 2014; Gunter et al., 2014; Joughin et al., 2014; McMillan et al., 2014; Mengel and Levermann, 2014; Mouginot et al., 2014; Rignot et al., 2014; Holland et al., 2015).

The long-term development of the ice sheets is hugely important in determining the consequences of climate change. Amplifying feedback mechanisms, including slowdown of meridional overturning circulation, may accelerate ice sheet mass loss (Hansen et al., 2015). A coupled ice sheet–ice shelf model suggests that, if atmospheric warming exceeds 1.5 to 2 °C above present, the major Antarctic ice shelves would collapse, which would trigger a centennial- to millennial-scale response of the Antarctic ice sheet and cause an unstoppable contribution to sea level rise (Golledge et al., 2015). Although current estimates of sea level rise by 2100 suggest that they will fall in a range of some tens of centimetres (Clark et al., 2015), collapsing ice sheets could, in the long term, result in a faster and greater rise in sea level than currently assumed, underlining the urgency of climate change mitigation (EASAC, 2015; Golledge et al., 2015; Hansen et al., 2015). The uncertainties in the long-term projections are significant, however. Assumptions concerning, for example, bedrock uplift and sea surface drop associated with ice sheet retreat have a significant effect on the results with respect to sea level rise (Gomez et al., 2015; Konrad et al., 2015).

3.3.4 Glaciers

Key messages

- The vast majority of glaciers in the European glacial regions are in retreat. Glaciers in the European Alps have lost approximately half of their volume since 1900, with clear acceleration since the 1980s.
- Glacier retreat is expected to continue in the future. It has been estimated that the volume of European glaciers will decline between 22 and 84 % compared with the current situation by 2100 under a moderate greenhouse gas forcing scenario, and between 38 and 89 % under a high forcing scenario.
- Glacier retreat contributed to global sea level rise by about 0.8 mm per year in 2003–2009. It also affects freshwater supply and run-off regimes, river navigation, irrigation and power generation. Furthermore, it may cause natural hazards and damage to infrastructure.

Relevance

Glaciers are particularly sensitive to changes in the global climate because their surface temperature is close to the freezing/melting point (Zemp et al., 2006). When the loss of ice, mainly from melting and calving in summer, is larger than the accumulation from snowfall in winter, the mass balance of the glacier turns negative and the glacier shrinks.

Glaciers are an important freshwater resource and act as 'water towers' for lower lying regions. The water from melting glaciers contributes to water flow in rivers during summer months and thus helps maintain water levels for irrigation, hydropower production, cooling water and navigation. The effects of a reduction in glaciers are, however, complex and vary from location to location (SGHL and CHy, 2011). Glacier melting also contributes to global sea level rise (Marzeion et al., 2012; Gardner et al., 2013).

Past trends

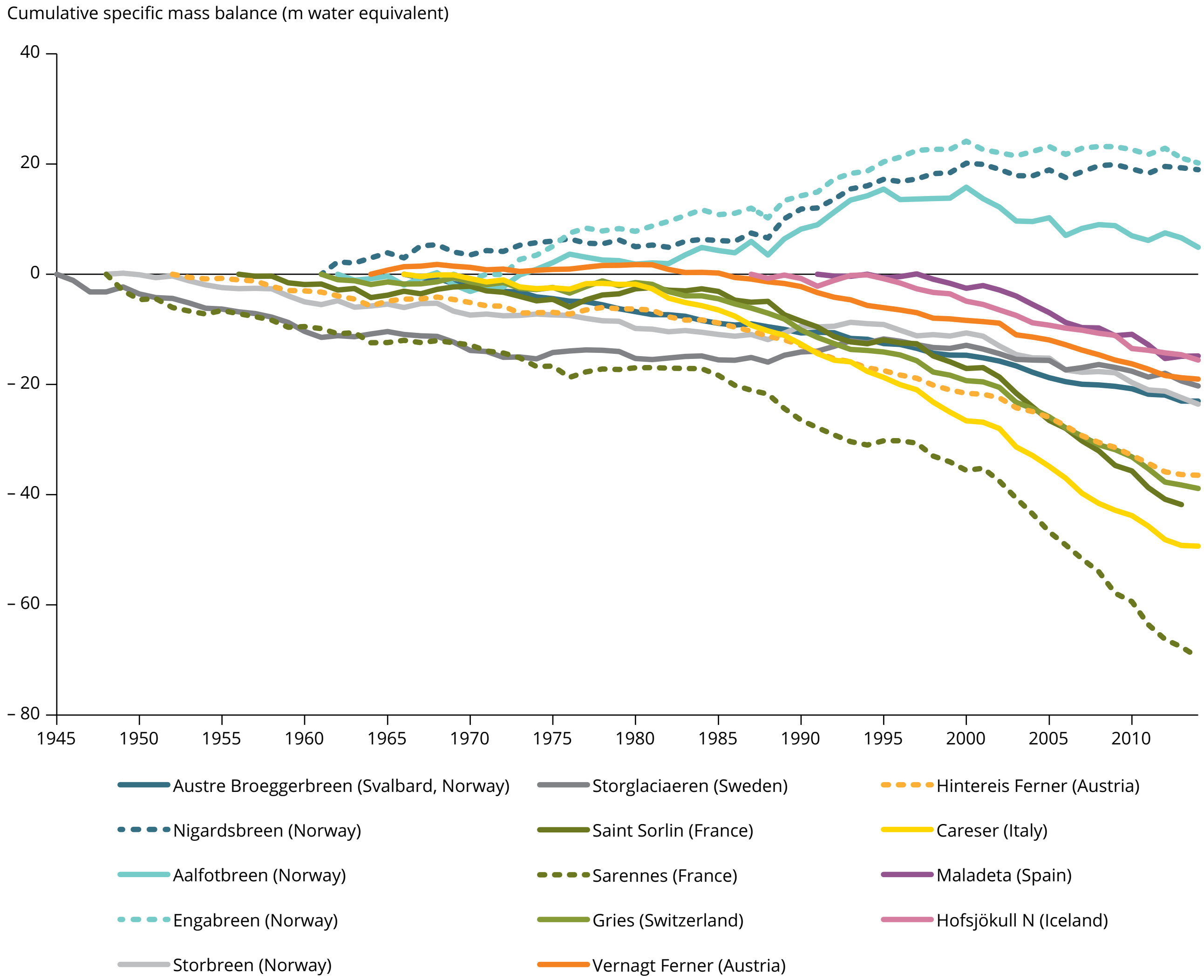
A general loss of glacier mass since the beginning of the measurements has occurred in all European glacier regions, except some glaciers in Norway (Figure 3.12). The Alps have lost roughly 50 % of their ice mass since 1900 (Zemp et al., 2008, 2015; Huss, 2012). Norwegian coastal glaciers were expanding and gaining mass up to the end of the 1990s owing to increased winter snowfall on the North Atlantic Coast; now these glaciers are also retreating (Nesje et al., 2008; Engelhardt et al., 2013; Hanssen-Bauer et al., 2015). Some ice caps at higher elevations in north-eastern Svalbard, Norway, seem to be increasing in thickness, but estimates for Svalbard as a whole show a declining mass balance (Bevan et al., 2007; Lang et al., 2015). The centennial retreat of European glaciers is attributed primarily to increased summer temperatures. However, changes in winter precipitation, reduced glacier albedo due to the lack of summer snowfall and various other feedback processes, such as the increasing debris cover on the glacier, can influence the behaviour of glaciers, in particular on regional and decadal scales.

The melting of glaciers is contributing significantly to global sea level rise. For the period 2003–2009, the global contribution was 0.71 ± 0.08 mm per year, accounting for 29 ± 13 % of the observed sea level rise (Gardner et al., 2013; Vaughan et al., 2013).

Projections

The retreat of European glaciers is projected to continue throughout the 21st century (Figure 3.13). One study estimates that the volume of European glaciers will decline between 22 and 84 % relative to their extent in 2006 under a moderate greenhouse gas forcing scenario (RCP4.5) and between 38 and 89 % under a high forcing scenario (RCP8.5) (all European regions combined) (Radić et al., 2014). The relative volume loss is largest in central Europe (83 ± 10 % for RCP4.5 and 95 ± 4 % for RCP8.5). Similar results were achieved in other studies (Marzeion et al., 2012; Huss and Hock, 2015). In Norway, nearly all smaller glaciers are projected to disappear and, overall, glacier area as well as volume may be reduced by about one-third by 2100, even under the low SRES B2 emissions scenario (Nesje et al., 2008).

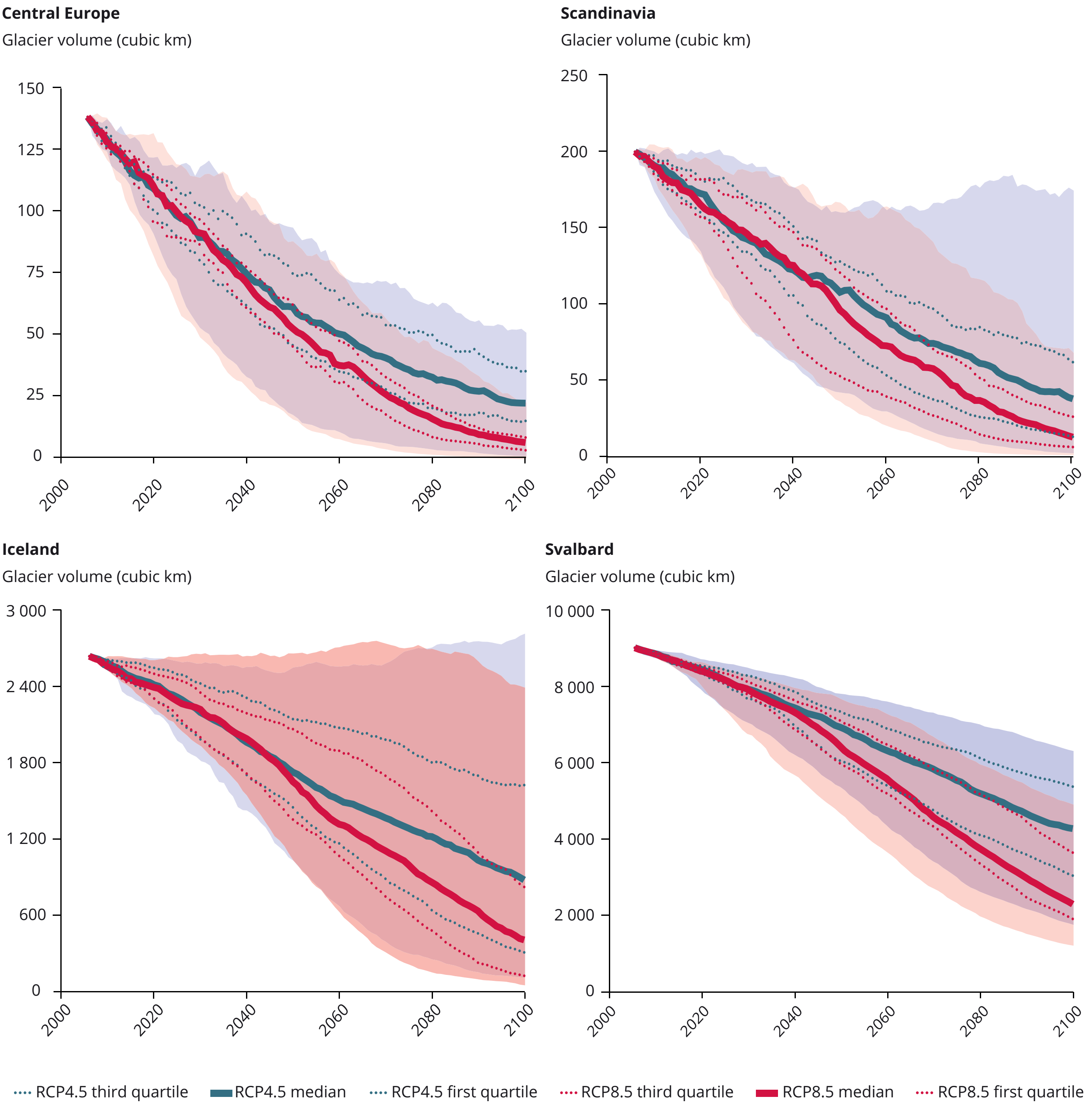
Figure 3.12 Cumulative net mass balance of European glaciers



Note: The figure shows cumulative specific net mass balance (m water equivalent) of European glaciers in the period 1946–2014.

Source: Fluctuation of Glaciers Database (FoG), World Glacier Monitoring Service.

Figure 3.13 Projected change in the volume of mountain glaciers and ice caps in European glaciated regions



Note: The figure shows the projected volume for 2006–2100 of all mountain glaciers and ice caps in the European glaciated regions, derived using a mass balance model driven with temperature and precipitation scenarios from 14 GCMs, in central Europe, consisting of the European Alps and Pyrenees (top left), Scandinavia (top right), Iceland (bottom left) and Svalbard (bottom right).

Source: Radić et al., 2014.

3.3.5 Snow cover

Key messages

- Snow cover extent in the northern hemisphere has declined significantly over the past 90 years, with most of the reductions occurring since 1980. Over the period 1967–2015, snow cover extent in the northern hemisphere has decreased by 7 % on average in March and April and by 47 % in June; the observed reductions in Europe are even larger, at 13 % for March and April and 76 % for June.
- Snow mass in the northern hemisphere is estimated to have decreased by 7 % in March from 1982 to 2009; snow mass in Europe has decreased more rapidly than the average for the northern hemisphere, but with large interannual variation.
- Model simulations project widespread reductions in the extent and duration of snow cover in the northern hemisphere and in Europe over the 21st century.
- Changes in snow cover affect the Earth's surface reflectivity, water resources, flora and fauna and their ecology, agriculture, forestry, tourism, snow sports, transport and power generation.

Relevance

Snow influences the climate and climate-related systems because of its high reflectivity, insulating properties, effects on water resources and ecosystems, and cooling of the atmosphere. A decrease in snow cover accelerates climate change (Flanner et al., 2011).

In Europe, about half of the population lives in areas that have snow cover in January in an average winter. Changes in snow cover affect human well-being through effects on water availability, hydropower, navigation, infrastructure, the livelihoods of indigenous Arctic people, environmental hazards, winter recreation and outdoor light conditions. Variation in snow cover affects winter road and rail maintenance, as well as the exploitation of natural resources (ACIA, 2005; UNEP, 2007).

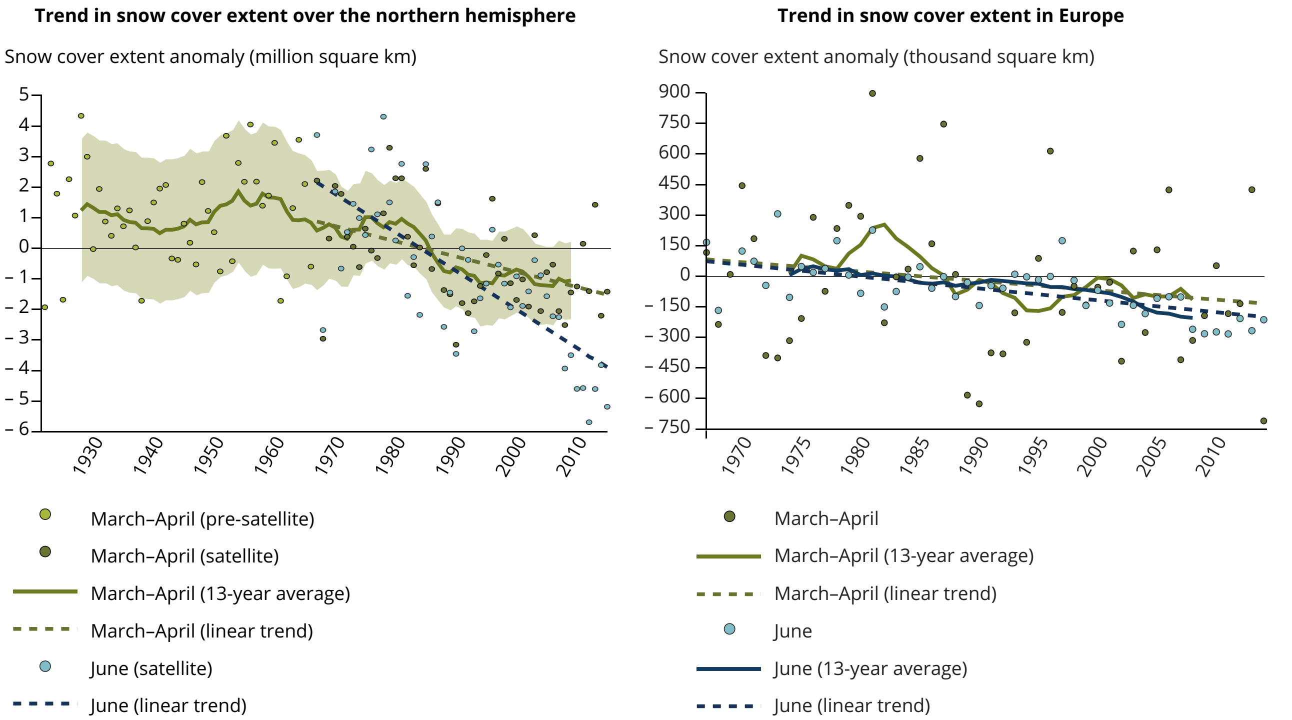
Past trends

Satellite observations of monthly snow cover extent in the northern hemisphere are available from 1967 onwards (Estilow et al., 2015). A detailed analysis based on multiple sources shows there have been significant decreases in northern hemisphere snow cover extent during the spring melt season since about 1980 (March to June; Figure 3.14, left) (Brown and Robinson, 2011; Vaughan et al., 2013); in other seasons, the snow cover extent has remained stable or even slightly increased. A separate analysis for Europe (EEA-39 region) shows even larger reductions of 13 % for March and April, and 76 % for June between 1980 and 2015 (Figure 3.14, right).

Decreases in snow cover extent are caused by an earlier onset of melting and a shorter duration of the snow season. Since 1972, the duration of the snow season averaged over the northern hemisphere declined by five days per decade, but with substantial regional variation. The duration of the snow season has decreased by up to 25 days in western, northern and eastern Europe due to earlier spring melt, whereas it has increased by up to 15 days in south-eastern Europe due to an earlier onset of the snow season (Choi et al., 2010; Mioduszewski et al., 2015).

The snow mass (i.e. the amount of water that the snow contains) is an important variable, as it affects the role of snow in the hydrological cycle. For the whole of the northern hemisphere, a 7 % decrease in March snow mass was observed between 1982 and 2009 (Takala et al., 2011). An extension of these data focusing on EEA member countries demonstrate a stronger average decline of 30 % for the period 1980–2015, although the year-to-year variation is large (Figure 3.15). Winter increases in precipitation have also led to an increase in snow mass at higher altitudes in Norway.

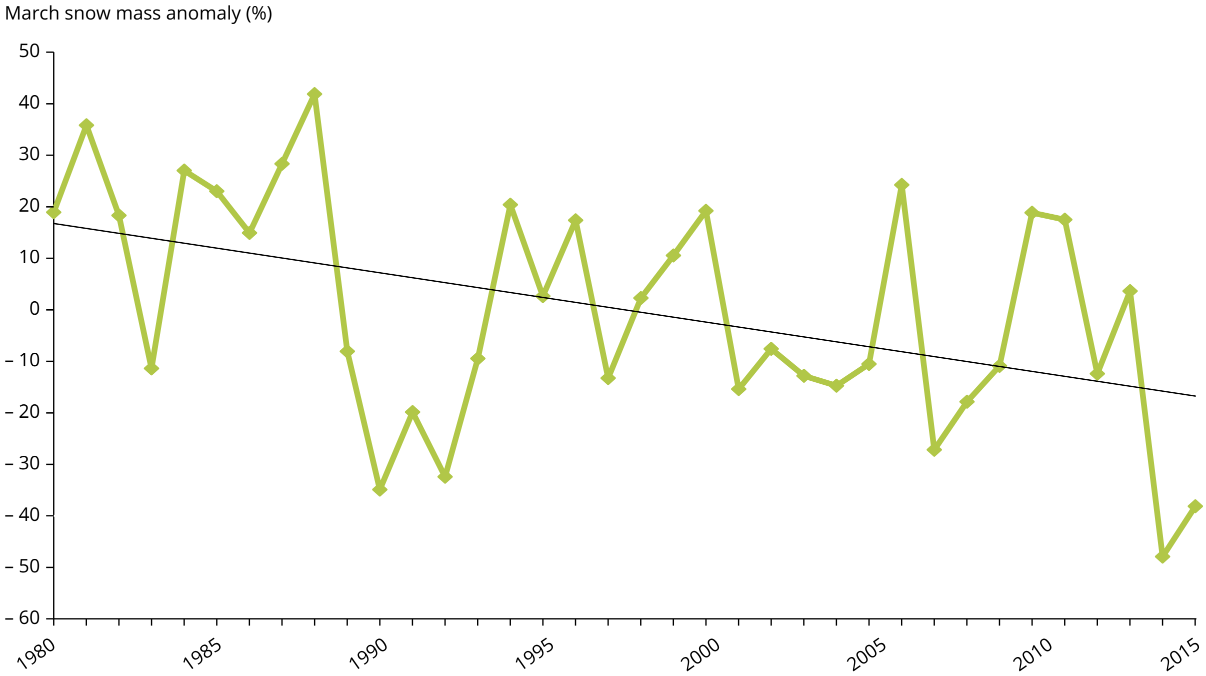
Figure 3.14 Trend in snow cover extent over the northern hemisphere and Europe



Note: This figure shows satellite-derived time series of snow cover extent for the period 1967–2015 over the northern hemisphere (left) and Europe (right). The time series for the northern hemisphere is extended back to 1922 by including reconstructed historical estimates.

Source: Brown and Robinson, 2011; RUGSL, 2011; Vaughan et al., 2013; Estilow et al., 2015. Data for Europe (EEA-39 region) was calculated and kindly provided by the Rutgers University Global Snow Lab, based on RUGSL, 2011.

Figure 3.15 Trend in March snow mass in Europe (excluding mountain regions)



Note: This figure shows the satellite-derived anomaly in March snow mass in Europe for the period 1980–2015 relative to the 1980–2012 average.

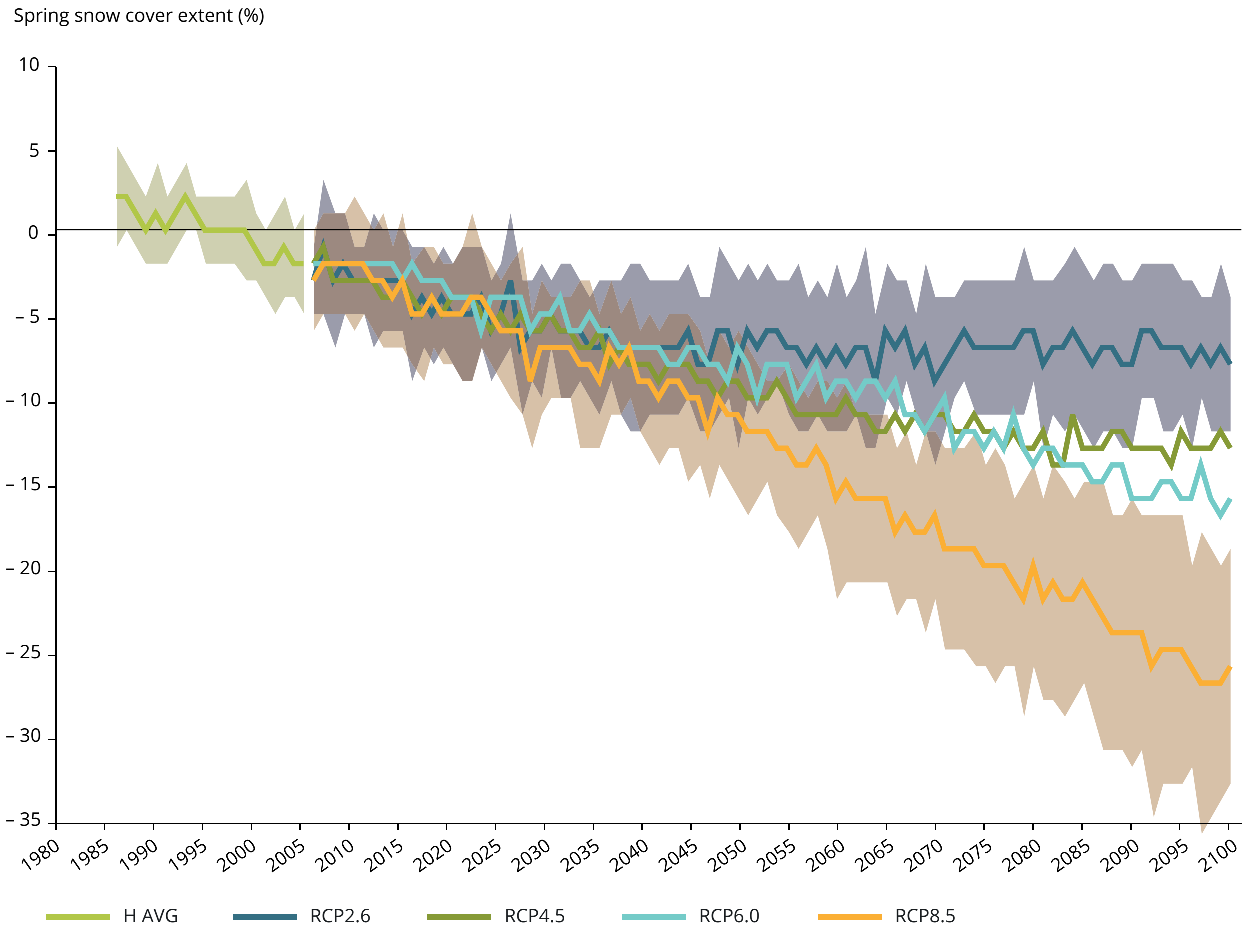
Source: GlobSnow, updated from Luojus et al., 2011.

Projections

northern hemisphere snow cover will continue to shrink and snow seasons shorten as temperatures rise (Vaughan et al., 2013), although in the coldest regions snowfall can also increase in the middle of winter (Hanssen-Bauer et al., 2015; Räisänen, 2016). The multi-model mean from the CMIP5 modelling exercise projects changes in March/April snow cover extent in the northern hemisphere during the 21st century ranging from 7 % for a low emissions scenario (RCP2.6) to 25 % for a high emissions scenario (RCP8.5) (Figure 3.16). The projected snow mass generally follows the snow cover extent with an estimated range of reduction from about 10 % for RCP2.6 to about 30 % for RCP8.5; projected reductions in the duration of the snow season range from about 10 days for RCP2.6 to about 40 days for RCP8.5 (Brutel-Vuilmet et al., 2013).

Specific regional studies suggest significant reductions in snow mass in, for example, the Alps in general (Steger et al., 2013; Schmucki et al., 2015), Switzerland (BAFU, 2012), the alpine range of Italy (Soncini and Bocchiola, 2011), the Pyrenees (López-Moreno et al., 2009), Norway (Hanssen-Bauer et al., 2015), the Turkish mountains (Özdoğan, 2011) and the Balkan mountains (FAO, 2010). These changes can have dramatic downstream effects as melt water contributes up to 60–70 % to annual river flows. Despite the projected decrease in long-term mean snow mass in the northern hemisphere, model simulations indicate occasional winters of heavy snowfall, but these become increasingly uncommon towards the end of the 21st century.

Figure 3.16 Projected changes in northern hemisphere spring snow cover extent



Note: This figure shows the northern hemisphere spring (March to April average) snow cover extent based on the CMIP5 ensemble for actual emissions (up to 2005) and different forcing scenarios (RCPs). Values are given relative to the 1986–2005 reference period (H AVG). Thick lines mark the multi-model average and shading indicates the inter-model spread (one standard deviation).

Source: Adapted from IPCC (2013a, Figure 12.32). Data were provided by Gerhard Krinner (Laboratoire de Glaciologie et Géophysique de l'Environnement, France).

4 Climate change impacts on environmental systems

Changes in climatic conditions have direct consequences on the physical and chemical properties of environmental systems, as well as on the ecosystems supported by them. This chapter presents selected observed and projected changes in a variety of climate-sensitive characteristics of environmental systems in Europe. Section 4.1 covers physical, chemical and biological changes in oceans and marine environments. Section 4.2 addresses physical changes and (to a limited extent) economic risks in coastal zones, focusing on sea level rise. Section 4.3 presents physical and biological changes in freshwater systems. Section 4.4 gives an overview of physical and biological changes in terrestrial ecosystems, including soils and forests. The concluding Section 4.5 summarises how ecosystem services in Europe are affected by climate change and other human pressures, such as habitat change and pollution.

Box 4.1 Policy and institutional context

The EU's Seventh Environment Action Programme (EAP), which sets out the priorities for environmental policy until 2020, recognises the urgent need to protect and enhance our environmental systems, that is, our natural capital. Priority objective 1 aims 'to protect, conserve and enhance the Union's natural capital, where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society's resilience' (EU, 2013). The time line requires the EU and its Member States to speed up the implementation of existing strategies to protect natural capital, to fill gaps where legislation does not yet exist and to improve existing legislation. Key strategies include the EU Biodiversity Strategy to 2020 (EC, 2011), which implements the global Aichi targets of the Convention on Biological Diversity in Europe (EC, 2014), the Blueprint to Safeguard Europe's Water Resources (EC, 2012) and the Marine Strategy Framework Directive (EC, 2008b). These are supported by a number of earlier measures including legally binding commitments in the Habitats Directive (EC, 1992), the Birds Directive (EC, 2009), the Water Framework Directive (EC, 2000) and the Air Quality Directive (EC, 2008a), and a series of regulations addressing different environmental sectors such as agriculture (EC, 2010), forestry (EU, 2010) and invasive species (EU, 2014), as well as the nature protection network Natura 2000 (EC, 2016b).

Achieving the policy targets of the Seventh EAP requires our knowledge about environmental systems, their functioning and their interactions to be improved. This calls for a more integrated assessment of natural capital and for better understanding of the interactions between the different components of the environment to support more targeted and efficient policy measures. An important instrument for integrated assessments is implemented in Target 2, Action 5, of the Common Implementation Framework (CIF) of the EU Biodiversity Strategy to 2020. The activity foresees 'Member States, with the assistance of the Commission, will map and assess the state of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020' (EC, 2016a).

The EU has developed an analytical framework for the assessment of the condition of ecosystems and their services. For the practical purposes of policy-relevant mapping and assessment at national and European levels, ecosystems are considered here at the level of land/sea cover-related units. The framework distinguishes between urban areas, cropland, grassland, woodland and forest, heathland and shrubs, wetland, sparsely vegetated land, rivers and lakes, transitional waters, coastal areas and open oceans. These ecosystems represent key elements for human management, i.e. in agriculture, forestry, fisheries and water management, to make the best use of their services (Maes et al., 2013). At the same time, this spatial scale also reflects the existing policy sections established in European environmental legislation. Efforts for helping ecosystems in Europe to adapt to climate change are also supported by the European Nature Conservation Agencies (ENCA) network ([45]) (e.g. Bonn et al., 2014; Korn et al., 2014).

A recent review of the EU biodiversity policy in the context of climate change has identified a number of policy gaps: (1) conservation targets need to better match conservation needs; (2) targets need to be set in a spatially coherent manner across national scales; and (3) current monitoring appears insufficient to address these gaps (van Teeffelen et al., 2014).

([45]) http://www.encanetwork.eu.

4.1 Oceans and marine environment

Key messages

- The primary impacts of climate change observed in Europe's seas are acidification, increased ocean heat content and increased sea surface temperature. The extent to which physical impacts have been documented varies among the seas.
- Climate change affects physical conditions differently in Europe's seas, and consequently its biological impacts also vary depending on the region. Ocean temperature is one of the strongest regulators of marine life. Changes in temperature cause significant shifts in the distribution of marine species, both horizontally, towards the poles, and vertically, with changes in depth distribution.
- The impacts of climate change in combination with synergistic impacts of other anthropogenic stressors will potentially cause widespread changes to marine ecosystems and ultimately the services and benefitss humans receive from the seas.
- **North-east Atlantic Ocean:** sea surface temperature and ocean heat content are increasing in all regions, although at different rates. Sea surface temperature changes have already resulted in an increased duration of the marine growing season and in the northwards movement of marine zooplankton. Marine species are shifting their distributions northwards in response to increased temperatures. Of the commonly observed demersal fish species, 72 % have experienced changes in abundance and/or distribution in response to warming waters. This change has already had important impacts on fisheries in this region.
- **Baltic Sea:** future climate change is projected to warm the Baltic Sea, to decrease its salinity, to decrease sea ice extent by 50–80 % during the 21st century, and to further expand oxygen depleted 'dead zones'. These changes in physical variables will have predominantly negative impacts on the Baltic Sea ecosystems.
- **Mediterranean Sea:** temperature is projected to increase, and run-off to the Mediterranean Sea is projected to decrease, thereby increasing salinity. Stratification is projected to remain largely constant because of the compensating effects of increasing temperature and increasing salinity on the density of sea water. The observed invasion and survival of alien species has been correlated with the warming trend in sea surface temperature.

4.1.1 Overview

Relevance

The oceans cover about 72 % of the Earth's surface. Oceans interact closely with the atmosphere. On the one hand, oceans influence weather patterns on local to global scales. On the other hand, changes in the atmosphere can alter the properties of the oceans. Changes in ocean properties driven by an increase in atmospheric greenhouse gas concentrations, such as ocean acidification and warming, can have a substantial impact on marine ecosystems, their productivity and marine biodiversity, and thus ecosystem-service provision (Walther et al., 2002; Lotze et al., 2006; Ruckelshaus et al., 2013).

The atmospheric concentrations of greenhouse gases, such as CO_2, have increased substantially since pre-industrial times, thus trapping increasingly more solar energy within the atmosphere (see Section 3.1). Most of this heat is stored by the ocean, where it affects sea surface temperature, ocean heat content, sea levels, salinity, ocean circulation and sea ice cover. The rest melts ice and warms the atmosphere and land. The ocean also absorbs significant amounts of CO_2 from the atmosphere, thereby mitigating the magnitude of climate change. However, the increased levels of dissolved carbon are changing the chemistry of seawater and making it more acidic. Sea level rise is addressed in Section 4.2.

Changes to the physical and chemical properties of the ocean can have substantial impacts on marine biodiversity and thus alter marine ecosystem productivity, functioning and ecosystem-service provision. As such, climate change affects the health and resilience of marine ecosystems and the provision of services to society, such as through fisheries. These effects of climate change are now being seen in all of Europe's seas, although the extent to which impacts have been documented varies among the seas (Conversi et al., 2010). The magnitude of future impacts on marine ecosystems and the services they provide to humans is strongly dependent on the future emissions scenario (Gattuso et al., 2015).

By influencing a multitude of physical properties of the oceans, climate change can cause abrupt changes across whole ecological systems (EEA, 2015). Such abrupt changes are called regime shifts and lead to new regime conditions. Regime shifts are always caused by multiple drivers lowering overall ecosystem resilience. For example, the collapse of seagrass populations can be caused by several key drivers such as atmospheric CO_2, disease, fishing, nutrient inputs, sea level rise, sediment changes and temperature changes (Rocha et al., 2014). It should be noted that these drivers do not apply uniform pressure on the different components of the marine ecosystems and that climate change could exacerbate some of these pressures.

Given the global extent of climate change, it can cause continent-wide regime shifts. For example, in the 1980s, the Mediterranean Sea underwent a major climate-induced change, which encompassed atmospheric (e.g. changes in precipitation and winter wind regimes), hydrological (e.g. changes in circulation patterns) and ecological systems (e.g. significant changes in copepod communities). It appears that this event in the Mediterranean Sea was linked to similar ecological shifts in the North Sea, Baltic Sea and Black Sea, indicating that local hydrography is linked to large-scale changes in the northern hemisphere (Conversi et al., 2010). These new conditions can last for decades and often cannot provide the same services and benefits to humans that were enjoyed under the previous ecological regime. In some cases, there may be no return to the previous state (Jackson et al., 2001; Weijerman et al., 2005; Conversi et al., 2015; Mollmann et al., 2014). Climate change-induced regime shifts thus affect all trophic levels of the food web and their associated biogeochemical cycles. As a result, the overall resilience of ecosystems decreases, making marine ecosystems more vulnerable to other high-intensity ecological stressors. Such high-intensity stressors include the individual and cumulative impacts of human activities (e.g. overexploitation, pollution and the introduction of non-indigenous species).

Selection of indicators

The remainder of this section considers the following physical and biological indicators of oceans and marine ecosystems in Europe's seas:

- ocean acidification;
- ocean heat content;
- sea surface temperature;
- distribution shifts of marine species; and
- ocean oxygen content.

Of these indicators, the last one is less developed than the others in terms of data coverage. Furthermore, this section presents information about observed and projected impacts of climate change on fish and fisheries. This information is not suitable for presentation as an EEA indicator owing to limited data availability.

Uncertainties and data gaps

In general, changes related to the physical and chemical marine environment are better documented than biological changes. For example, systematic observations of sea surface temperature began around 1880. More recently, these manual measurements have been complemented by satellite-based observations that have a high resolution in time and a wide geographical coverage, as well as by Argo floats ([46]) that automatically measure temperature and salinity below the ocean surface. In contrast, the longest available time series of plankton from the Continuous Plankton Recorder (CPR) ([47]) is around 60 years. Sampling was started in the North Sea in the 1950s and today a network covering the entire North Atlantic Ocean has been established.

Our understanding is improving of how climate change, in combination with the synergistic impacts of other stressors, can cause regime shifts in marine ecosystems, but additional research is still needed to untangle the complex interactions and their effects upon biodiversity. Ecological thresholds for individual species are still only understood in hindsight, i.e. once a change has occurred.

([46]) http://www.argo.ucsd.edu.
([47]) https://www.sahfos.ac.uk/services/the-continuous-plankton-recorder.

4.1.2 *Ocean acidification*

Key messages

- Ocean surface pH has declined from 8.2 to below 8.1 over the industrial era as a result of the increase in atmospheric CO_2 concentrations. This decline corresponds to an increase in oceanic acidity of about 30 %.
- Ocean acidification in recent decades has been occurring 100 times faster than during past natural events over the last 55 million years.
- Observed reductions in surface water pH are nearly identical across the global ocean and throughout continental European seas, except for variations near the coast. The pH reduction in the northernmost European seas, i.e. the Norwegian Sea and the Greenland Sea, is larger than the global average.
- Ocean acidification already reaches into the deep ocean, particularly at the high latitudes.
- Models consistently project further ocean acidification worldwide. Ocean surface pH is projected to decrease to values between 8.05 and 7.75 by the end of 21st century, depending on future CO_2 emissions levels. The largest projected decline represents more than a doubling in acidity.
- Ocean acidification is affecting marine organisms and this could alter marine ecosystems.

Relevance

Across the ocean, the pH of surface waters has been relatively stable for millions of years. Over the last million years, average surface water pH oscillated between 8.3 during cold periods (e.g. during the last glacial maximum, 20 000 years ago) and 8.2 during warm periods (e.g. just prior to the industrial revolution). Rapid increases in atmospheric CO_2 concentration due to emissions from human activities are now threatening this stability, as the CO_2 is subsequently partially absorbed in the ocean. Currently, the ocean takes up about one-quarter of the global CO_2 emissions coming from human activities, e.g. combustion of fossil fuels. The uptake of CO_2 in the sea causes ocean acidification, as the pH of sea water declines, even though ocean surface waters will remain alkaline.

When CO_2 is absorbed by the ocean, it reacts with water, producing carbonic acid. Carbonic acid dissociates to form bicarbonate ions and protons, which further react with carbonate ions. The carbonate ions act as a buffer, helping to limit the decline in ocean pH; however, they are being used up as more and more anthropogenic CO_2 is added to the ocean. As carbonate ion concentrations decline, so does the ocean's capacity to take up more anthropogenic CO_2. Hence, the ocean's ability to moderate atmospheric CO_2 and thus climate change comes at the cost of substantial changes in its fundamental chemistry.

Ocean acidification can have wide-ranging impacts on biological systems by reducing the availability of carbonate (Secretariat of the Convention on Biological Diversity, 2014). Decreasing carbonate ion concentrations reduce the rate of calcification of marine calcifying organisms, such as reef-building corals, mussels and plankton. pH also affects biological molecules and processes, e.g. enzyme activities and photosynthesis. Thus, anthropogenic acidification could affect entire marine ecosystems. Organisms appear to be increasingly sensitive to acidification when they are concurrently exposed to elevated seawater temperature (Kroeker et al., 2013). Of equal importance is the effect of acidification on primary producers, as it changes the bioavailability of essential nutrients, such as iron and zinc. Primary producers are responsible for a significant part of global carbon fixation, thereby forming the basis of marine food webs (Reid et al., 2009).

Past trends

The annual mean atmospheric CO_2 concentration reached 397 ppm in 2014, which is 40 % above the pre-industrial level (280 ppm); half of that increase has occurred since the 1980s. Over the same time period, ocean pH has been reduced from 8.2 to below 8.1, which corresponds to an increase of about 30 % in ocean acidity (defined here as the hydrogen ion concentration). This change has occurred at rates ranging between – 0.0014 and – 0.0024 per year, which is about a hundred times faster than any change in acidity experienced during the last 55 million years

(Rhein et al., 2013). The measured reduction in surface pH in the surface mixed layer (depths to 100 m) is consistent with that calculated on the basis of increasing atmospheric CO_2 concentrations, assuming thermodynamic equilibrium between the ocean surface and the atmosphere (Byrne et al., 2010; Rhein et al., 2013). The northernmost seas, i.e. the Norwegian Sea and the Greenland Sea, have experienced surface water pH reductions of 0.13 and 0.07, respectively, since the 1980s, both of which are larger than the global average (Ingunn et al., 2014).

Figure 4.1 shows the decline in ocean surface pH over the period 1988–2014 from a station offshore of Hawaii, for which the longest time series is available (Dore et al., 2009; Dore, 2012). The changes observed at two other ocean stations suitable for evaluating long-term trends (offshore of the Canary Islands and Bermuda) are very similar (Rhein et al., 2013).

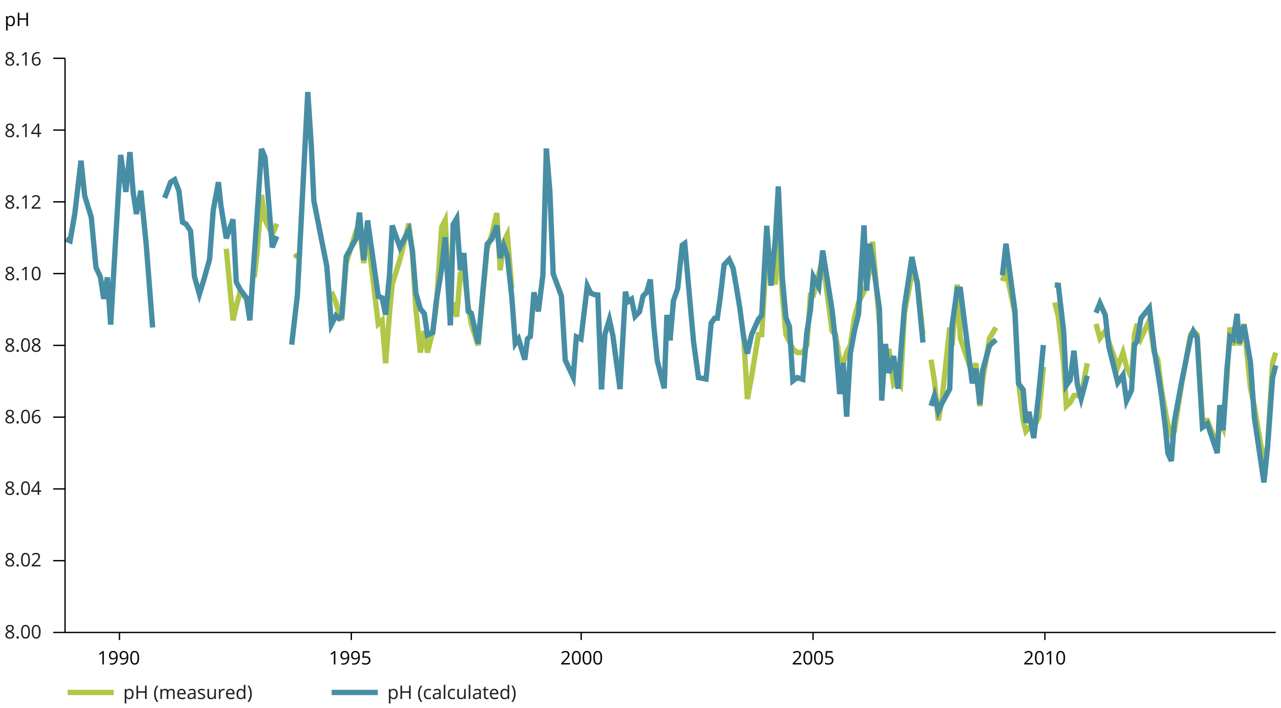
Projections

Average surface water pH is projected to decline further to between 8.05 and 7.75 by 2100, depending on future CO_2 emissions (Figure 4.2). Similar declines are also expected for enclosed, coastal seas such as the Baltic Sea (HELCOM, 2013). The largest projected decline represents more than a doubling in acidity (Joos et al., 2011; Bopp et al., 2013; Ciais et al., 2013; IGBP et al., 2013).

Surface waters are projected to become seasonally corrosive to aragonite in parts of the Arctic within a decade and in parts of the Southern Ocean within the next three decades in most scenarios. Aragonite is a less stable form of calcium carbonate and under-saturation will become widespread in these regions at atmospheric CO_2 levels of 500–600 ppm (McNeil and Matear, 2008; Steinacher et al., 2009; Ciais et al., 2013). The waters of the Baltic Sea will also become more acidic before the end of the century (HELCOM, 2013). Such changes affect many marine organisms and could alter marine ecosystems and fisheries. These rapid chemical changes are an added pressure on marine calcifiers and ecosystems of Europe's seas.

Without substantial reductions in CO_2 emissions, recovery from human-induced acidification will require thousands of years for the Earth system to re-establish roughly similar ocean chemical conditions (Archer, 2005; Tyrrell et al., 2007; Archer and Brovkin, 2008) and millions of years for coral reefs to return, based on palaeo-records of natural coral reef extinction events (Orr et al., 2005; Veron, 2008).

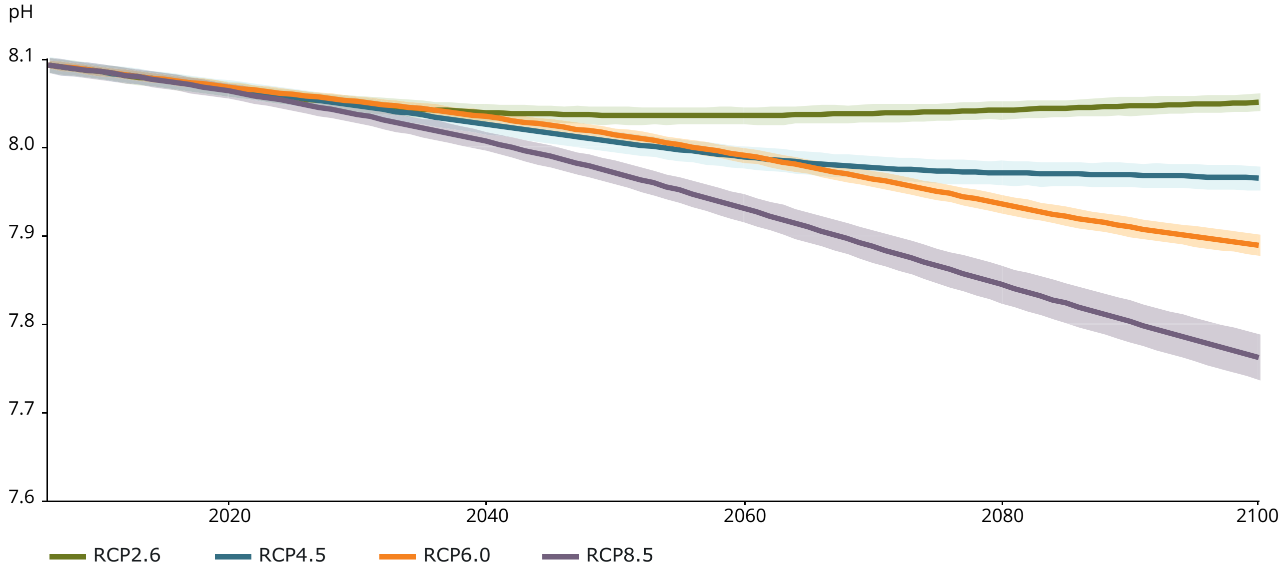
Figure 4.1 Decline in ocean surface pH measured at the Aloha station, 1988–2014



Note: A decline in pH corresponds to an increase in the acidity of ocean water. Data originate from the Aloha station pH time series. Changes here are similar to those that are observed at a shorter time scale in Europe.

Source: Adapted from Dore et al., 2009; Dore, 2012.

Figure 4.2 Projected change in global ocean surface pH



Note: The figure shows the projected change in ocean acidity for various emissions scenarios (RCPs) until 2100. A decline in pH corresponds to an increase in the acidity of ocean water. The thick lines show the model average and the shaded areas show the minimum to maximum range for each RCP.

Source: Adapted from IPCC (2013, Figure SPM7(c)).

Box 4.2 Ocean acidification effects on marine biodiversity

Ocean acidification can have a negative impact on the biology and ecology of numerous plants and animals (Secretariat of the Convention on Biological Diversity, 2014). Impacts include the following:

- Phytoplankton form the base of many marine food webs. Any impacts on their survival and growth due to climate change could therefore have major impacts on all other marine organisms and also affect commercial fisheries.
- Ocean acidification can affect a range of functions within organisms, such as membrane transport, photosynthesis in plants, neural processes in animals, growth, reproductive success and survival. Effects can be seen at all levels ranging from individual organisms to ecosystems. The effects on individual species depends on that species' capacity for adapting to new conditions (Pörtner et al., 2014).
- The behaviour and sensory performance of marine fish could be impaired at the CO_2 levels projected in the ocean within 50–100 years (Welch et al., 2014).
- Acidification will affect species with calcium carbonate skeletons such as reef-building corals causing shifts from coral to macroalgae dominance on reefs (Enochs et al., 2015).
- The effects of acidification can also include increased mortality and decreased fertilisation rates in sea urchins, decreased calcification rates and reduced growth rates in mussels, oysters and abalones, and impaired oxygen transport in squids (Fabry et al., 2008; Hall-Spencer et al., 2008). Many of these observations have been made in laboratory controlled environments with a surface water pH that may be reached in 2100.
- Ocean acidification and synergistic impacts of other anthropogenic stressors provide the potential for widespread changes to marine ecosystems (Fabry et al., 2008; Dupont et al., 2010).
- Acidification may not affect all marine environments uniformly. It may have the most effect in open oceanic waters, with some coastal organisms appearing to be able to alter the pH of their calcifying environment as a result of temporal and spatial variations in pH (Hendriks et al., 2014).
- Ocean acidification is happening, but the effects on marine biodiversity need to be better understood, especially in regard to the synergistic effects of other stressors (Hendriks and Duarte, 2010; Hendriks et al., 2010).

4.1.3 Ocean heat content

Key messages

- The warming of the oceans has accounted for approximately 93 % of the warming of the Earth since the 1950s. Warming of the upper (0–700 m) ocean accounted for about 64 % of the total heat uptake.
- A trend for increasing heat content in the upper ocean has become evident since the 1950s. Recent observations also show substantial warming of the deeper ocean (between depths of 700 and 2 000 m and below 3 000 m).
- Further warming of the oceans is expected with the projected climate change. The amount of warming is strongly dependent on the emissions scenario.

Relevance

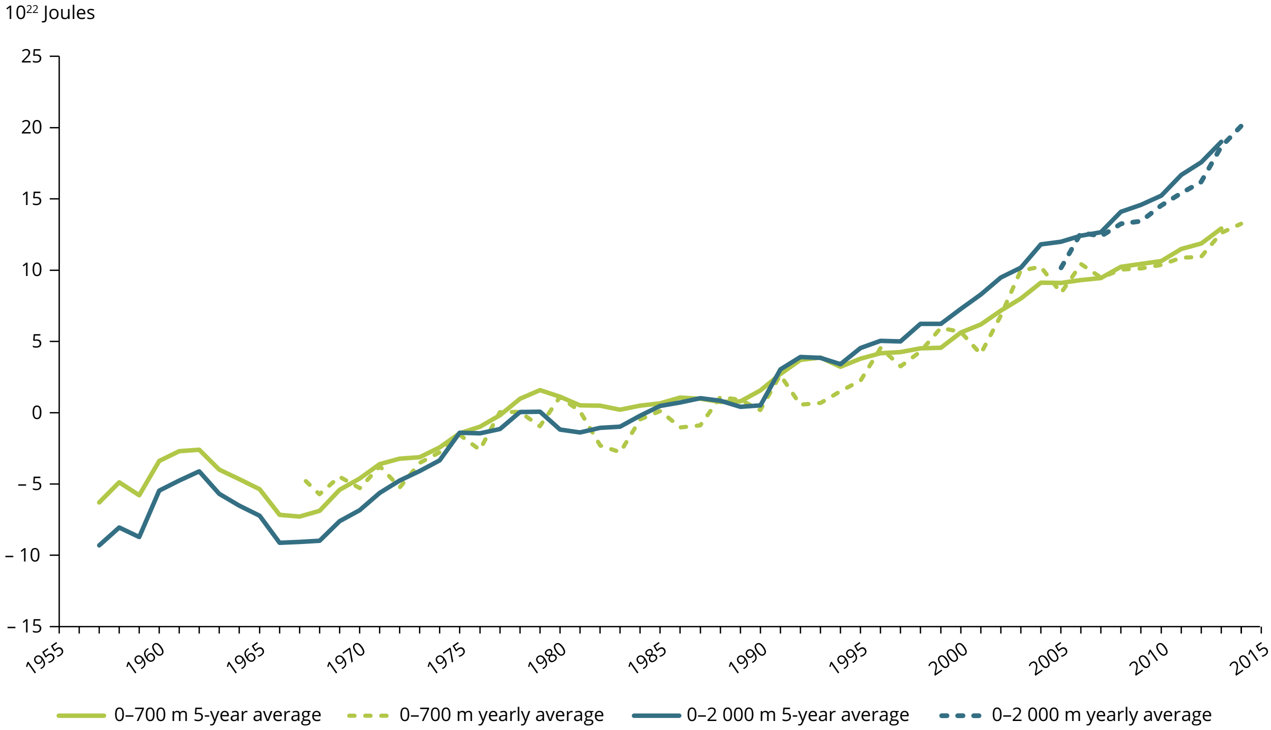
The ocean is the most dominant component of the Earth's heat balance, and most of the total warming caused by climate change is manifested in increased ocean heat content (OHC) (Hansen et al., 2011). Isotherms (i.e. contour lines of a given temperature) in the ocean have moved at comparable or faster rates than on land, causing species distribution shifts (Burrows et al., 2011; Poloczanska et al., 2013). Good estimates of past changes in OHC are essential for understanding the role of the oceans in past climate change, and for assessing future climate change. OHC integrates temperature change, the density of seawater and specific heat capacity from the surface down to the deep ocean. OHC is an anomaly calculated in comparison with a reference period. OHC is estimated based on temperature measurements or on reanalyses using a combination of models and observations (Levitus et al., 2012). Changes in heat content cause the ocean to expand or contract, thereby changing global sea level. This thermosteric effect has contributed about one-quarter to global sea level rise since 1993 (Church et al., 2011) (see Section 4.2.2).

Past trends

The warming of the oceans has accounted for approximately 93 % of the warming of the Earth since the 1950s (Hansen et al., 2011; Rhein et al., 2013; Howes et al., 2015). OHC has increased since around 1970 (Figure 4.3). Differences in the values for yearly and five-yearly averages are the result of the particular method used for spatial gap filling. The linear warming trends of the uppermost 700 m of the ocean and the 700–2 000 m layer over the time period 1955–2013 were 0.27 W/m^2 and 0.39 W/m^2 (per unit area of the ocean), respectively. It is likely that the ocean warmed between 700 and 2 000 m from 1957 to 2014 and between 3 000 m and the bottom of the ocean from 1992 to 2005, while trends in ocean temperature between depths of 2 000 and 3 000 m were not statistically significant (Purkey and Johnson, 2010; Levitus et al., 2012; Abraham et al., 2013; Rhein et al., 2013).

Two-thirds of the observed increase in OHC has occurred in the upper 700 m of the ocean, with increases in the layers below a depth of 700 m accounting for the remaining third. The strongest warming is found near the sea surface, with the upper 75 m having warmed by more than 0.1 °C per decade since 1971. It has been estimated that heat uptake has doubled in recent decades (Gleckler et al., 2016). At a depth of 700 m, the warming decreases to about 0.015 °C per decade (Rhein et al., 2013). Recently, it has been determined that past increases in OHC have been substantially underestimated because of poor sampling of the Southern Hemisphere and limitations of the analysis methods (Durack et al., 2014). These concerns have not yet been considered in the datasets presented here.

Figure 4.3 Global ocean heat content at different depths



Source: Data produced by NOAA's National Centers for Environmental Information (NCEI) (formerly the National Oceanographic Data Center (NODC)).

Projections

All available ocean temperature projections suggest that the global ocean will continue to warm. The largest warming is projected for the upper few hundred metres of the sub-tropical gyres, similar to the observed pattern of ocean temperature changes. Mixing and advection processes will gradually transfer the additional heat to deeper levels.

The rate of increase of OHC is approximately proportional to the global mean change in surface air temperature. Under the low-to-medium (RCP4.5) emissions scenario, half of the energy taken up by the ocean by the end of the 21st century will be by the uppermost 700 m, and 85 % will be by the uppermost 2 000 m. Projected ocean warming varies considerably across forcing scenarios. Globally averaged projected surface warming ranges from about 1 °C for RCP2.6 to more than 3 °C for RCP8.5 during the 21st century, and at a depth of 1 000 m ranges from 0.5 °C for RCP2.6 to 1.5 °C for RCP8.5 (Taylor et al., 2012; Church et al., 2013; Collins et al., 2013; Kirtman et al., 2013).

4.1.4 Sea surface temperature

Key messages

- All European seas have warmed considerably since 1870, and the warming has been particularly rapid since the late 1970s. The multi-decadal rate of sea surface temperature rise during the satellite era (since 1979) has been between 0.21 °C per decade in the North Atlantic and 0.40 °C per decade in the Baltic Sea.
- Globally averaged sea surface temperature is projected to continue to increase, although more slowly than atmospheric temperature.

Relevance

Sea surface temperature (SST) is an important physical characteristic of the oceans. SST varies naturally with latitude, being warmer at the equator and coldest in Arctic and Antarctic regions. As the oceans absorb more heat, SST will increase (and heat will be redistributed to deeper water layers). Information on changes in regional SST complements the information on changes in global OHC presented in Section 4.1.3.

Increases in SST can lead to an increase in atmospheric water vapour over the oceans, influencing entire weather systems. For Europe, the North Atlantic Ocean plays a key role in the regulation of climate over the European continent by transporting heat northwards and by distributing energy from the atmosphere into the deep parts of the ocean. The Gulf Stream and its extensions, the North Atlantic Current and Drift, partly determine weather patterns over the European continent, including precipitation and wind regimes. One of the most visible physical ramifications of increased temperature in the ocean is the reduced area of sea ice coverage in the Arctic polar region (see Section 3.3.2).

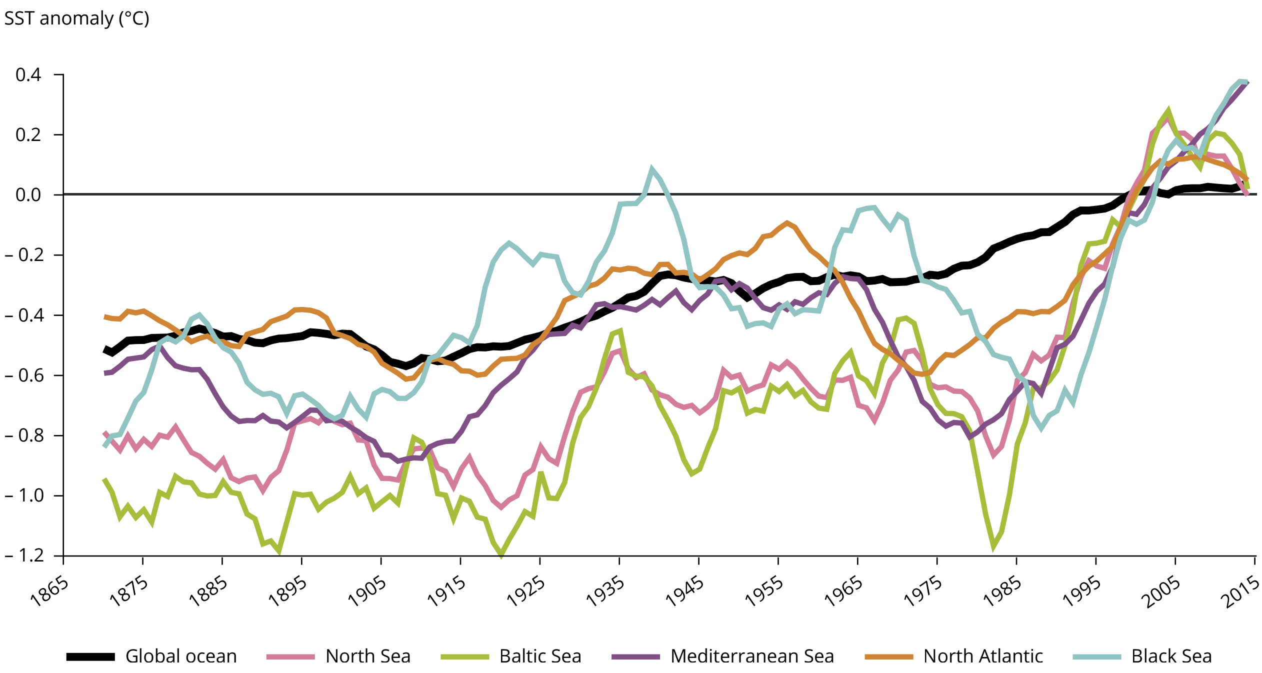
Temperature is a determining factor for the metabolism of species, and thus for their distribution and phenology, such as the timing of seasonal migrations, spawning events or peak abundances (e.g. plankton bloom events) (Box 4.3). There is an accumulating body of evidence suggesting that many marine species and habitats, such as cetaceans in the North Atlantic Ocean, are highly sensitive to changes in SST (Pinsky et al., 2013; Lambert et al., 2014). Increased temperature may also increase stratification of the water column. Such changes can have a significant influence on vertical nutrient fluxes in the water column, thereby influencing primary production and phytoplankton community structure (Hordoir and Meier, 2012). Further changes in SST could have widespread effects on marine species and cause the reconfiguration of marine ecosystems (Edwards and Richardson, 2004; Poloczanska et al., 2013; Glibert et al., 2014).

Past trends

The production of consistent, long time series of SST faces challenges owing to different measurement devices (*in situ* measurements from ships and buoys, as well as remote measurements from satellites), associated different definitions (e.g. water depth and time of day of measurement), different bias correction methods, and different interpolation methods to account for incomplete spatial and temporal coverage. As a result, substantially different values for absolute SST and for SST trends may be reported for a particular ocean basin, depending on the underlying global or regional SST dataset. In fact, there is still considerable uncertainty about the trend in global SST for the recent period 1979–2012 (Hartmann et al., 2013, Table 2.6). Furthermore, observed SST trends for regional seas reflect the combined effects of anthropogenic warming and natural climate variability (e.g. Atlantic Multidecadal Oscillation) (Macias et al., 2013). Despite those uncertainties, it is undisputed that SST has been increasing globally and in Europe during the last century.

The current indicator primarily uses information from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) dataset (Rayner et al., 2006). Information on the Mediterranean for the satellite era is complemented by data from the Copernicus Marine Environmental Monitoring Service (CMEMS). The trends, although not necessarily the absolute SST levels, are consistent between HadISST1 and available high-resolution SST datasets for the regional seas (Mediterranean Sea, Baltic Sea and North Sea). The trends reported here cannot be directly compared with those in previous versions of this indicator, which used different underlying datasets.

Figure 4.4 Trend in average sea surface temperature anomaly in Europe's seas



Note: This figure shows time series of average sea surface temperature (°C), smoothed over 11 years, and expressed as anomalies with reference to the average temperature between 1993 and 2012, of the global ocean and of each of Europe's seas.

Source: SST datasets from the CMEMS (Mediterranean Sea) and HADISST1 (global and all other regional seas).

All European seas have warmed considerably since 1870, and the warming has been particularly rapid since the late 1970s (Figure 4.4). The multi-decadal rate of SST rise during the satellite era (1979–2015) has been between 0.21 °C per decade in the North Atlantic and 0.40 °C per decade in the Baltic Sea.

Projections

It is very likely that globally averaged ocean temperatures at the surface and for different ocean depths will further increase in the near-term and beyond. Owing to the thermal inertia of the ocean, global SST is projected to rise more slowly than atmospheric temperature (Kirtman et al., 2013). Quantitative SST projections are available only for some regional seas in Europe (Macias et al., 2013; Chust et al., 2014). For the Baltic Sea, the increase in summer SST during the 21st century under medium to high emissions scenarios is projected to be about 2 °C in the southern parts and about 4 °C in the northern parts (HELCOM, 2013). An increase in harmful algal blooms, with increased risks to human health, ecosystems and aquaculture, has been projected for the North Sea and the Baltic Sea as a result of the projected warming (Glibert et al., 2014).

4.1.5 Distribution shifts of marine species

Key messages

- Increases in regional sea temperatures have triggered a major northwards expansion of warmer water plankton and a northwards retreat of colder water plankton in the North-east Atlantic. This northerly movement has amounted to about 10 ° latitude (1 100 km) over the past 40 years, and it seems to have accelerated since 2000.
- Sub-tropical species are occurring with increasing frequency in Europe's seas, and sub-Arctic species are receding northwards.
- Wild fish stocks are responding to changing temperatures and food supply by changing their distribution. This can have impacts on those local communities that depend on those fish stocks.
- Further changes in the distribution of marine species, including fish stocks, are expected with the projected climate change, but quantitative projections of these distribution changes are not widely available.

Relevance

Most marine organisms are 'ectotherms' that rely on the temperature of their environment to function optimally and are adapted to the temperature regime of their existing distribution range. Because of this relationship between the physical environment and species' life requirements, the redistribution of species has emerged as one of the most significant and visible species responses to climate change (Sunday et al., 2012).

Climate velocities (the rate and direction that isotherms shift through space) can be up to seven times higher in the ocean than on land (Poloczanska et al., 2013). Combined with fewer dispersal barriers in the marine environment, this allows marine species to seek out optimal temperature regimes faster than most terrestrial species (Pinsky et al., 2013). Changes in species distribution can therefore be used as an indicator of climate change impacts in marine ecosystems, bridging the gap between observed changes in physical conditions of the sea and observed changes in biological parameters.

As the distribution and abundance of a species changes, so will the role of that particular species in the local or regional marine community. Changes in species distribution can, in turn, change the overall productivity and stability of the local ecosystem, thereby ultimately affecting the food available to (other) fish, birds and marine mammals (Thackeray et al., 2010; Cardinale et al., 2012).

Changes in species distribution will also create challenges for local communities that depend on fish stocks and other marine resources. For example, the recent mackerel dispute between the EU and the Faroe Islands was caused by the fact that the mackerel stock had increased the time it spent in the waters of the Faroe Islands rather than in EU waters. This caused a heated discussion on stock allocation between countries. Ultimately, it led to an increase in the Faroe Islands' total allowable catch from 5 to 13 %, with further increases planned (Hartman and Waibel, 2014). Such disputes will most likely occur again as coldwater species retreat northwards. New opportunities may arise as new species come in from the south, but it is uncertain whether these will be of a similar commercial value to the receding ones.

In addition to changes in species distribution, rising sea surface temperatures are also causing changes in the phenology of marine species (see Box 4.3).

Past trends

Increases in regional sea temperatures have triggered a major northwards movement of species. As a result, sub-tropical species are occurring with increasing frequency in European waters, and sub-Arctic species are receding northwards. However, in areas with geographical constraints, i.e. where a coastline hinders northwards movement, some species shift into deeper and cooler waters (Dulvy et al., 2008; Brattegard, 2011; Pinsky et al., 2013). Some examples are provided below.

Plankton in the Greater North Sea have shown a northerly movement of about 10 ° latitude over the past 40 years. This corresponds to a mean polewards movement of around 250 km per decade, which appears to have accelerated since 2000 (Beaugrand, 2009). As a result, the ratio of the coldwater *Calanus finmarchicus* to the warmwater *Calanus helgolandicus*

Box 4.3 Examples of observed changes in species phenology in Europe's seas

The timing of spawning of sole in the Irish Sea and parts of the Greater North Sea has shifted to earlier in the year, at a rate of 1.5 weeks per decade since 1970, in response to increasing sea surface temperature (MCCIP, 2013).

Long-term changes in the phytoplankton communities in the northern Baltic Sea and the Gulf of Finland have occurred over the past 30 years. This can be seen in a decline in the spring bloom but an increase in the phytoplankton biomass during summer in this period. These changes appear to reflect both climate-induced changes and the eutrophication process.

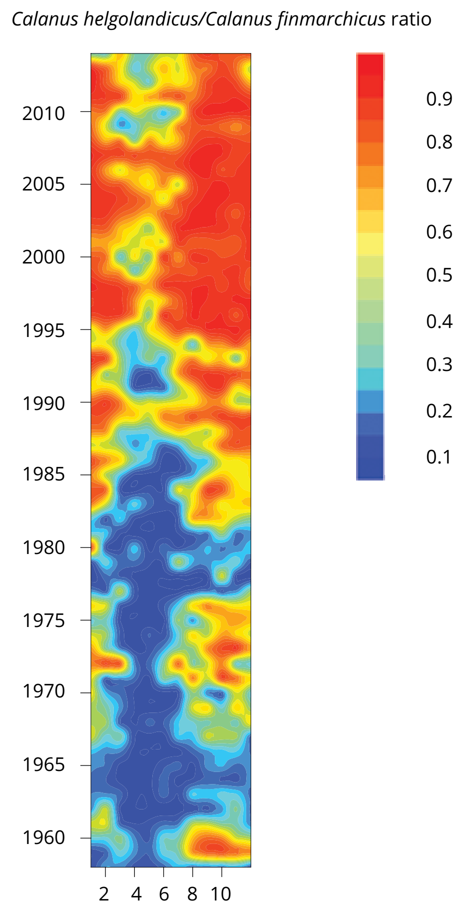
A change in the annual timing of peak seasonal abundance of decapoda larvae from 1958 to 2009 in the central North Sea has been observed. Since the 1990s, the seasonal development of decapoda larvae has occurred four to six weeks earlier than the long-term average. This trend towards an earlier seasonal appearance of decapoda larvae during the 1990s was correlated with sea surface temperature rise. These phenological shifts are a response at the species level, and not simply different seasonal timings by different species (Lindley and Kirby, 2010).

copepod species has changed considerably over time (Figure 4.5). While *C. helgolandicus* is becoming more abundant in the North Sea, the overall *Calanus* biomass has declined by 70 % since the 1960s (Edwards et al., 2016). Such rapid shifts in distribution range can reorganise marine species communities and have an impact on human communities that depend on them. For example, it has been shown that occurrences of European sprat are positively correlated with *C. finmarchicus*, while species such as Atlantic horse mackerel are positively correlated with *C. helgolandicus* (Montero-Serra et al., 2015).

Benthic invertebrates are also shifting their distribution range as temperatures change in the Greater North Sea, but their response lags behind the temperature increase. Unless the individual species are able to withstand a change in thermal regime, this mismatch could lead to a drop in benthic diversity (Hiddink et al., 2015). Such reorganisation will have an impact upon human communities and challenge traditional approaches to management of, for example fisheries, which have to consider species responses to temperature when planning future fishing opportunities (Rutterford et al., 2015).

Very fast rates of northwards movement were observed in the coastal waters of southern Norway from 1997 and 2010. About 1 600 benthic marine species were found, and of these 565 species had expanded their distribution northwards along the coast, at rates of 500–800 km per decade (Brattegard, 2011). Phytoplankton and highly mobile pelagic species are the fastest migrating organisms; their migration rate can be an order of magnitude faster than those of terrestrial species (Poloczanska et al., 2013).

Figure 4.5 Ratio of *Calanus* species in the Greater North Sea



Note: Temporal and seasonal distribution of the ratio of *Calanus* species from 1958 to 2014.

Source: Edwards et al., 2016. © 2016 Sir Alister Hardy Foundation for Ocean Science (SAHFOS). Reproduced with permission.

Increases in the surface temperature of the North Sea in recent decades have triggered establishment of warmwater swimming crabs, which in turn has allowed establishment of colonies of lesser black-backed gulls in Belgium and northern France (Luczak et al., 2012). There is also evidence that the overwintering distributions of many water birds have changed. In recent decades, in response to warming, their distributions have shifted northwards and eastwards out of the United Kingdom (MCCIP, 2013).

In the eastern Mediterranean Sea, the introduction of warmwater and tropical alien species from the Red Sea has been exacerbated by observed warming, leading to a 150 % increase in the annual mean rate of species entry after 1998 (Raitsos et al., 2010).

Impacts on fisheries

Climate change is also affecting fish stocks of commercial interest. Wild fish stocks seem to be responding to changing temperatures and food supply by changing their geographical distribution and their phenology. Mackerel and horse mackerel are spawning earlier in the English Channel, and both earlier and further north on the Porcupine Bank (off the west coast of Ireland). International commercial landings from the North-east Atlantic Ocean of fish species identified as 'warm-adapted' (e.g. grey gurnard, red mullet and hake) have increased by 250 % since the 1980s, while landings of cold-adapted species (e.g. cod, haddock and whiting) have halved (MCCIP, 2013). A striking example for the potentially large economic consequences of the northwards movement of marine species is the recent establishment of the Northeast Atlantic mackerel in Greenlandic waters. This temperature-sensitive epipelagic fish was first observed in Greenlandic waters in 2011, following record-high summer temperatures. Following the rapid development of a large-scale fishery, mackerel already contributed 23 % to the export value of all goods from Greenland in 2014 (Jansen et al., 2016).

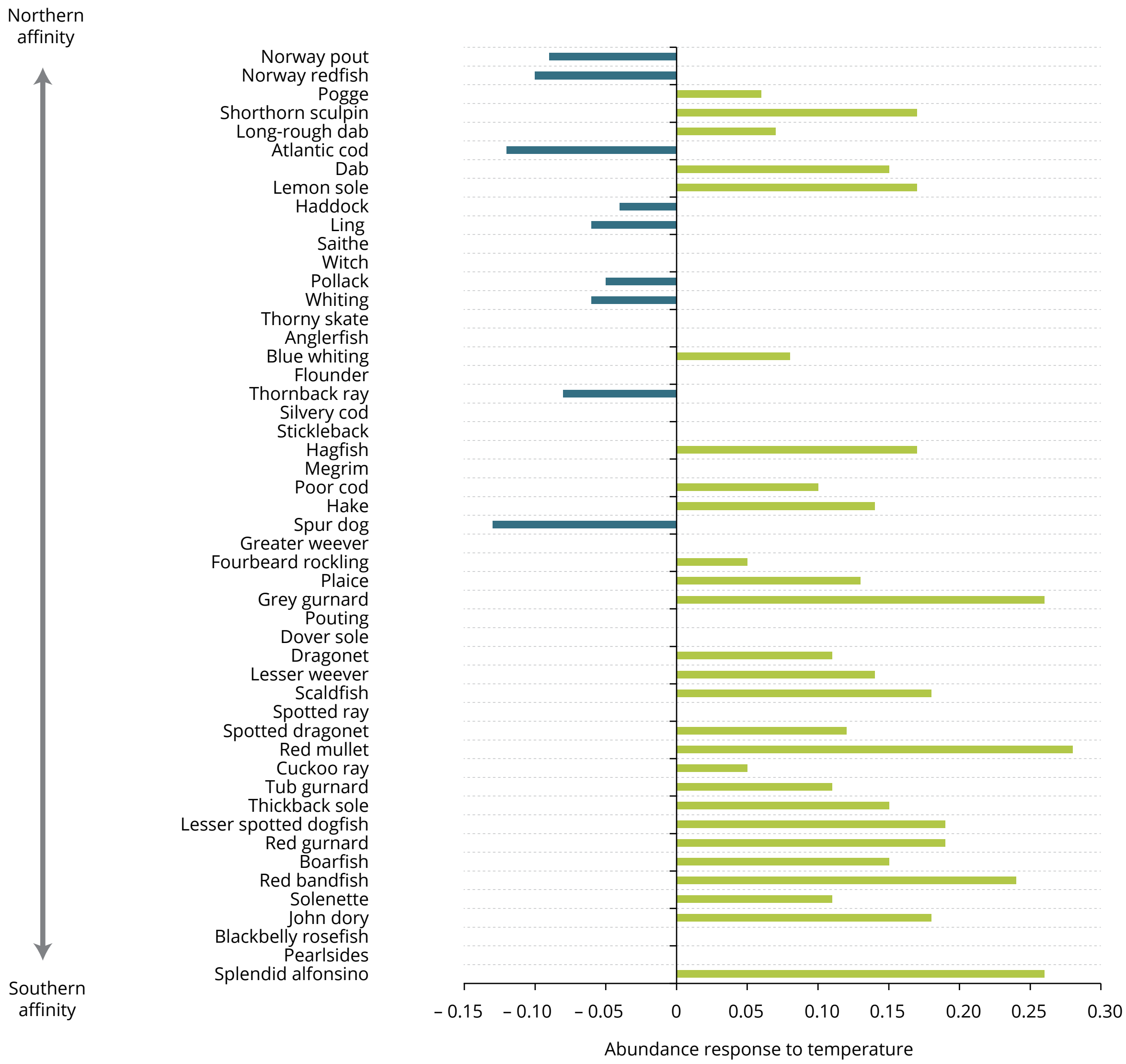
In the North-east Atlantic Ocean, 72 % of commonly observed fish species have responded to warming waters by changing their abundance and/or distribution (Figure 4.6). Traditionally exploited fish species have moved further northwards in the region, while new species have moved in, most likely as a result of a shift in the thermal regime. While warming can lead to an increase in fish biodiversity in a region, there is often a concurrent decrease in the size structure of the fish population. For example, in the Greater North Sea, the relatively small species sprat, anchovy and horse mackerel have increased in recent decades, whereas the larger species cod and plaice have decreased at their southern distribution limit (Perry, 2005). This change may have important socio-economic consequences, as the stocks moving out tend to have a higher value than the stocks moving in. Pronounced changes in community structures and species interactions of demersal fish are projected over the next 50 years, as fish will experience constraints in the availability of suitable habitat (Rutterford et al., 2015).

Global projections of changes in total catch of marine fish and invertebrates in response to ocean warming suggest a large-scale redistribution of global catch potential, with an increase in high-latitude regions and a decline in the tropics. In Europe, a considerable increase in catch potential is expected in the Arctic (Cheung et al., 2009; Gattuso et al., 2015).

Projections

As sea surface temperatures increase, marine species will continue to seek out the most optimal temperature regime for their metabolic demands, thus leading to further northwards movement of marine species. However, quantitative projections are not widely available. Furthermore, non-indigenous species might become invasive if conditions favour their metabolic demands, while native species are weakened (Jones and Cheung, 2015).

Figure 4.6 **Observed change in the distribution of demersal fish in response to the observed rise in sea surface temperature**



Note: The changes in abundance in response to observed temperature change are relative changes (unitless).

Source: Adapted from Simpson et al., 2011.

4.1.6 Ocean oxygen content

Key messages

- Dissolved oxygen in sea water affects the metabolism of species. Therefore, reductions in oxygen content (i.e. hypoxic or anoxic areas) can lead to changes in the distribution of species, including so called 'dead zones'.
- Globally, oxygen-depleted areas have expanded very rapidly in recent decades. The number of 'dead zones' has roughly doubled every decade since the 1960s and has increased from about 20 in the 1950s to about 400 in the 2000s.
- Oxygen-depleted zones in the Baltic Sea have increased more than 10-fold, from 5 000 to 60 000 km^2, since 1900, with most of the increase happening after 1950. The Baltic Sea now has the largest dead zone in the world. Oxygen depletion has also been observed in other European seas in recent decades.
- The primary cause of oxygen depletion is nutrient input from agricultural fertilisers, causing eutrophication. The effects of eutrophication are exacerbated by climate change, in particular increases in sea temperature and in water-column stratification.

Relevance

Accelerated nutrient flow into the sea (mostly from agricultural fertilisers) in combination with warming water temperatures can lead to large phytoplankton blooms and subsequent increases in primary production (a process called eutrophication). When these organisms sink to the sea floor, oxygen is utilised in their decomposition. If mixing within the water column cannot supply enough oxygen to the sea floor, this can lead to oxygen reduction (hypoxia) to levels that severely limit biological activity and ultimately to complete oxygen depletion (anoxia).

Most organisms, including marine organisms, require oxygen for their metabolism. Therefore, lower oxygen concentrations in seawater affect the physiology, composition and abundance of species. Rising water temperatures will have knock-on effects on a number of different chemical processes in the marine environment. For example, as the temperature rises, oxygen becomes less soluble in water, resulting in lower oxygen concentrations (Keeling et al., 2010); at the same time, the oxygen demand for metabolism increases (Pörtner, 2010). Insufficient oxygen supply to organisms will eventually have knock-on effects on productivity, species interactions and community composition at the ecosystem level.

Oxygen depletion can occur episodically (less than once per year), periodically (several times per year for short periods) and seasonally (each summer), and eventually it can become persistent. The Baltic Sea has the largest dead zone in the world, which includes large areas of persistent oxygen depletion. Oxygen-depleted areas are an example of how one type of anthropogenic pressure, nutrient input causing eutrophication, is exacerbated by climate change (here increasing temperature) through multiple different linkages with biology, from cellular levels to community and ecosystem levels. For example, land-based nutrient enrichment can lead to a redistribution in the vertical distribution of primary production. Such increased nutrient input can increase primary production in the surface layer, where the oxygen produced can be exchanged with the atmosphere. The organic material produced will sink through the pycnocline (i.e. the ocean layer with a stable density gradient, which hinders vertical transport) using oxygen as it decomposes. At the same time, when primary production occurs below the pycnocline, the oxygen produced will stay in the bottom layer. As climate change influences stratification parameters (see Section 4.1.4), and consequently the depth of the pycnocline, it could influence light availability for primary production in the deeper layer, possibly decreasing oxygen production. In this case, the interaction between climate change and eutrophication can have impacts on biodiversity, plankton communities and oxygen conditions (Lyngsgaard et al., 2014). Oxygen depletion may also interact with other anthropogenic stressors in affecting marine ecosystems and fisheries, such as overfishing or the introduction of invasive species (Diaz and Rosenberg, 2008).

Past trends

Dissolved oxygen in marine ecosystems has changed drastically in a very short period compared with other variables of the marine environment. While hypoxic zones occur naturally in some regions, increased nutrient loads from agricultural fertilisers have caused oxygen-depleted areas or even anoxic areas (so-called 'dead zones') to expand globally since the mid-20th century. The number of 'dead zones' globally has increased from about 20 in the 1950s to about 400 in the 2000s (Diaz and Rosenberg, 2008).

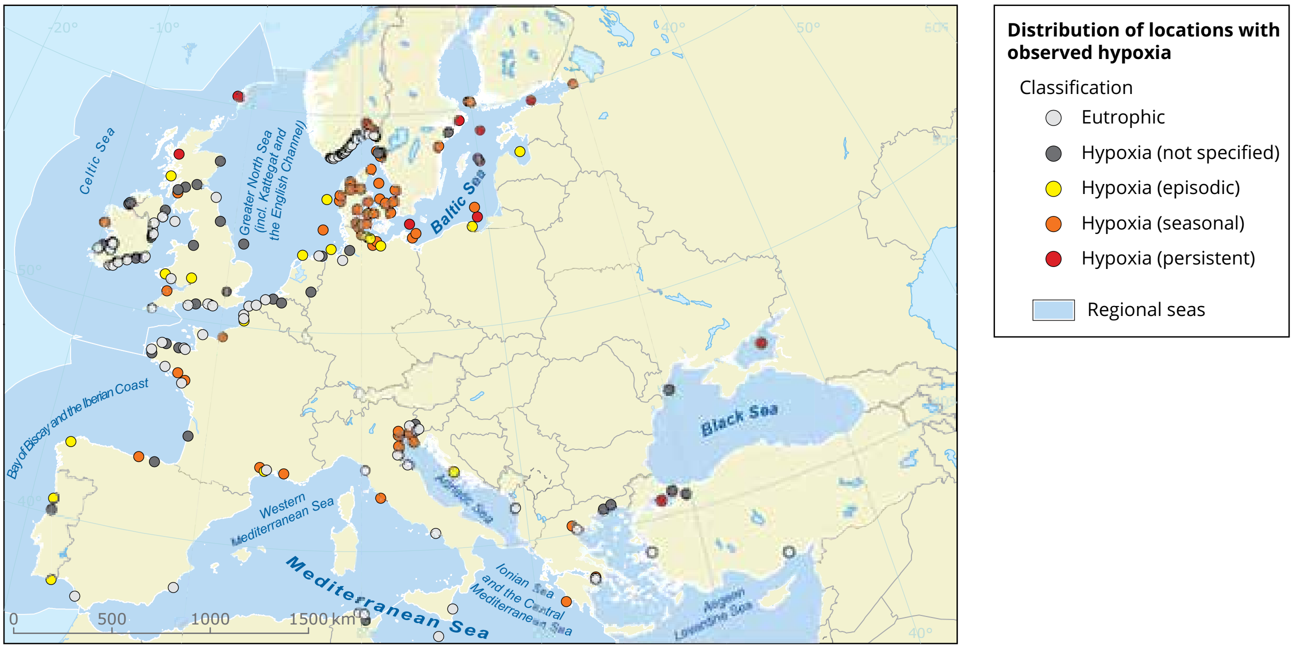
Extensive areas with oxygen depletion or even anoxic areas have been observed for decades in all European seas (Map 4.1) (Diaz and Rosenberg, 2008; HELCOM, 2009; UNEP/MAP, 2013; Friedrich et al., 2014; Djakovac et al., 2015; Topcu and Brockmann, 2015).

The largest area of human-induced hypoxia in Europe, and in fact globally, is found within the Baltic Sea (including the adjacent seas towards the North Sea). The Baltic Sea is a shallow basin with restricted inlets, meaning that the water has a high residence time, making this water body prone to hypoxia. Hypoxic areas in the Baltic Sea have increased more than 10-fold, from 5 000 to 60 000 km², since 1900, with most of the increase happening after 1950 (Map 4.2).

This expansion is primarily linked to increased inputs of nutrients from the land, but increased respiration from higher temperatures during the last two decades (since the early 1990s) has contributed to worsening oxygen levels (Carstensen et al., 2014; Pyhälä et al., 2014).

Oxygen depletion initially affects benthic organisms (i.e. those living on or in the seabed). Benthic organisms carry out important ecosystem functions, such as bioturbation, bioirrigation and sediment nutrient cycling. Benthic organisms also play a crucial role in the marine food web, so reductions in benthic organisms can have large impacts to commercial fisheries. The loss of benthic macrofauna in the Baltic Sea (including adjacent seas) as a result of hypoxia has been estimated at 3 million tonnes or about 30 % of Baltic secondary production (Karlson et al., 2002; Diaz and Rosenberg, 2008).

Map 4.1 Distribution of oxygen-depleted 'dead zones' in European seas



Note: Circles depict scientifically reported accounts of eutrophication-associated 'dead zones'. The area covered by 'dead zones' is not presented, as such information is not generally available.

Source: Adapted from Diaz and Rosenberg, 2008.

Map 4.2 Development of oxygen depletion in the Baltic Sea over time

Development of oxygen depletion in the Baltic Sea over time

Estimated bottom concentrations (mg/l)

- < 2
- 0

100 km

Note: This map shows the observed spatial distribution of bottom hypoxia (red; < 2 mg/l) and anoxia (black; 0 mg/l) in 1906 (left), 1955 (centre) and 2012 (right). The spatial distribution represents means across all months.

Source: Adapted from Carstensen et al., 2014.

Projections

Sea surface temperature is projected to continue to increase in the Baltic Sea and other European seas (see Section 4.1.4). As a result, oxygen-depleted areas will further expand, in particular in the Baltic Sea, unless nutrient intakes are reduced (Caballero-Alfonso et al., 2015). The combined effects of oxygen loss and ocean warming could force polewards movement and vertical contraction of metabolic viable habitats and species distribution ranges during this century (Deutsch et al., 2015).

4.2 Coastal zones

Key messages

- Mean and extreme sea level have increased globally and along most coasts in Europe. Global mean sea level in 2015 was the highest yearly average over the record. There is increasing evidence of an acceleration in the rate of global mean sea level rise during recent decades.
- The global mean sea level rise in the 21st century is very likely to be greater than that of the 20th century. Several recent model-based studies and expert assessments have suggested an upper bound for the global mean sea level rise in the 21st century in the range of 1.5–2.0 m.
- Sea level rise will continue for many centuries, even if greenhouse gas emissions and temperature are stabilised. The main uncertainty for multi-century sea level rise is how fast the large ice sheets will disintegrate. Individual studies have suggested that the melting of the Antarctic ice sheet could contribute up to 15 m to sea level rise by 2500 under a high emissions scenario, but these projections are associated with very large uncertainties.
- Projected increases in extreme high coastal water levels in Europe are likely to mostly be the result of increases in local relative mean sea level in most locations. However, recent studies suggest that increases in storm activity can also play a substantial role, in particular along the northern European coastline.
- Projected sea level rise, possible changes in the frequency and intensity of storm surges, and the resulting coastal erosion are expected to cause significant ecological damage, economic loss and other societal problems along low-lying coastal areas across Europe unless additional adaptation measures are implemented.

4.2.1 Overview

Relevance

Coastal zones in Europe are centres of population and economic activity, and they are home to diverse ecosystems, in particular wetland and littoral ecosystems. Some low-lying coastal regions, in particular on islands, are important biodiversity hotspots (Bellard et al., 2013, 2014). Projected climate change, including sea level rise and associated changes in the frequency and/or intensity of storm surges and erosion, threatens human and natural systems along continental coasts and on islands in various ways.

The management of coastal zones needs to consider the multiple functions of many coastal areas, and this is increasingly occurring through integrated coastal zone management. Adaptation policies also need to consider the full range of adaptation options, including measures such as dike building, beach nourishment, rehabilitation of coastal ecosystems, spatial planning, integrated coastal zone management, and elaboration and distribution of flood hazard and flood risk maps for costal zones according to the EU Floods Directive (EC, 2007).

Policy context

Building on the existing EU policy on integrated coastal zone management (confirmed by EU, 2014b) and its gradual uptake by Member States, the new initiatives for maritime spatial planning (launched by the EU Integrated Maritime Policy) and coastal and marine issues of climate change adaptation (part of the EU Strategy on adaptation to climate change, EC, 2013) have expanded the horizontal policy platform, and offer new opportunities for integrated spatial management and adaptation of Europe's coastlines.

In July 2014, the European Parliament and the Council adopted legislation to create a common framework for maritime spatial planning in Europe (EU, 2014a). This directive established a framework for 'maritime spatial planning' (public policy that deals exclusively with managing maritime space but not land space) and provided new guidance for integrated coastal management. The directive clearly presents the need for an integrated planning and management approach to tackle the multiple pressures on coastal resources. Specifically, while clearly leaving terrestrial spatial planning along the coast up to individual Member States, it addresses land–sea interactions as part of the framework and suggests how these can feed in to integrated coastal management processes.

The coastal zones can be rendered sustainable only through a broad-based coalition of policy actions based on national and/or regional integrated coastal management platforms (or strategies). The key components of such an alliance include the economic sectors based on sustainable use of coastal resources, the implementation of existing environmental legislation (for an overview, see EEA, 2013) and actions (strategies) for adaptation to climate change that together contribute to increased resilience of coastal areas and communities.

Selection of indicators

The following section presents the indicator 'global and European sea level' in relation to climatic threats to the coastal zone. This indicator, which is part of the EEA core set of indicators, addresses global mean sea level rise and changes in mean and extreme sea level along European coasts.

One of the prominent issues across European coastlines is *coastal erosion*. Information on coastal erosion is not presented as an EEA indicator because the underlying information base is out-dated and regular updates cannot be expected. Instead, a brief summary of the available information base is presented here. Coastal erosion is the process of the wearing away of material from a coastal profile as a result of an imbalance in the supply and export of material from a certain coastline section, which results in coastline retreat and loss of land. It takes place mainly during strong winds, high waves and high tides, which are all potentially influenced by climate change. The increasing human use of the coastal zone has turned coastal erosion from a natural phenomenon into a problem of growing importance for societies. Coastal erosion in Europe causes significant economic loss, ecological damage and societal problems. Loss of property, residential and commercial buildings, infrastructure, beach width, and valuable coastal habitat causes millions of euros worth of economic damage each year and presents significant management issues. At the same time, protection is expensive. For example, in Portugal, EUR 500 million was invested in dune and seafront rehabilitation and hard defence between 1995 and 2003 along a coastal stretch from the harbour of Aveiro to the resort of Vagueira (Marchand, 2010).

Many European coasts are being affected by coastal erosion. According to the Eurosion project ([48]) (Eurosion, 2004), in total, ca. 15 % of the European coastline was eroding, about the same amount was accreting (almost exclusively in northern Europe), 40 % was stable, and data were missing for the remaining 30 %. About 4 700 km of the European coastline have become artificially stabilised, and 2 900 km thereof were retreating in spite of coastal protection works. Coastal erosion will be increased by climate change. Sea level rise is one of the most important drivers of accelerated erosion because it implies an increase in sediment demand, as retreating coastlines and higher sea levels will raise extreme water levels, allow waves to break nearer to the coast and transmit more wave energy to the shoreline. Other drivers of climate change that may exacerbate erosion rates are increased storminess, higher waves and changes in prevalent wind and wave directions (Marchand, 2010). Despite their high relevance, no data collection on coastal erosion trends and impacts has been undertaken at the European level since 2004. Thus, the knowledge base for dealing with this prominent hazard remains a patchwork of case-based research projects and practical coastal defence solutions at the local level.

Saltwater intrusion into freshwater reservoirs is another significant risk along low-lying coastal regions. Saltwater intrusion can be caused by relative sea level rise and by overexploitation of groundwater resources. It can threaten freshwater supply, agriculture and ecosystems in coastal regions. However, the data currently available are insufficient for developing an indicator on saltwater intrusion.

Information on the *ecological impacts* of climate change (including sea level rise) in coastal zones is available for some regions (see, for example, The BACC II Author Team, 2015). However, it is not presented in this report because of a lack of data at the European scale. Further information on the *economic and health risks* associated with sea level rise is presented in Sections 5.2.3 and 6.3.

([48]) http://www.eurosion.org.

4.2.2 Global and European sea level

Key messages

- Global mean sea level has risen by 19.5 cm from 1901 to 2015, at an average rate of 1.7 mm/year, but with significant decadal variation. The rate of sea level rise since 1993, when satellite measurements have been available, has been higher, at around 3 mm/year. Global mean sea level in 2015 was the highest yearly average over the record and ~ 70 mm higher than in 1993.
- Evidence for a predominant role of anthropogenic climate change in the observed global mean sea level rise and for an acceleration during recent decades has strengthened since the publication of the IPCC AR5.
- Most coastal regions in Europe have experienced an increase in absolute sea level and in sea level relative to land, but there is significant regional variation.
- Extreme high coastal water levels have increased at most locations along the European coastline. This increase appears to be predominantly due to increases in mean local sea level rather than to changes in storm activity.
- Global mean sea level rise during the 21st century will very likely occur at a higher rate than during the period 1971–2010. Process-based models considered in the IPCC AR5 project a rise in sea level over the 21st century that is likely in the range of 0.26–0.54 m for a low emissions scenario (RCP2.6) and 0.45–0.81 m for a high emissions scenario (RCP8.5). However, several recent studies suggest substantially higher values. Several national assessments, expert assessments and recent model-based studies have suggested an upper bound for 21st century global mean sea level rise in the range of 1.5–2.0 m.
- Available process-based models project that global mean sea level rise by 2300 will be less than 1 m for greenhouse gas concentrations that peak and decline and do not exceed 500 ppm CO_2-equivalent, but will be in the range of 1 m to more than 3 m for concentrations above 700 ppm CO_2-equivalent. However, these models are likely to systematically underestimate the sea level contribution from Antarctica, and some recent studies suggest substantially higher rates of sea level rise in the coming centuries.
- The rise in sea level relative to land along most European coasts is projected to be similar to the global average, with the exception of the northern Baltic Sea and the northern Atlantic Coast, which are experiencing considerable land rise as a consequence of post-glacial rebound.
- Projected increases in extreme high coastal water levels are likely to mostly be the result of increases in local relative mean sea level in most locations. However, recent studies suggest that increases in the meteorologically driven surge component can also play a substantial role, in particular along the northern European coastline.

Relevance

Sea level is an important indicator of climate change because it can have significant impacts on settlements, infrastructure, people and natural systems. It acts on time scales much longer than those of indicators that are closely related to near-surface temperature change. Even if greenhouse gas concentrations were stabilised immediately, sea level would continue to rise for many centuries (IPCC, 2013, 2014).

Changes in global mean sea level (GMSL) result from a combination of several physical processes. Thermal expansion of the oceans occurs as a result of warming ocean water. Additional water is added to the ocean from a net melting of glaciers and small ice caps, and from the disintegration of the large Greenland and Antarctic ice sheets. Further contributions may come from changes in the storage of liquid water on land, in either natural reservoirs such as groundwater or man-made reservoirs.

The locally experienced changes in sea level differ from global average changes for various reasons (Church et al., 2013, FAQ 13.1). First, changes in water density are not expected to be spatially uniform, and the spatial pattern also depends on changes in large-scale ocean circulation. Second, changes in the gravity field, for instance as water moves from melting ice on land to the ocean, also varies across regions. Finally, at any particular location, there may be a vertical movement of the land in either direction, for example due to the ongoing effects of post-glacial rebound (also known as glacial isostatic adjustment), which is particularly strong in northern Europe, to local groundwater extraction or to other processes, including tectonic activity.

In Europe, the potential impacts of sea level rise include flooding, coastal erosion and the submergence of flat regions along continental coastlines and on islands. Rising sea levels can also cause saltwater intrusion into low-lying aquifers, thus threatening water supplies and endangering coastal ecosystems and wetlands. Higher flood levels increase the risk to life and property, including to sea dikes and other infrastructure, with potential impacts on tourism, recreation and transportation functions. Low-lying coastlines with high population densities and small tidal ranges are most vulnerable to sea level rise, in particular where adaptation is hindered by a lack of economic resources or by other constraints.

Damage associated with sea level rise is mostly caused by extreme events, such as storm surges. Of most concern are events when the surge coincides with high tidal levels and increases the risk of coastal flooding owing to extreme water levels. Changes in the climatology of extreme water levels (i.e. the frequency and height of maximum water levels) may be caused by changes in local mean sea level (i.e. the local sea level relative to land averaged over a year or so), changes in tidal range, changes in the local wave climate or changes in storm surge characteristics. One multi-model study concluded that climate change can both increase and decrease average wave height along the European coastline, depending on the location and season. Wave height is projected to change by less than 5 % during the 21st century (Hemer et al., 2013).

Changes in storm surge characteristics are closely linked to changes in the characteristics of atmospheric storms, including the frequency, track and intensity of the storms (see Section 3.2.6). The intensity of storm surges can also be strongly affected by regional and local-scale geographical features, such as the shape of the coastline. Typically, the highest water levels are found on the rising limb of the tide. The most intense surge events typically occur during the winter months in Europe.

The most obvious impact of extreme sea level is flooding. The best known coastal flooding event in Europe in living memory occurred in 1953 when a combination of a severe storm surge and a high spring tide caused in excess of 2 000 deaths in the Netherlands, Belgium and the United Kingdom, and damaged or destroyed more than 40 000 buildings (Baxter, 2005; Gerritsen, 2005). Currently, around 200 million people live in the coastal zone in Europe, as defined by Eurostat (Collet and Engelbert, 2013). Coastal storms and storm surges can also have considerable ecological impacts, such as seabird wrecks, disruption to seal mating and pupping, and increases in large mammal and turtle strandings.

Past trends: global mean sea level

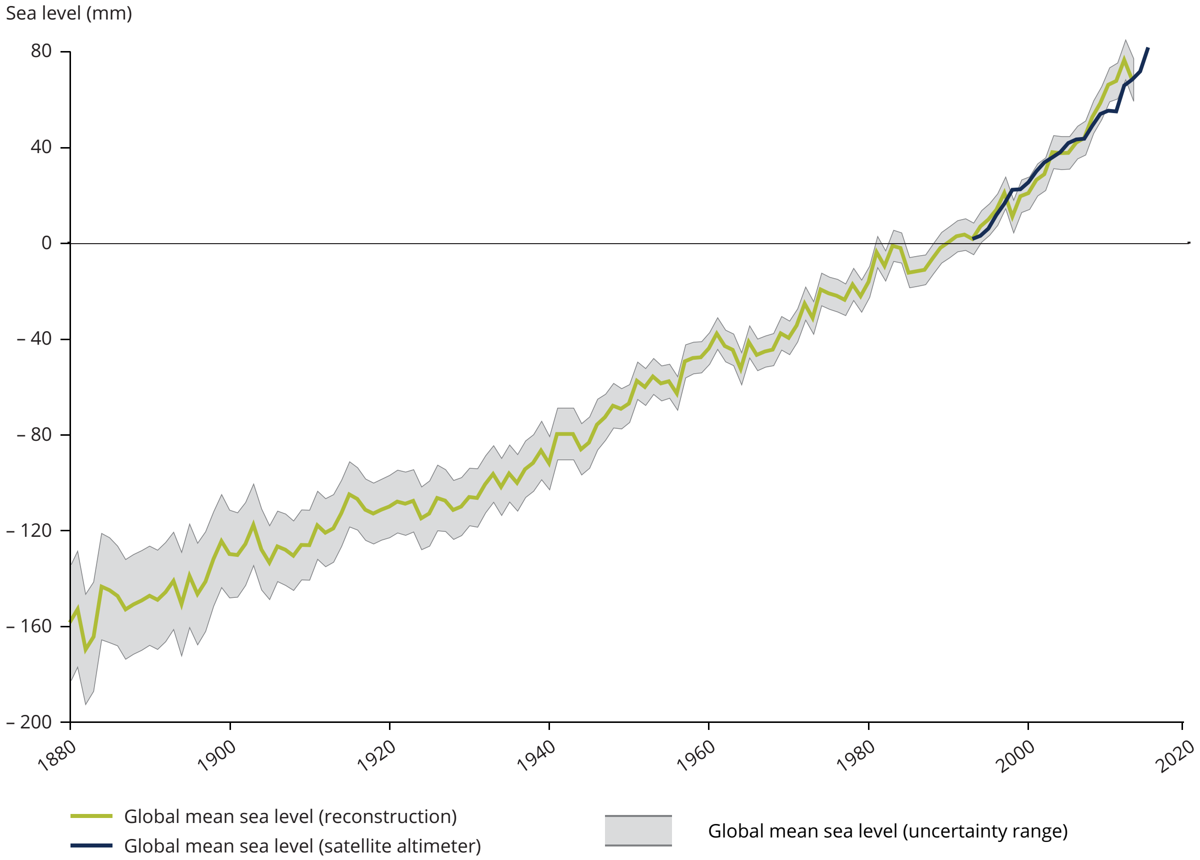
Sea level changes can be measured using tide gauges and remotely from space using satellite altimeters. Many tide gauge measurements have long multi-decade time series, with some exceeding more than 100 years. However, the results can be distorted by various local effects. Satellite altimeters enable sea level to be measured from space and give much better spatial coverage (except at high latitudes). However, the length of the altimeter record is limited to only about two decades.

The IPCC AR5 estimated that GMSL rose by 19.5 cm in the period between 1901 and 2015, which corresponds to an average rate of around 1.7 mm/year (Figure 4.7, updated from IPCC AR5). This rate is somewhat higher than the sum of the known contributions to sea level rise over this period (Church et al., 2013). This value has been confirmed by more recent studies (Jevrejeva, Moore et al., 2014; Wenzel and Schröter, 2014). One reanalysis suggests that GMSL during the 20th century rose at a lower rate of 1.2 ± 0.2 mm/year (Hay et al., 2015), but this reanalysis has been criticised for its non-representative selection of tide gauges (Hamlington and Thompson, 2015). Evidence from formal detection and attribution studies showing that most of the observed increase in GMSL since the 1950s can be attributed to anthropogenic climate change has increased since the publication of the IPCC AR5 (Jordà, 2014; Slangen, Church et al., 2014; Clark et al., 2015).

All estimates for the rate of GMSL rise during the period since 1993, for which satellite-based measurements are available, are considerably higher than the 20th century trend, at 2.6–3.2 mm/year (Church and White, 2011; Masters et al., 2012; Church et al., 2013; Rhein et al., 2013; Jevrejeva, Moore, et al., 2014; Clark et al., 2015; Hay et al., 2015; Watson et al., 2015). Different statistical methods for assessing sea level trends and changes therein can come to somewhat different conclusions (Visser et al., 2015). However, available assessments agree that an acceleration in the rate of GMSL rise since the early 1990s is detectable, despite significant decadal variation. Global mean sea level in 2015 was the highest yearly average over the record and ~ 70 mm higher than in 1993 (Blunden and Arndt, 2016).

The causes of GMSL rise over recent decades are now reasonably well understood. Thermal expansion and melting of glaciers account for around 75 % of the measured sea level rise since 1971. The contribution

Figure 4.7 Observed change in global mean sea level



Note: The figure depicts the rise in global mean sea level from 1880 to 2015, relative to the 1990 level, based on two sources. The green line shows a reconstruction for 1880 to 2013 from coastal and island tide gauge data. The uncertainty interval is shown in grey. The dark blue line shows a time series for 1993 to 2015 based on altimeter data from the TOPEX/Poseidon, Jason-1 and Jason-2 satellites. Corrections for the inverse barometer effect and glacial isostatic adjustment have been applied.

Source: Adapted from Church and White, 2011; Masters et al., 2012. Data supplied by Benoit Legresy (Commonwealth Scientific and Industrial Research Organisation (CSIRO)).

from melting of the Greenland and Antarctic ice sheets has increased since the early 1990s. Changes in land water storage have made only a small contribution, but the rate of groundwater extraction has increased recently and now exceeds the rate of storage in reservoirs (Church et al., 2011, 2013; Clark et al., 2015). A recent study concludes that climate-driven variability in precipitation has resulted in increased water storage on land, and that global sea level rise in the period 2002–2014 would have been 15–20 % higher in the absence of this climate variability (Reager et al., 2016).

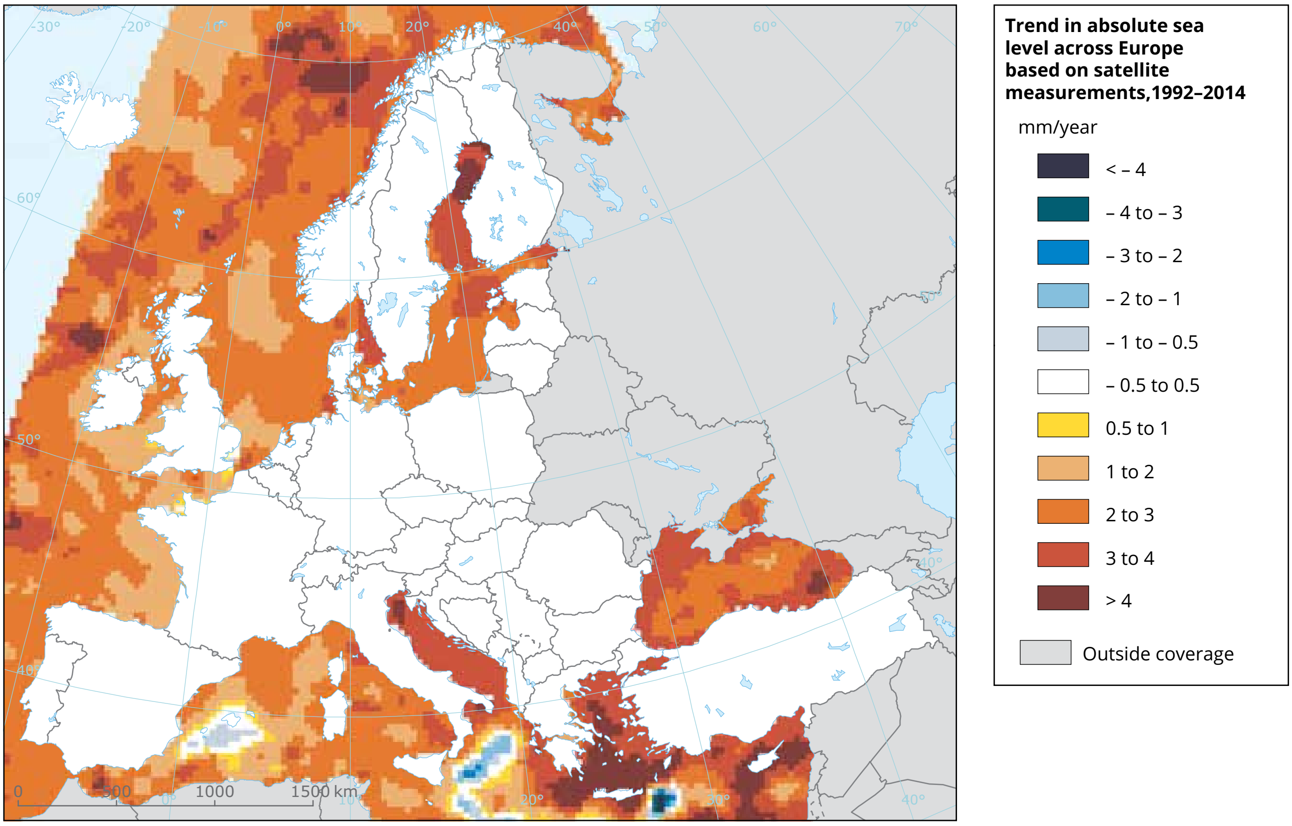
Past trends: mean sea level along the European coastline

Sea level measurements for the European region are available from satellite altimeter observations (Map 4.3) and from tide gauges (Map 4.4). Satellite observations, which show changes in absolute sea level, are available from 1993. Tide gauge records can be more than 100 years long; they show changes in relative sea level considering also land changes, which is more relevant for coastal protection than absolute sea level. Most European coastal regions experience increases in both absolute and relative sea level, but there are sizeable differences between the rates of absolute and relative sea level change across Europe.

Map 4.3 shows linear trends in absolute sea level from 1992 to 2014 as observed by satellites. The main differences between regional seas and basins are primarily the result of different physical processes being the dominant cause of sea level change at different locations. For instance, the Mediterranean Sea is a semi-closed, very deep basin, exchanging water with the Atlantic Ocean through only the narrow Gibraltar Strait. Salinity in the Mediterranean Sea may increase in the future and this will tend to offset rises in sea level due to thermal expansion from warming. The NAO, interannual wind variability, changes in ocean circulation patterns, and the location of large-scale gyres and small-scale eddies are further factors that can influence local sea level in the European seas. Obviously, sea level changes in coastal zones are most relevant for society.

Map 4.4 shows linear trends in relative sea level from 1970 to 2014 as observed by tide gauge stations in Europe. These trends can differ from those measured by satellites because of the longer time period covered and because tide gauge measurements are influenced by vertical land movement whereas satellite measurements are not. In particular, since the last ice age, the lands around the northern Baltic Sea have been, and are still, rising owing to the post-glacial rebound (Johansson et al., 2002).

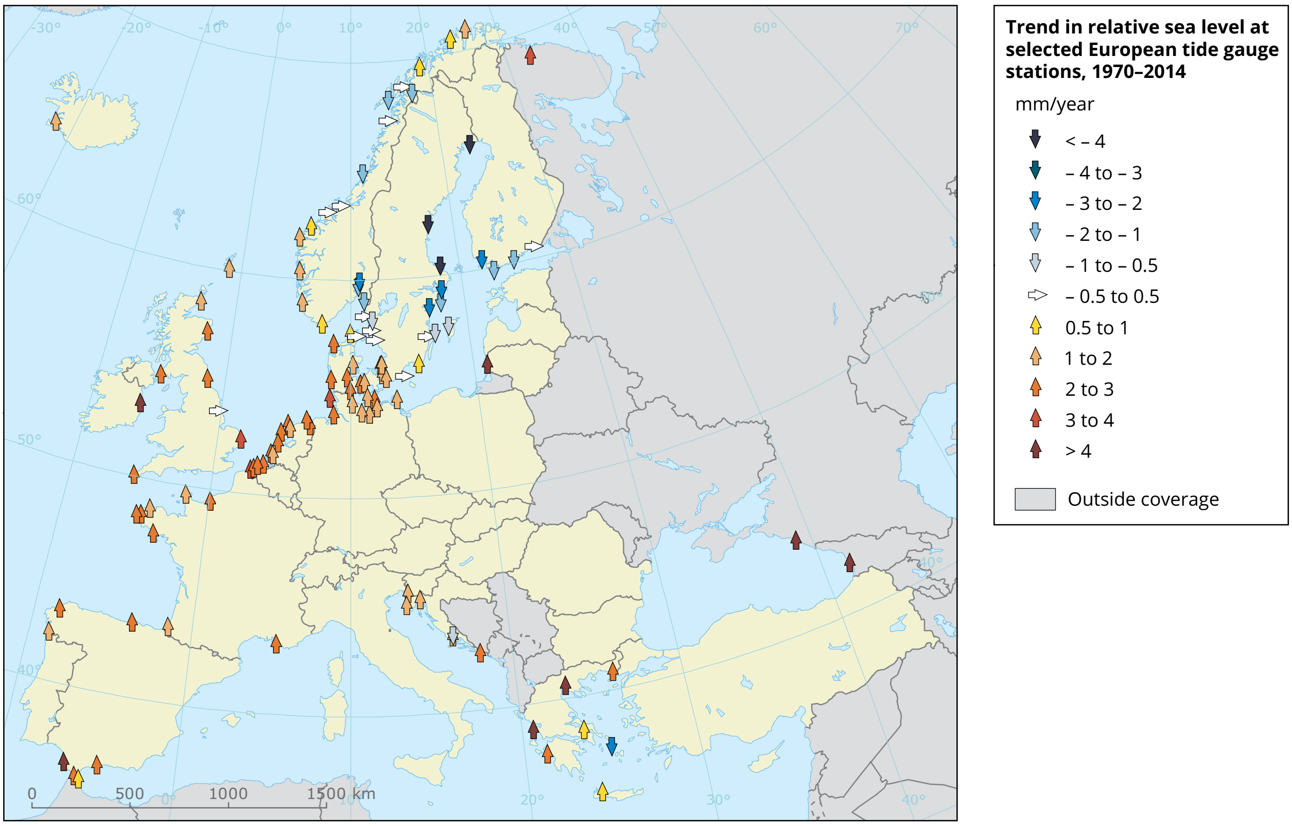
Map 4.3 Trend in absolute sea level across Europe based on satellite measurements



Note: The map shows the linear trend in sea level change over the period 1992–2014. Data uncertainty is higher along coastal zones than in areas further away from the coast. In some regions of the Mediterranean Sea, the depicted trends reflect long-term variability in gyres (i.e. rotating ocean currents) rather than the effects of climate change.

Source: Data supplied by CLS/CNES/LEGOS group (also available through CMEMS).

Map 4.4 Trend in relative sea level at selected European tide gauge stations



Note: These measured trends for 1970–2014 are not corrected for local land movement. No attempt has been made to assess the validity of any individual fit, so results should not be treated as suitable for use in planning or policymaking. Geographical coverage reflects the reporting of tide gauge measurements to the Permanent Service for Mean Sea Level (PSMSL).

Source: Holgate et al., 2012; PSMSL, 2016.

Past trends: extreme sea level along the European coastline

Producing a clear picture of either past changes or future projections of extreme high water levels for the entire European coastline is a challenging task because of the impact of local topographical features on surge events. While there are numerous studies for the North Sea coastline, fewer are available for the Mediterranean Sea and the Baltic Sea, although this situation is starting to improve.

Extreme sea levels show pronounced short- and long-term variability. A recent review of extreme sea level trends along European coasts concluded that long-term trends are mostly associated with the corresponding mean sea level changes. Changes in wave and storm surge climate mostly contribute to interannual and decadal variability, but do not show substantial long-term trends (Weisse et al., 2014). When the contribution from local mean sea level changes and variations in tide are removed from the recent trends, the remaining effects of changes in storminess on extreme sea level are much smaller or even no longer detectable (Menéndez and Woodworth, 2010; Hov et al., 2013; Weisse et al., 2014). Additional studies are available for some European coastal locations, but these typically focus on more limited spatial scales (Araújo and Pugh, 2008; Haigh et al., 2010; Marcos et al., 2011; Dangendorf et al., 2014). The only region where significant increases in storm surge height were found during the 20th century is the Estonian coast of the Baltic Sea (Suursaar et al., 2009).

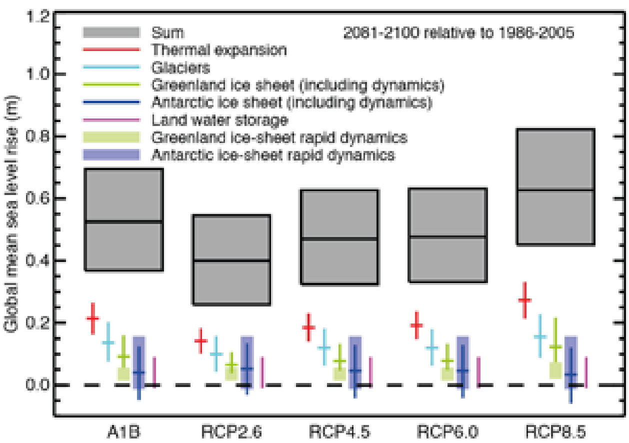
In conclusion, while there have been detectable changes in extreme water levels around the European coastline, most of these are the result of changes in local mean sea level. The contribution from changes in storminess is currently small in most European locations and there is little evidence that any trends can be separated from long-term natural variability.

Projections: global mean sea level

Currently, there are two main approaches to projecting future sea level. Process-based models represent the most important known physical processes explicitly, whereas empirical statistical models look at the relationship between temperature (or radiative forcing) and sea level that has been observed in the past and extrapolate it into the future. A significant recent step forwards in projecting future sea levels is the improved understanding of the contributing factors to recently observed sea level rise, which has increased confidence in the use of process-based models for projecting the future (Church et al., 2013).

The IPCC AR5 concludes that the rate of GMSL rise during the 21st century will very likely exceed the rate observed in the period 1971–2010 for all emissions scenarios. Process-based models estimate the rise in GMSL for the period 2081–2100, compared with 1986–2005, to be likely in the range of 0.26–0.54 m for RCP2.6, 0.32–0.62 m for RCP4.5, 0.33–0.62 m for RCP6.0 and 0.45–0.81 m for RCP8.5. For RCP8.5, the rise in GMSL by 2100 is projected to be in the range of 0.53–0.97 m, with a rate during 2081–2100 of 7–15 mm/year. Based on current understanding, only a collapse of marine-based sectors of the Antarctic Ice Sheet (i.e. those areas where the bed lies well below sea level and the edges flow into floating ice shelves) could cause GMSL to rise substantially (by up to several tenths of a metre) above the likely range projected for the 21st century, but the evidence is insufficient for estimating the likelihood of such a collapse (Figure 4.8). Projections of sea level rise from recent empirical statistical models calibrated with newly available sea level reconstructions align with those from current process-based models (Kopp et al., 2016; Mengel et al., 2016).

Figure 4.8 Projections of global mean sea level rise and its contributing factors



Note: This figure shows projections for global mean sea level rise and its contributing factors in 2081–2100 relative to 1986–2005 from process-based models for the four RCPs and the emissions scenario SRES A1B used in the IPCC AR4. The grey boxes show the median of the model projections (central bar) and the likely range, which comprises two-thirds of the model projections. The coloured bars and boxes show estimates for the different contributions to global mean sea level rise. For further information, see the source document.

Source: Church et al., 2013 (Figure 13.10). @ 2013 Intergovernmental Panel on Climate Change. Reproduced with permission.

Some recent studies highlight the contributions to recent sea level rise from ice sheet melting that were not included in the process-based models underlying the AR5 estimates above (e.g. Khan et al., 2014; DeConto and Pollard, 2016; Fürst et al., 2016; Hansen et al., 2016) (see also Section 3.3.3). A broad expert assessment of future sea level rise resulted in higher estimates than those from the process-based models reviewed in the AR5. The best expert estimates for sea level rise during the 21st century were 0.4–0.6 m for the low forcing scenario (RCP2.6) and 0.7–1.2 m for the high forcing scenario (RCP8.5) (Horton et al., 2014). Similar results were derived in other recent studies (Kopp et al., 2014; Johansson et al., 2014). A study that combined the model-based assessments from the AR5 with updated models and probabilistic expert assessment of the sea level contributions from the Greenland and Antarctic ice sheets suggests an upper limit for GMSL rise during the 21st century of 180 cm, which has a 5 % probability of being exceeded under the RCP8.5 forcing scenario (Jevrejeva, Grinsted et al., 2014). Various national reports have also used values in the range of 1.5–2.0 m as upper estimates for GMSL rise during the 21st century. One recent study suggests that ice sheet melting in Antarctica and Greenland could occur much faster than previously assumed, which would result in sea level rise of several metres during the 21st century (Hansen et al., 2016), but these findings have been controversial. These high-end scenarios are somewhat speculative, but their consideration is nevertheless important for long-term coastal risk management, in particular in densely populated coastal zones (Hinkel et al., 2015).

Sea level rise will continue far beyond 2100. Based on a limited number of available simulations with process-based models, the AR5 suggests that the GMSL rise by 2300 will be less than 1 m for greenhouse gas concentrations that do not exceed 500 ppm CO_2-equivalent, but will be in the range of 1 m to more than 3 m for concentrations above 700 ppm CO_2-equivalent. However, the AR5 also considered it likely that the underlying models systematically underestimate Antarctica's future contribution to sea level rise (Jevrejeva et al., 2012; Schaeffer et al., 2012; Church et al., 2013). Estimates for GMSL rise beyond

2100 from the above-mentioned expert assessment are broadly comparable (Horton et al., 2014; Kopp et al., 2014). A more recent study suggests that melting of the Antarctic ice sheet alone could lead to sea level rise of more than 15 m by 2500 under a high emissions scenario (DeConto and Pollard, 2016).

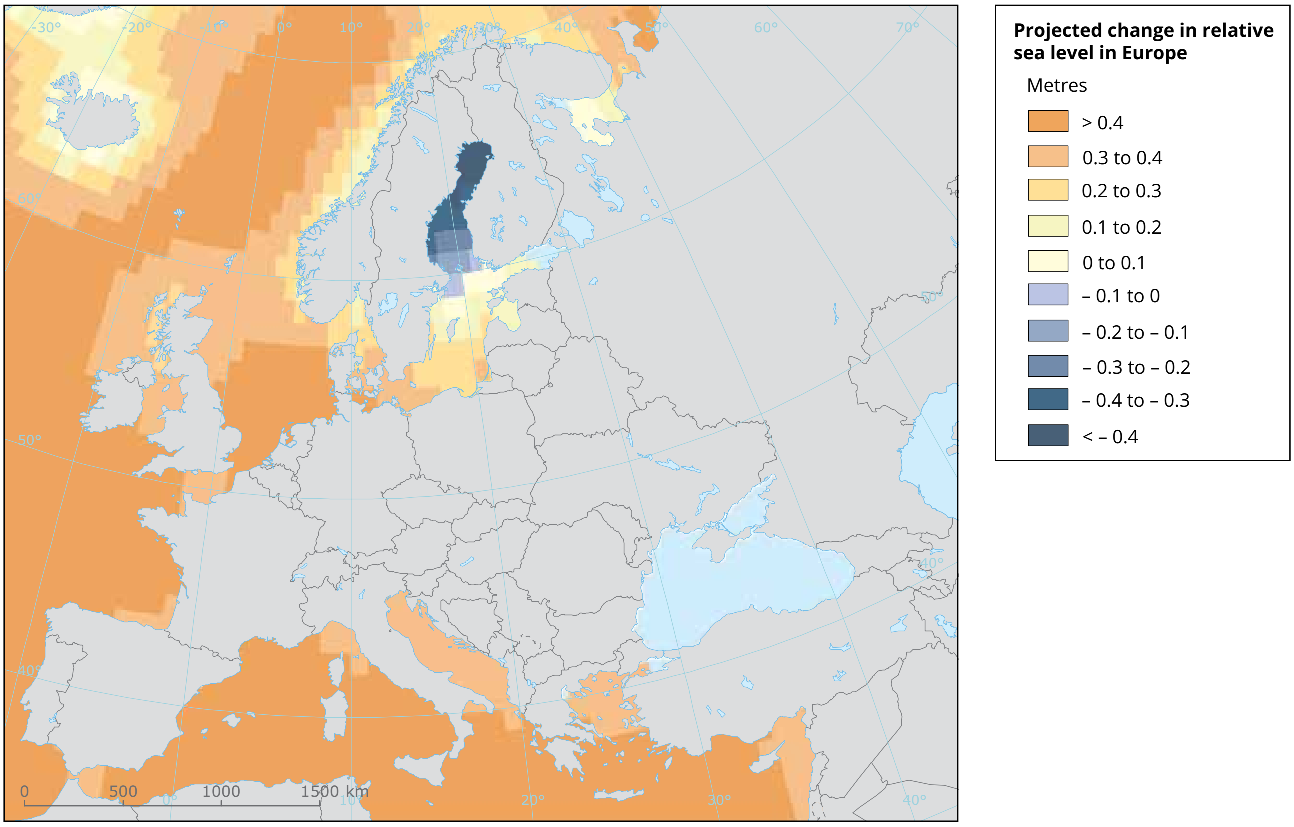
On a multi-millennial time scale, projections based on process-based models suggest a quasi-linear GMSL rise of 1–3 m per degree of global warming for sustained warming over a period of 2 000 years. Significantly higher estimates for GMSL rise on multi-millennial time scales, of up to 50 m over 10 000 years for a high emissions scenario, have been derived from the geological record (Church et al., 2013; Foster and Rohling, 2013; Levermann et al., 2013; Clark et al., 2016; DeConto and Pollard, 2016; Hansen et al., 2016).

Projections: mean sea level along the European coastline

Regional and local sea levels differ from the global mean owing to large-scale factors such as non-uniform changes in ocean density and changes in ocean circulation. Furthermore, disintegrating land-ice affects sea level differentially because of gravitational effects and the viscoelastic response of the lithosphere (Konrad et al., 2013). Sea level is also affected by changes in atmospheric loading (the 'inverse barometer' effect) and vertical land movement. While there remains considerable uncertainty in the spatial patterns of future sea level rise, around 70 % of the world's coastlines are expected to experience a local mean sea level change within ± 20 % of the projected GMSL change (Church et al., 2013).

Relative sea level change along most of the European coastline is projected to be reasonably similar to the global average. The main exceptions are the northern Baltic Sea and the northern Atlantic coast, which are experiencing considerable land rise as a consequence of post-glacial rebound. As a result, sea level relative to land in these regions is rising slower than elsewhere or may even decrease (Map 4.5) (Church et al., 2013;

Map 4.5 Projected change in relative sea level in Europe



Note: This map shows projected change in relative sea level in the period 2081–2100 compared with 1986–2005 for the medium-to-low emissions scenario RCP4.5 based on an ensemble of CMIP5 climate models. Projections consider gravitational fingerprinting and land movement due to glacial isostatic adjustment, but not land subsidence as a result of human activities. No projections are available for the Black Sea.

Source: Adapted from IPCC, 2013 (Figure TS.23 (b)). Data were supplied by Mark Carson (ZMAW, Germany).

HELCOM, 2013; Slangen, Carson et al., 2014; Johansson et al., 2014). A probabilistic assessment of regional sea-level rise in northern Europe reported central estimates of relative sea level change during the 21st century for the RCP8.5 emissions scenario from – 14 cm (in Luleå, northern Sweden) to 84 cm in Den Helders (Netherlands); high estimates (with a 5 % probability to be exceeded) range from 52 cm to 181 cm, respectively (Johansson et al., 2014).

A recent review study estimated that 21st century sea level rise along the Dutch coast would be in the range of 25 to 75 cm for a low warming scenario and 50 to 100 cm for a high warming scenario (year 2100, compared with the 1986–2005 baseline period) (KNMI, 2014). Making regional projections for relatively small isolated and semi-closed ocean basins, such as the Mediterranean or the Baltic, is even more difficult than for the open ocean.

Sea level rise substantially increases the risk of coastal flooding, which affects people, communities and infrastructure. For example, the ClimateCost and PESETA II projects have estimated that a 30 cm sea level rise by the end of the 21st century, in the absence of public adaptation, would more than triple annual damages from coastal floods in the EU from EUR 5 to 17 billion (Brown et al., 2011; Ciscar et al., 2014). These potential impacts can be substantially reduced by timely adaptation measures, but they are associated with significant costs (Mokrech et al., 2014). For further information, see Sections 5.1, 5.2 and 6.2.

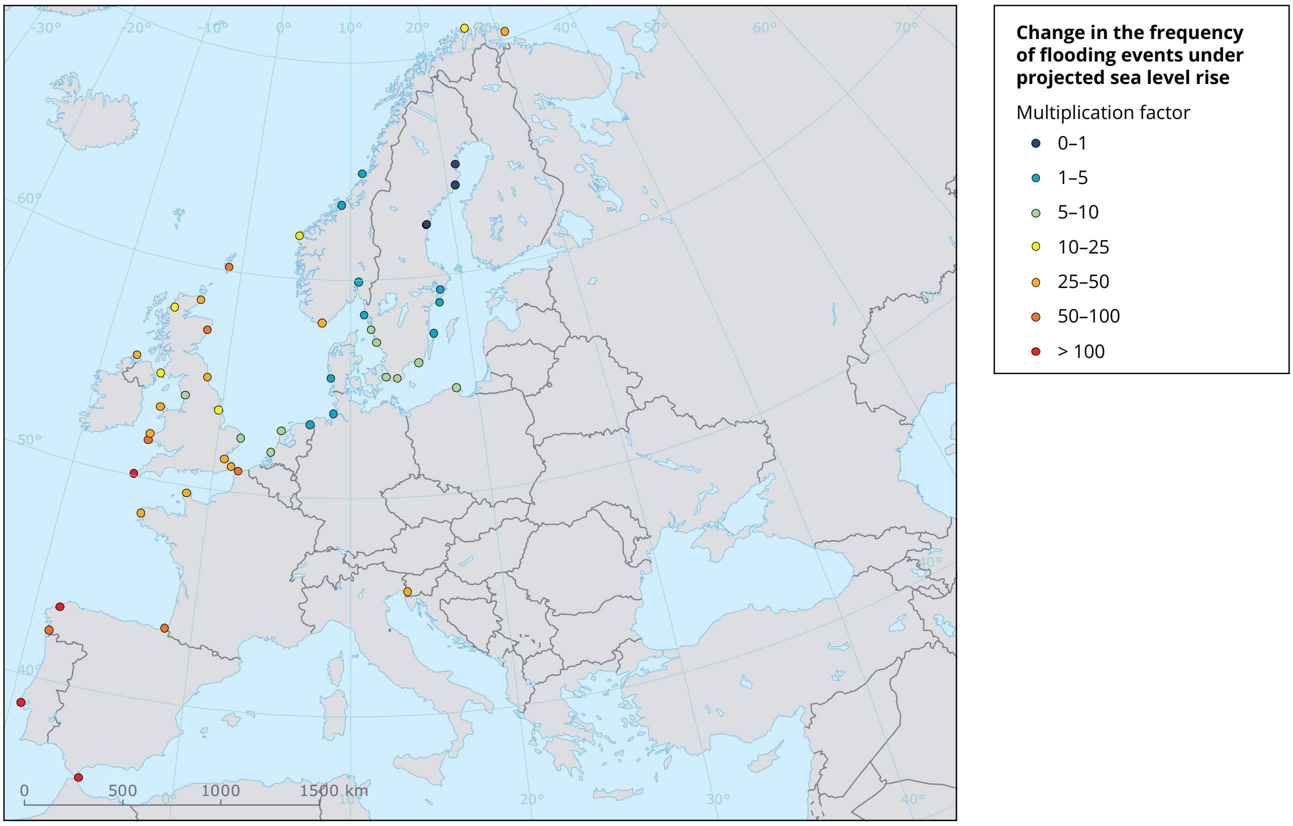
Projections: extreme sea level at the European coastline

Future projections of extreme sea level can be made using either process-based (dynamic) or empirical statistical modelling of storm surge behaviour driven by the output of global climate models (Lowe et al., 2010). Uncertainty in these projections for Europe remains high and is ultimately linked to the uncertainty in future mid-latitude storminess changes. This is an area where current scientific understanding is advancing quickly, as climate model representations of aspects of northern hemisphere storm track behaviour are showing improvements associated with, for instance, greater ocean and atmosphere resolution. However, the newest global climate models have not yet, typically, been downscaled to suitably fine scales and used in studies of future storm surges (Hov et al., 2013; Scaife et al., 2014).

It has generally been expected that projected increases in extreme sea level along the European coast during the upcoming decades will mostly be the result of mean sea level changes rather than changes in wave and storm surge climate (Weisse et al., 2014). However, several recent studies suggest that changes in wave and storm surge climate may also play a substantial role in sea level changes during the 21st century in some regions. One recent study based on a multi-model ensemble projects an increase in storm surge level for most scenarios and return periods along the northern European coastline, which is more prominent for RCP8.5 than for RCP4.5, and which can exceed 30 % of the relative sea level rise. Storm surge levels along most European coastal areas south of 50 °N showed small changes (Vousdoukas et al., 2016). Similar results were obtained by another study, which found that increases in storm surges can contribute significantly to the projected increases of the 50-year flood height in north-western Europe, particularly along the European mainland coast (Howard et al., 2014). Sea level rise may also change extreme water levels by altering the tidal range. Tidal behaviour is particularly responsive in resonant areas of the Bristol Channel and the Gulf of Saint-Malo (with large amplitude decreases) and in the south-eastern German Bight and Dutch Wadden Sea (with large amplitude increases) (Pickering et al., 2012).

The frequency of flooding events is estimated to increase by more than a factor of 10 in many European locations, and by a factor of more than 100 in some locations (Map 4.6) for the RCP4.5 scenario (Hunter, 2012; Church et al., 2013; Hunter et al., 2013). Large changes in flood frequency mean that what is an extreme event today may become the norm by the end of the century in some locations (see Box 4.4, for an example from Denmark). A 10 cm rise in sea level typically causes an increase by about a factor of three in the frequency of flooding to a given height. However, for any particular location, it is important to look in detail at the change in the height of flood defences that might be required. Where the flood frequency curve is very flat, modest increases in flood defences be sufficient. Where the flood frequency curve is steeper, larger increases in protection height or alternative adaptation, including managed retreat, might be needed.

Map 4.6 **Projected change in the frequency of flooding events in Europe**



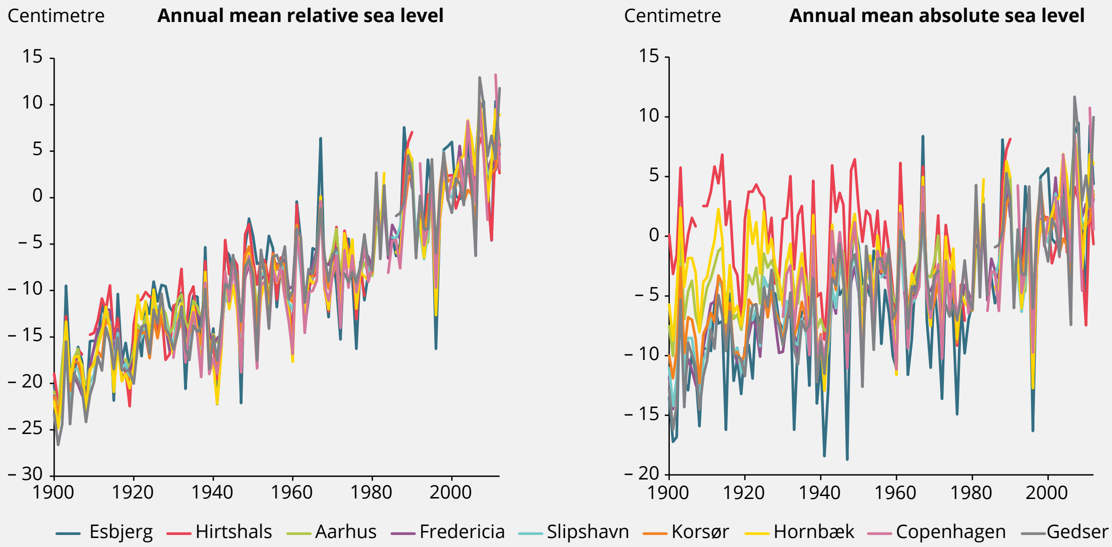
Note: This map shows the multiplication factor (shown at tide gauge locations by coloured dots) by which the frequency of flooding events of a given height is projected to increase between 2010 and 2100 as a result of regional relative sea level rise under the RCP4.5 scenario. Values larger than 1 depict an increase; values smaller than 1 depict a decrease. The decreases occurring in the northern parts of the Baltic Sea are caused by glacial isostatic adjustment.

Source: Adapted from Church et al., 2013 (Figure 13.25b).

Box 4.4 Sea level variability and storm surges in Denmark: past and future

Local sea level measured by tide gauges is influenced by GMSL rise due to anthropogenic warming, by vertical land movement (which can have natural and anthropogenic causes) and by natural variations at different time scales ranging from daily to annual and decadal. Figure 4.9 (left) illustrates the complex pattern of interannual variability and long-term trends by showing the observed annual mean relative sea level at nine Danish tide gauges, all within a distance of less than 400 km of each other. The increasing spread of the curves in the earlier decades, relative to the later, reference, period 1986–2005 is caused primarily by differences in vertical land movement across the various sites. In contrast, Figure 4.9 (right) shows the absolute sea level at the same sites, which is calculated by removing the effect of land changes. Following this correction, the overall trend of about 1.9 ± 0.3 mm/year is clearly distinguishable from the interannual variability. Furthermore, both the trend and the variability are generally coherent within the region. However, the interannual variability of sea level at local and regional scales is so large that trends calculated over short time periods (i.e. a few decades) are associated with large uncertainty.

Figure 4.9 Observed trend in absolute and relative sea level from nine Danish tide gauges with more than 100 years of data



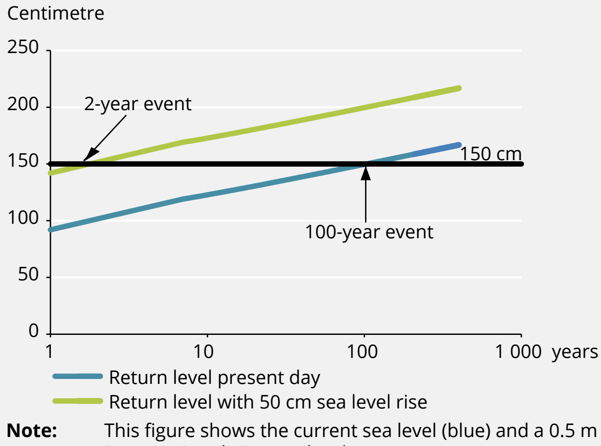
Note: Sea level is shown as anomaly (in cm) relative to the reference period 1986–2005.

Source: Hansen, 2013; Madsen and Schmith, 2014.

Various analyses have shown that the Danish coast will be significantly more exposed to storm surges in the future as a result of the projected sea level rise (Hallegatte et al., 2011; Madsen and Schmith, 2014; Olesen et al., 2014). Adaptation is needed to protect communities and infrastructure against these impacts.

The largest changes in storm surge levels are projected along coasts already exposed to storm surges, where a given increase in absolute sea level and/or in storminess will have the largest effect. Even relatively protected coastlines may require attention if, when implementing the coastal protection, small natural variability was assumed. In this situation, therefore, small changes in mean sea level would lead to large increases in storm surge frequencies. Figure 4.10 shows in a concrete example how a 'moderate' rise in average sea level can strongly increase the risk of storm surges in Copenhagen. A storm surge of 1.5 m that is presently a 100-year event in Copenhagen would occur every second year following a relative sea level rise of 0.5 m.

Figure 4.10 Storm surge levels and return periods for Copenhagen under current and increased sea level



Note: This figure shows the current sea level (blue) and a 0.5 m increase in relative sea level (green).

Source: Madsen and Schmith, 2014; adapted from Sørensen et al., 2013.

4.3 Freshwater systems

Key messages

- In general, river flows in Europe have increased in winter and decreased in summer since the 1960s, but with substantial regional and seasonal variation. Climate change is an important factor in these observed changes, but other factors, such as river engineering, also have a strong influence.
- The number of very severe flood events in Europe have increased since 1980, but with large interannual variability. It is not currently possible to quantify the contribution of increased heavy precipitation in parts of Europe compared to better reporting and land-use changes.
- The severity and frequency of droughts appear to have increased in parts of Europe, in particular in southern and south-eastern Europe. Meteorological and hydrological droughts are projected to increase in frequency, duration, and severity in most of Europe, with the strongest increase projected for southern Europe.
- Climate change has increased the water temperature of rivers and lakes, and has shortened seasonal ice cover.
- Changes in river flows and water temperature have important impacts on water quality and on freshwater ecosystems.

4.3.1 Overview

Water is essential to life and is an indispensable resource for ecosystems and their services (see Section 4.5) and for nearly all human activities. It is intricately linked with climate, such that any alteration in the climate system will induce changes in the hydrological cycle. Consequently, the spatial and temporal distribution of freshwater resources and the socio-economic activities that are dependent upon water are affected by climate variability and climate change.

There is growing evidence that climatic changes in recent decades have already affected the global hydrological cycle, for example through changes in seasonal river flows (i.e. the rate of water flow, also known as river discharge) and increasing severity and frequency of both river floods and droughts in some regions. However, the detection of significant long-term trends in hydrological variables is generally difficult owing to substantial interannual and decadal variability. Furthermore, the attribution of observed changes is complicated because of modifications to natural water flows arising from morphological changes, water abstractions and land-use change.

Policy context

The Water Framework Directive (EC, 2000) does not mention climate change or adaptation directly. However, climate change pressures are exacerbated by human and economic activities, and climate change poses an additional threat to the flow regime of water ecosystems (EEA, 2012a).

The shifts in the extremes, rather than the trends in the averages, are likely to be the biggest challenge for adaptation (EEA, 2012c; IPCC, 2012) and are also likely to be the drivers of increasing cost for adapting infrastructure (OECD, 2013). The strategies for disaster risk management developed within the context of climate change requires measures that are specific to local circumstances, including sustainable land management and spatial planning (IPCC, 2012). The river basin approach avoids passing on negative consequences further downstream, and for international river basin districts it has to be ensured that relevant information is exchanged and that plans are coordinated across countries. The Floods Directive (EC, 2007b) and the Communication on water scarcity and droughts (EC, 2007a) specifically target water quantity extremes.

As almost all elements that define the status of water bodies are sensitive to climate change, the European Commission (EC, 2012) recommends a planning horizon that includes a scenario for climate change and socio-economic developments looking further into the future than the implementation of the next six-year cycle of the Water Framework Directive and of the Floods Directive. It is also seen as useful to integrate additional pressures, impacts and constraints caused by climate change in the economic analysis for the Water Framework Directive. The Water Blueprint Communication (EC, 2012) reviewed the most important water policy processes in the light of resource efficiency, including the part of Europe's climate change vulnerability and adaptation policy related to water (EEA, 2012b).

In the Blueprint, climate change as well as land use and economic activities are depicted as the main causes of negative impacts on Europe's water status. Adapting to climate change and developing resilience to disasters are presented as key activities for sustainable water management and for achieving good qualitative and quantitative status for water bodies in Europe and worldwide.

Indicator selection

The subsequent sections present information on the following indicators:

- *River flows:* this indicator monitors the changes in average river flows, which are important for the overall water availability to households, industry and agriculture.
- *River floods:* this indicator monitors changes in river floods, which are among the most costly weather and climate-related disasters in Europe.
- *Meteorological and hydrological droughts:* this indicator monitors droughts, in terms of both precipitation deficiencies and changes in low river flows, which can have significant negative impacts on households, industry, navigation, agriculture and ecosystems.
- *Water temperature of rivers and lakes:* this indicator monitors water temperature, which is one of the central parameters that determine the overall health of aquatic ecosystems, because aquatic organisms have a specific range of temperatures that they can tolerate.

The concluding section (Section 4.3.6) presents selected information on the impacts of past and projected changes in these indicators for *freshwater ecosystems and water quality*. This information is not presented in the indicator format because the impacts foreseen for different aquatic species and ecosystems are so diverse that relevant information cannot be conveyed in one indicator.

Further information on the economic impacts and effects on human health of extreme events, including floods and droughts, is presented in Sections 5.1 and 5.2, respectively.

Data quality and data needs

The data required for the indicators in this sector are time series of precipitation (for meteorological droughts), river flows (for average flows), extreme high and low flows (for floods and droughts, respectively), and river and lake temperatures (for water quality). These time series can be observed or simulated for historical time periods and can be projected for future time windows, taking into account climate change and potentially also other drivers of change, such as land-use changes.

River flow and water level data are influenced by rainfall run-off and by hydromorphological changes of the river bed, e.g. through river engineering. Furthermore, homogeneous time series are generally shorter than those for meteorological data. Therefore, substantially more time may be required before statistically significant changes in hydrological variables can be observed, especially with respect to extreme and exceptional events (floods and droughts). Notwithstanding recent improvements of climate models to simulate large-scale patterns of precipitation and extreme events, projections of changes in precipitation and high extremes remain uncertain, especially at catchment and local scales. Projections of river floods are plagued by the highest levels of uncertainty, as they often depend on changes in single extreme events, whereas changes in average and low-flow conditions depend on changes in precipitation on longer time scales (i.e. monthly to seasonal), which are more robust.

The main data sources for Europe-wide studies of the impacts of extreme hydrological events and their changes are global databases for natural disasters (see Section 5.1). Recently, the EEA has compiled a European Flood Impact Database ([49]) that combines information on past floods with significant observed impacts from global sources with the reporting by EU Member States for the Preliminary Flood Risk Assessment (PFRA) (EC, 2007b). This database has been collecting information on flood hazards and their impacts since 1980. At the European level, these inventories could assist in tracking the trends in flood disaster losses and in mitigation programmes, for both monitoring and obtaining a clearer picture of the linkages between climate change, floods and losses from flooding. Also at the European level, guidance for recording and sharing disaster damage and loss data is under development for Europe (De Groeve et al., 2014; JRC, 2015), coherent with the Sendai Framework for Disaster Risk Reduction (UN, 2015a, 2015b).

Reliable information on the extent and impacts of water scarcity and droughts is indispensable for decision-making at all levels. An overview of water

([49]) http://www.eea.europa.eu/data-and-maps/data/european-past-floods.

availability, water abstraction and water scarcity in Europe and more specifically for the Alpine region is discussed in several EEA reports (EEA, 2009, 2012c). The water exploitation index is currently being revised to be calculated on the level of river basins instead of the administrative boundaries of countries ([50]). The Joint Research Centre (JRC) of the European Commission has developed a European Drought Observatory (EDO) ([51]) for drought forecasting, assessment and monitoring. However, despite several activities, there is no systematic, comprehensive record of water scarcity and drought events in Europe, describing their duration, impact and severity, other than meteorological time series for precipitation.

([50]) http://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources/ds_resolveuid/9EKW4KDTGF.
([51]) http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000.

4.3.2 River flows

Key messages

- Available studies suggest that run-off in near-natural rivers during the period 1963–2000 increased in western and northern Europe, in particular in winter, and decreased in southern and parts of eastern Europe, in particular in summer. However, comprehensive observation data on river flows are not available across Europe.
- Long-term trends in river flows due to climate change are difficult to detect because of substantial interannual and decadal variability, as well as modifications to natural water flows arising from water abstractions, morphological changes (such as man-made reservoirs) and land-use changes.
- Climate change is projected to result in significant changes in the seasonality of river flows across Europe. Summer flows are projected to decrease in most of Europe, including in regions where annual flows are projected to increase. Where precipitation shifts from snow to rain, spring and summer peak flow will shift to earlier in the season.

Relevance

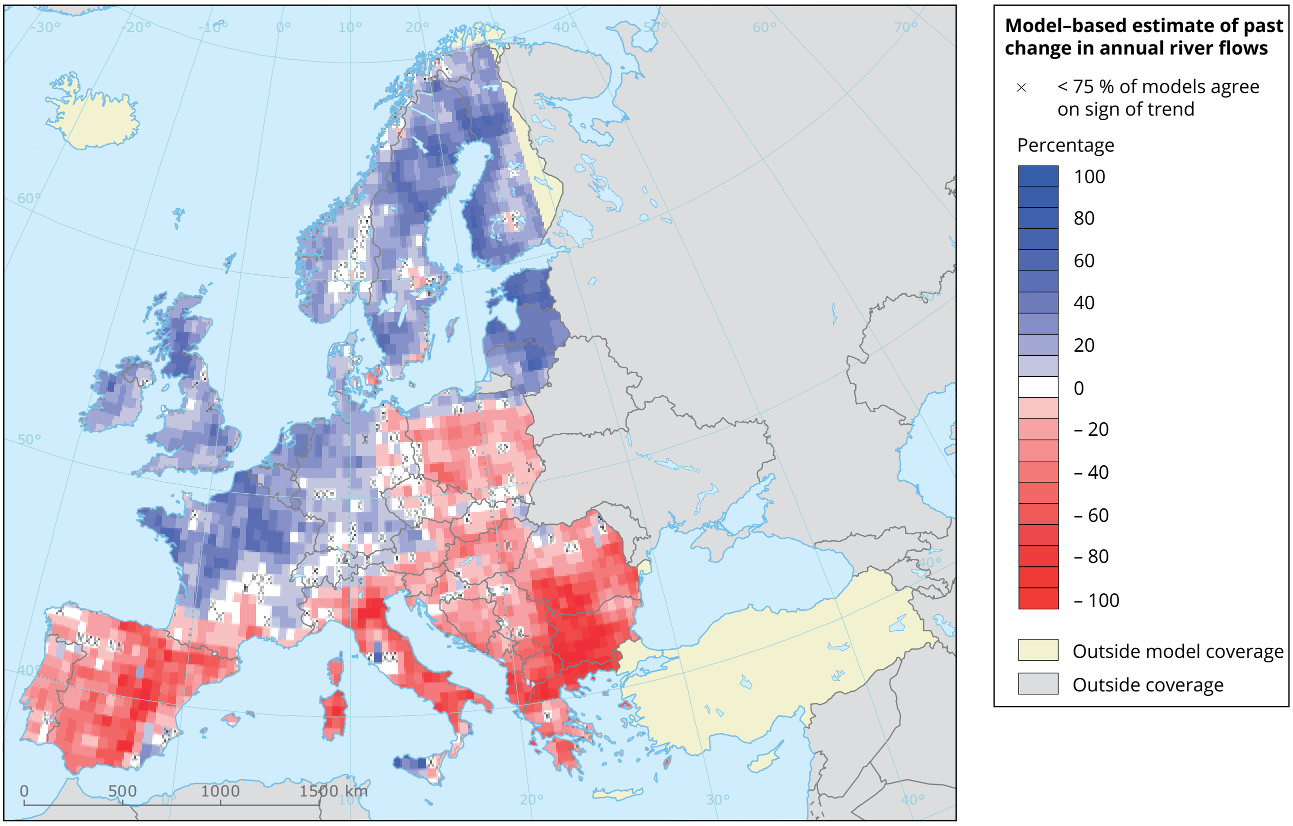
Annual average river flows are one of the elements that affect freshwater availability in a river basin, in addition to groundwater sources, lakes or artificial water storage facilities. Variations in river flows are determined mainly by the seasonality of precipitation and temperature, as well as by catchment characteristics such as geology, soil and land cover. Changes in temperature and precipitation patterns due to climate change modify the annual water budget of river basins and the timing and seasonality of river flows. The consequent changes in water availability may adversely affect ecosystems and several socio-economic sectors, including abstraction for drinking water, agriculture, industry, energy production and navigation. Extreme dry periods with low river flow events can have considerable economic, societal and environmental impacts (see Section 4.3.4).

Past trends

Human interventions in catchments, including water abstractions, river regulation and land-use change, have considerably altered river flow regimes in large parts of Europe, making it difficult to discern any climate-driven changes in river flow data. An inventory of river flows in Europe was produced by combining over 400 time series (from 1962 to 2004) of river catchments with near-natural flow conditions for Europe and an ensemble of eight large-scale hydrological models (for 1963–2000) (Stahl et al., 2012). According to this inventory, run-off showed positive trends in western and northern Europe and negative trends in southern and parts of eastern Europe (Map 4.7). The European pattern of annual run-off trends modelled by the ensemble mean shows a regionally coherent picture. The areas where models disagreed on the trend direction were largely located in areas of weak trends, notably in the transition areas between regions with consistent negative and positive trends. The pattern of changes in regional high flows is very similar to the pattern of changes in annual flows, whereas summer low flows have also decreased in various regions where annual flows have increased. Overall, positive trends in annual stream flow appear to reflect the marked wetting trends of the winter months, whereas negative annual trends result primarily from a widespread decrease in stream flow in spring and summer months, consistent with a decrease in summer low flow in large parts of Europe. The model uncertainties were largest in complex terrain with high spatial variability and in snow-dominated regimes.

The magnitude of the observed seasonal changes clearly raises concerns for water resource management both today and in future decades. To date, however, despite the evidence of changes in the seasonality of flows, there is no conclusive evidence that low river flows have generally become more severe or frequent in Europe during recent decades (Stahl et al., 2010, 2012). Whereas many studies detect significant hydrological changes in observed datasets, more scientific rigour is needed in the attribution of river flow changes, as these studies often fall short in proving and quantifying the relationship between these changes and potential drivers (Merz et al., 2012).

Map 4.7 Model-based estimate of past change in annual river flows



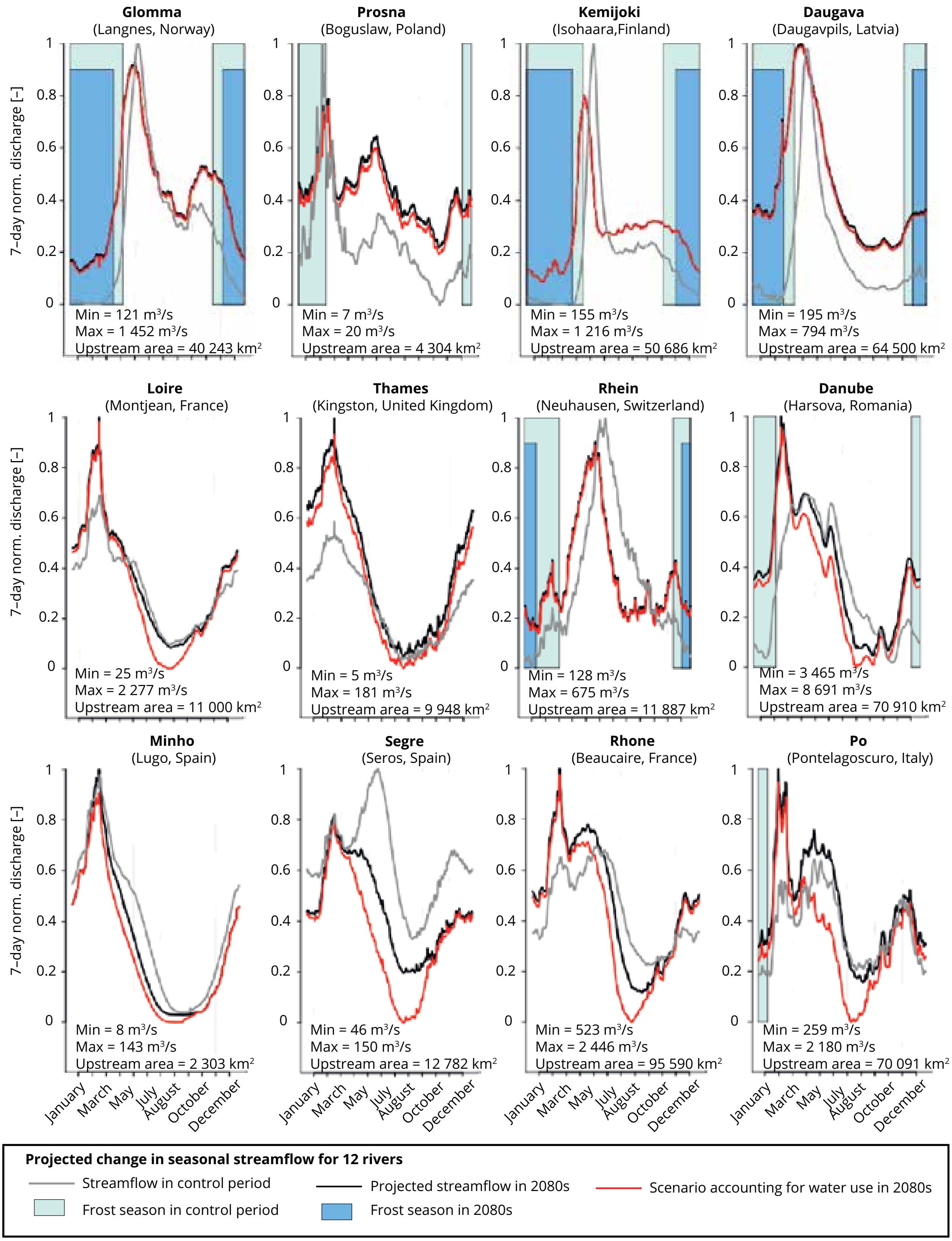
Note: This map shows the ensemble mean trend in annual run-off from 1963 to 2000. 'x' denotes grid cells where less than three-quarters of the hydrological models agree on the direction of the trend.

Source: Adapted from Stahl et al., 2012.

Projections

Annual river flows are projected to decrease in southern and south-eastern Europe and increase in northern and north-eastern Europe (Rojas et al., 2012; Alfieri, Burek et al., 2015). Changes are projected in the seasonality of river flows, with large differences across Europe. For most parts of Europe, the peak of the average daily flow at the end of the 21st century is projected to occur earlier in the year than currently (van Vliet et al., 2013; Forzieri et al., 2014). In snow-dominated regions, such as the Alps, Scandinavia and parts of the Baltic, the reduction in winter retention as snow, earlier snowmelt and, in some cases, reduced summer precipitation are projected to lead to increases in river flows in winter and reductions in summer (Alfieri, Burek et al., 2015). Reductions of flow can be exacerbated by water abstractions, especially in summer when consumption is highest and input is typically low. These changes result in a further decrease of water availability in summer (see Figure 4.11) (Forzieri et al., 2014).

Figure 4.11 Projected change in seasonal streamflow for 12 rivers



Note: This figure shows simulated seven-day average river flows at 12 European river monitoring stations in the control period (light-grey lines) and the 2080s (black lines). The red lines reflect a future river flow scenario accounting for projected changes in water use. Blue shaded areas indicate the frost season in both periods (control as light blue, 2080s as dark blue).

Source: Adapted from Forzieri et al., 2014. Reproduced with permission.

4.3.3 River floods

Key messages

- Almost 1 500 floods have been reported for Europe since 1980, of which more than half have occurred since 2000.
- The number of very severe flood events in Europe increased over the period 1980–2010, but with large interannual variability. This increase has been attributed to better reporting, land-use changes and increased heavy precipitation in parts of Europe, but it is not currently possible to quantify the importance of these factors.
- Global warming is projected to intensify the hydrological cycle and increase the occurrence and frequency of flood events in large parts of Europe.
- Pluvial floods and flash floods, which are triggered by intense local precipitation events, are likely to become more frequent throughout Europe. In regions with projected reduced snow accumulation during winter, the risk of early spring flooding could decrease. However, quantitative projections of changes in flood frequency and magnitude remain highly uncertain.

Relevance

There are many different types of floods. They can be distinguished based on the source of flooding (e.g. rivers and lakes, urban storm water and combined sewage overflow, or seawater), the mechanism of flooding (e.g. natural exceedance, defence or infrastructural failure, or blockage) and other characteristics (e.g. flash flooding, snowmelt flood, or debris flows) (EC, 2013).

River floods are a common natural disaster in Europe, and — along with storms — are the most important natural hazard in Europe in terms of economic damage. They are mainly caused by prolonged or heavy precipitation events and/or snowmelt. River floods can result in huge economic losses as a result of damage to infrastructure, property and agricultural land, and indirect losses in or beyond the flooded areas, such as production losses caused by damaged transport or energy infrastructure. They can also lead to loss of life, especially in the case of flash floods, and displacement of people, and can have adverse effects on human health, the environment and cultural heritage.

Large areas throughout Europe have been affected by flooding since 2000, many of them even multiple times (e.g. Chorynski et al., 2012; EEA, 2016a). According to the NatCatSERVICE database ([52]), almost 1 500 flood and wet mass movement events happened in EEA member countries ([53]) in the period 1980–2013, with more than half of them since 2000. These floods have resulted in over 4 700 fatalities and caused direct economic losses of more than EUR 150 billion (based on 2013 values), which is almost one-third of the damage caused by all natural hazards. Less than a quarter of these damages were insured. Information about economic damages from floods is presented in Sections 5.1 and 6.3; their impacts on human health are discussed in Section 5.2.

Despite the general agreement that Europe-wide or at least transnational-scale flood hazard maps have the potential for many applications, including climate change studies, only a few products exist, and it remains difficult to compile large consistent datasets (Alfieri et al., 2014). The EU Floods Directive (EC, 2007b) has improved this situation only to a limited extent so far (EEA, 2016a).

Past trends

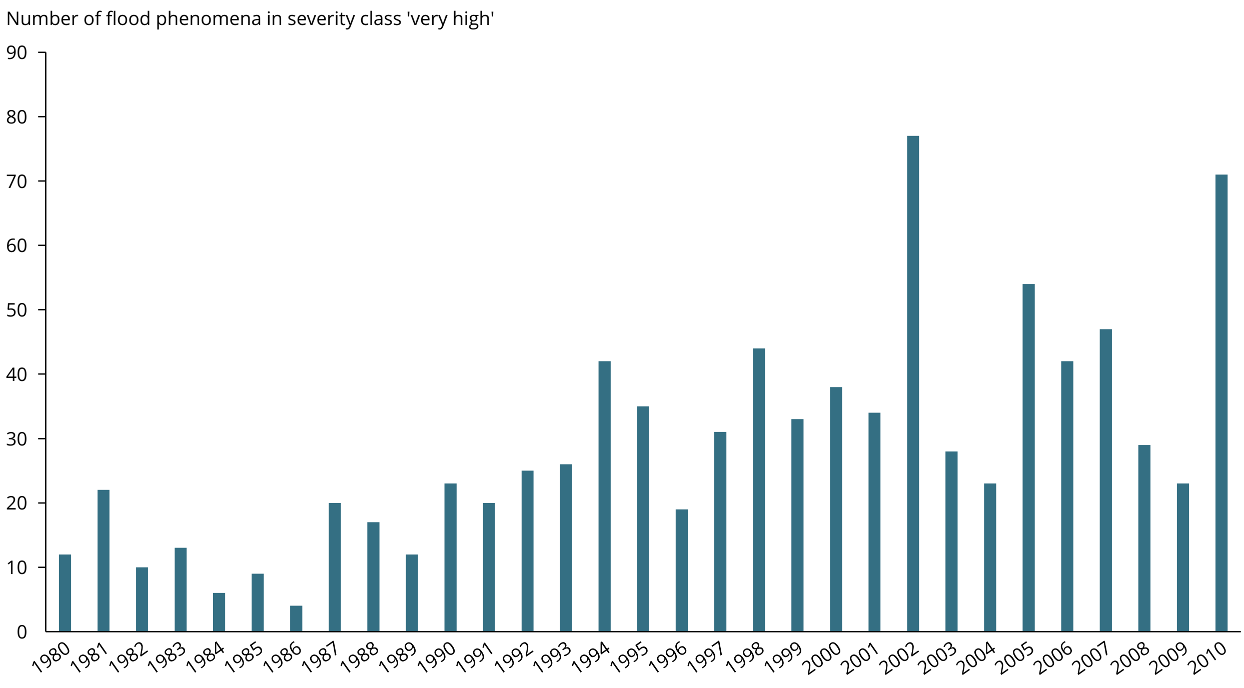
Figure 4.12 shows that the number of very severe flood events in Europe increased over the period 1980–2010, but with large interannual variability. The underlying data is obtained from a combination of information available in global databases such as the Dartmouth Flood Observatory ([54]) and the Emergency Events Database (EM-DAT) of the Centre for Research on the

([52]) NatCatSERVICE (http://www.munichre.com/natcatservice) is one of the most comprehensive natural catastrophe loss databases, managed by Munich Reinsurance Company (Munich RE), based in Munich, Germany. As a proprietary database, it is not publicly accessible. The entire Munich RE dataset, which was provided to the EEA under institutional agreement (June 2014), consists of 4 918 records and covers the period 1980–2013.
([53]) http://www.eea.europa.eu/about-us/countries-and-eionet.
([54]) http://floodobservatory.colorado.edu.

Epidemiology of Disasters (CRED) ([55]), data reported by EU Member States under the EU Floods Directive and an additional country consultation in all EEA member and cooperating countries (ETC/ICM, 2015). Less extreme events or events with small spatial extent are not included, but the combination of data sources still leads to a large improvement over an overview based on global data sources only. Furthermore, selection of 'larger' floods only (here with severity class 'very high') is expected to reduce the reporting bias (Kundzewicz et al., 2013). For comparison, the NatCatSERVICE database in total contains more than 1 200 flood events that have happened since 1990, which, on average, is over 50 per year.

Losses from flooding in Europe have increased substantially since the 1970s (Barredo, 2009). In recent years, some flood events have been so much stronger than previous events that they have led to significant changes in flood risk estimation methods for that region, e.g. in the United Kingdom (Miller et al., 2013; Schaller et al., 2016). The trend for increasing losses from river floods is primarily attributable to socio-economic factors, such as increasing wealth located in flood zones, but increases in heavy precipitation in parts of Europe may also play a role (see Section 3.2.5 and Section 5.1). Robust attribution is not yet possible because of insufficient data (Barredo, 2009; Feyen et al., 2012). In terms of regional GDP, flood risks are highest in large parts of eastern Europe, Scandinavia, Austria and the United Kingdom and parts of France and Italy (Lugeri et al., 2010). A shift from a purely technically oriented flood defense toward a more integrated flood risk management system that also considers nonstructural measures to minimize adverse effects of flooding has led to more effective flood management and to a reduction of damage caused by the 2013 floods in Germany, compared to the 2002 floods (Thieken et al., 2016).

Figure 4.12 Number of flood phenomena with 'very high' severity, 1980–2010



Note: A flood phenomenon with 'very high' severity means that:
- the frequency has been assessed as 'very rare' (typically with return periods of at least 100 years); or
- the degree of total damage has been reported as 'high' or 'very high'; or
- the severity class in the Dartmouth Flood Observatory database is equal to 1.5 or 2; or
- there have been fatalities reported; or
- more than nine individual 'flood events' have been reported for one 'flood phenomenon'.

Source: ETC/ICM, 2015; EEA, 2016a.

([55]) http://www.emdat.be, maintained by CRED.

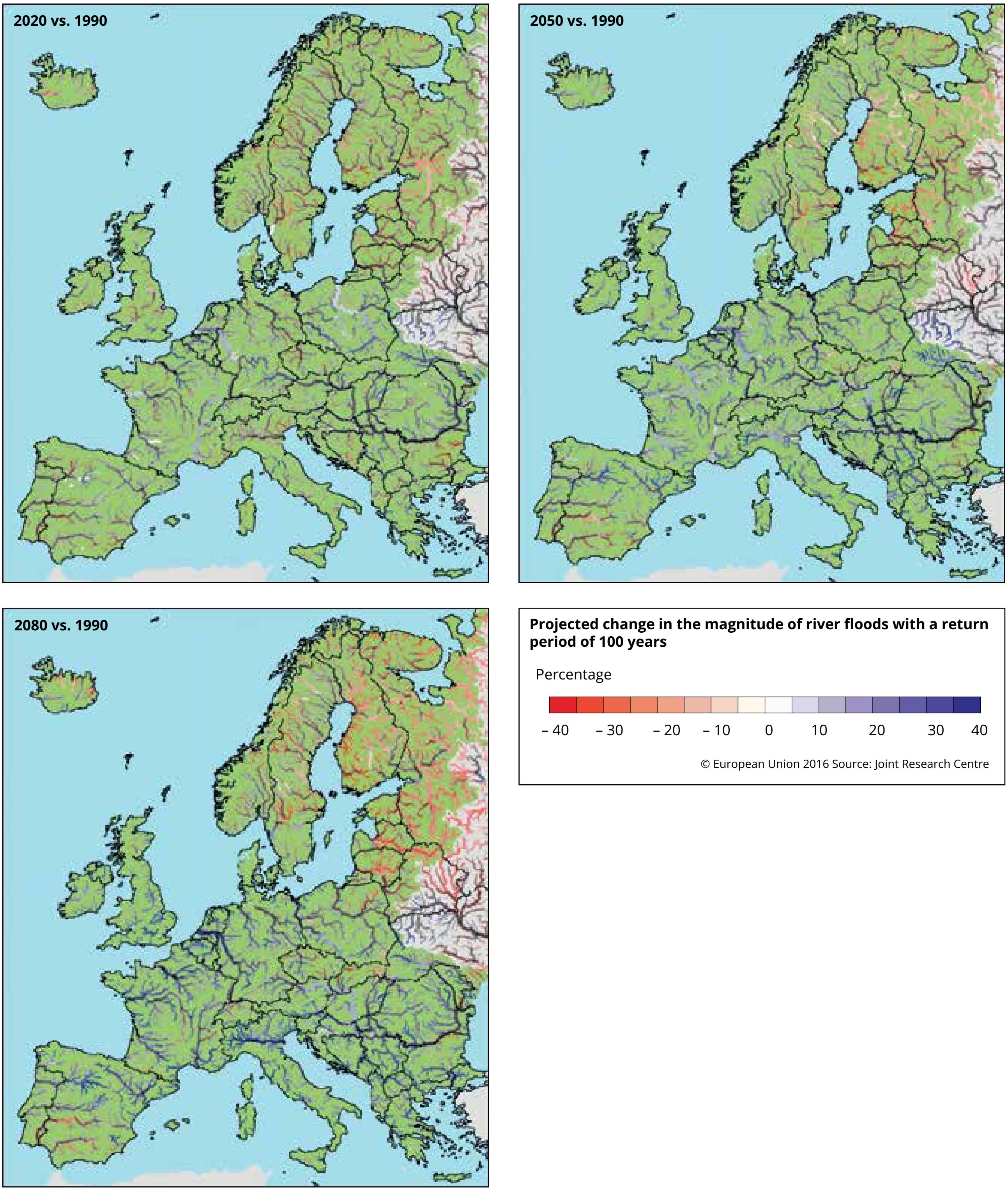
Projections

Future changes in the risk of river floods in Europe have been simulated using a hydrological model driven by an ensemble of climate simulations (Rojas et al., 2012; Alfieri, Burek et al., 2015). Of particular interest is the frequency analysis of flood peaks above the 100-year flood level, which is the average protection level of the European river network (albeit with significant differences) (Rojas et al., 2013; Jongman et al., 2014).

Map 4.8 shows the change in the level of one-in-a-century (Q100) floods between the reference period and three future time periods based on the hydrological model LISFLOOD and an ensemble of seven climate models (Alfieri, Burek et al., 2015). Blue rivers indicate an increase in flood level and red rivers indicate a decrease. For the end of the 21st century, the greatest increase in Q100 floods is projected for the British Isles, north-west and south-east France, northern Italy and some regions in south-east Spain, the Balkans and the Carpathians. Mild increases are projected for central Europe, the upper section of the Danube and its main tributaries. In contrast, decreases in Q100 floods are projected in large parts of north-eastern Europe owing to a reduction in snow accumulation, and hence melt-associated floods, under milder winter temperatures. These results are consistent with earlier studies (e.g. Dankers and Feyen, 2009; Ciscar et al., 2011; Rojas et al., 2012). While the ensemble mean presented in Map 4.8 provides the best assessment of all model simulations together, individual simulations can show important differences from the ensemble mean for individual catchments. This is partly the result of significant decadal-scale internal variability in the simulated climate (Feyen et al., 2012). Furthermore, the LISFLOOD analysis is restricted to the larger rivers in Europe, which may not be representative of a whole country or region. For example, in northern Europe, rainfall-dominated floods in smaller rivers may increase because of projected increases in precipitation amounts, even where snowmelt-dominated floods in large rivers are projected to decrease (Vormoor et al., 2016).

Changes in flood frequencies below the protection level are expected to have less significant economic effects and affect fewer people than even small changes in the largest events (e.g. with a return period of 500 years). For a number of European river basins, including the Po, Duero, Garonne, Ebro, Loire, Rhine and Rhone, an increase in extreme floods with a return period above 500 years is projected; this includes river basins such as Guadiana and Narva, where the overall frequency of flood events is projected to decline (Alfieri, Burek et al., 2015). A follow-up study combined the results of this flood hazard assessment with detailed exposure maps to estimate the economic and health risks from river floods in Europe. The results suggest that a high climate change scenario could increase the socio-economic impact of floods in Europe more than three-fold by the end of the 21st century. The strongest increase in flood risk is projected for Austria, Hungary, Slovakia and Slovenia (Alfieri, Feyen et al., 2015). A combination of different adaptation measures has been estimated to reduce economic damage from (fluvial and coastal) floods substantially by 67 to 99 % and reduce the number of people flooded by 37 to 99 % for the 100-year event (Mokrech et al., 2014).

Map 4.8 Projected change in river floods with a return period of 100 years



Note: This map shows the projected change in the level of one-in-a-century river floods (Q100). The relative changes for the time slices 2006–2035 (2020), 2036–2065 (2050) and 2066–2095 (2080) are compared with the ensemble mean of the baseline (1976–2005), based on an ensemble of seven EURO-CORDEX simulations forced by the RCP8.5 scenario and the LISFLOOD hydrological model. The consistency of the model projections is evaluated through the use of the coefficient of variation (CV) of the relative change. Smaller CVs indicate better model agreement of the projected mean change. Data points with CV > 1 are greyed out.

Source: Adapted from Alfieri, Burek et al., 2015.

4.3.4 Meteorological and hydrological droughts

Key messages

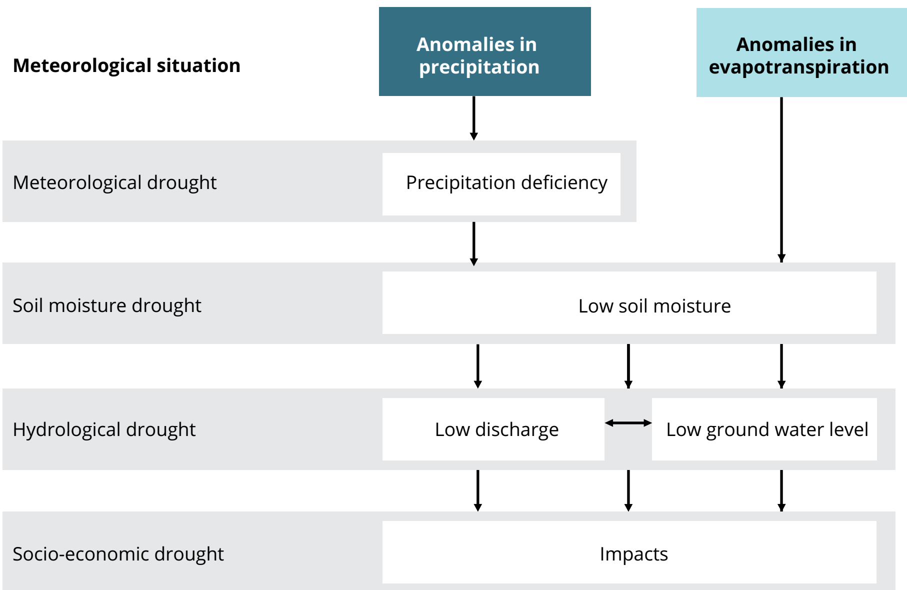
- Drought has been a recurrent feature of the European climate. From 2006–2010, on average 15 % of the EU territory and 17 % of the EU population have been affected by meteorological droughts each year.
- The severity and frequency of meteorological and hydrological droughts have increased in parts of Europe, in particular in south-western and central Europe.
- Available studies project large increases in the frequency, duration and severity of meteorological and hydrological droughts in most of Europe over the 21st century, except for northern European regions. The greatest increase in drought conditions is projected for southern Europe, where it would increase competition between different water users, such as agriculture, industry, tourism and households.

Relevance

Droughts have severe consequences for Europe's citizens and most economic sectors, including agriculture, energy production (see also Sections 5.3 and 5.4), industry and public water supply (Blauhut et al., 2015). However, the term 'drought' is used in different contexts, which may cause confusion when the language used is not carefully chosen. Figure 4.13 shows how a persistent meteorological drought can propagate to a soil moisture (agricultural) drought affecting plant and crop growth, which may deepen into a hydrological drought affecting watercourses, water resources and natural ecosystems. Furthermore, hydrological droughts have a detrimental impact on freshwater ecosystems including vegetation, fish, invertebrates and riparian bird life (EEA, 2012c, 2015, 2016a, 2016b). Hydrological droughts also have a significant impact on water quality by reducing the ability of a river to dilute pollution.

This indicator combines two types of droughts: meteorological droughts and hydrological droughts, focusing on river flow droughts in the case of the latter. A meteorological drought is defined in terms of precipitation deficiency, which may be exacerbated by high temperature associated with

Figure 4.13 Drought types and causes



Source: Adapted from Van Loon, 2015.

high evapotranspiration. Meteorological droughts are usually characterised using statistical indices, such as the Standardised Precipitation Index (SPI), Standardised Precipitation Evapotranspiration Index (SPEI) and Reconnaissance Drought Index (RDI). A river flow drought is characterised by unusually low river flow, which may result from a prolonged meteorological drought, possibly in combination with socio-economic factors.

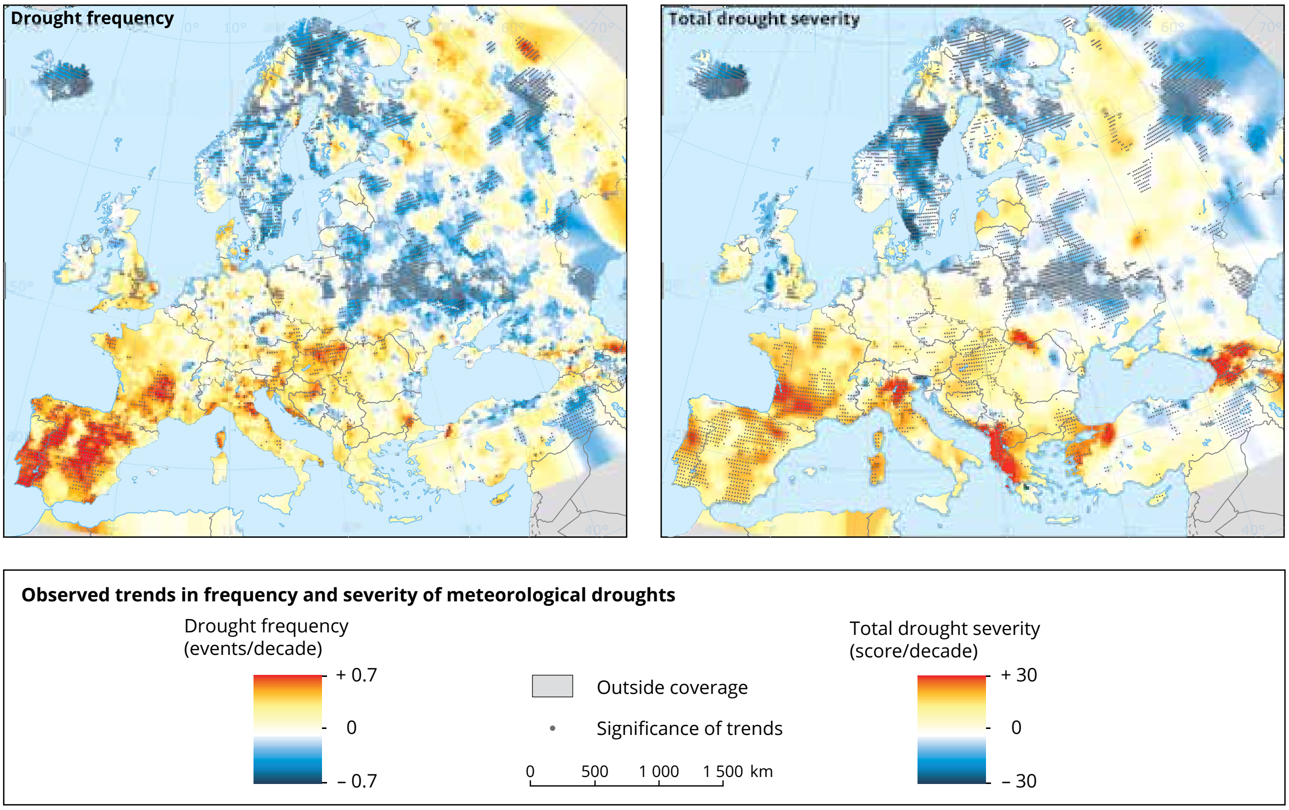
Past trends

Drought has been a recurrent feature of the European climate. From 2006–2010, on average 15 % of the EU territory and 17 % of the EU population have been affected by meteorological droughts each year. In the 1990s and 2000s the drought hotspots were the Mediterranean area and the Carpathian Region (Sepulcre-Canto et al., 2012; Spinoni et al., 2016).

The frequency of meteorological droughts in Europe has increased since 1950 in parts of southern Europe and central Europe (Austria and Hungary), but droughts have become less frequent in northern Europe and parts of eastern Europe (Map 4.9, left). Trends in drought severity (based on a combination of SPI, SPEI and RDI) also show significant increases in the Mediterranean region (in particular the Iberian Peninsula, France, Italy and Albania) and parts of central and south-eastern Europe, and decreases in northern and parts of eastern Europe (Map 4.9, right) (Gudmundsson and Seneviratne, 2015; Spinoni, Naumann, Vogt et al., 2015; Spinoni et al., 2016).

Most stream gauges in Europe show a decrease in summer low flows over the second half of the 20th century (Map 4.10). However, current data availability is insufficient for attributing this trend to global climate change (Stahl et al., 2010, 2012).

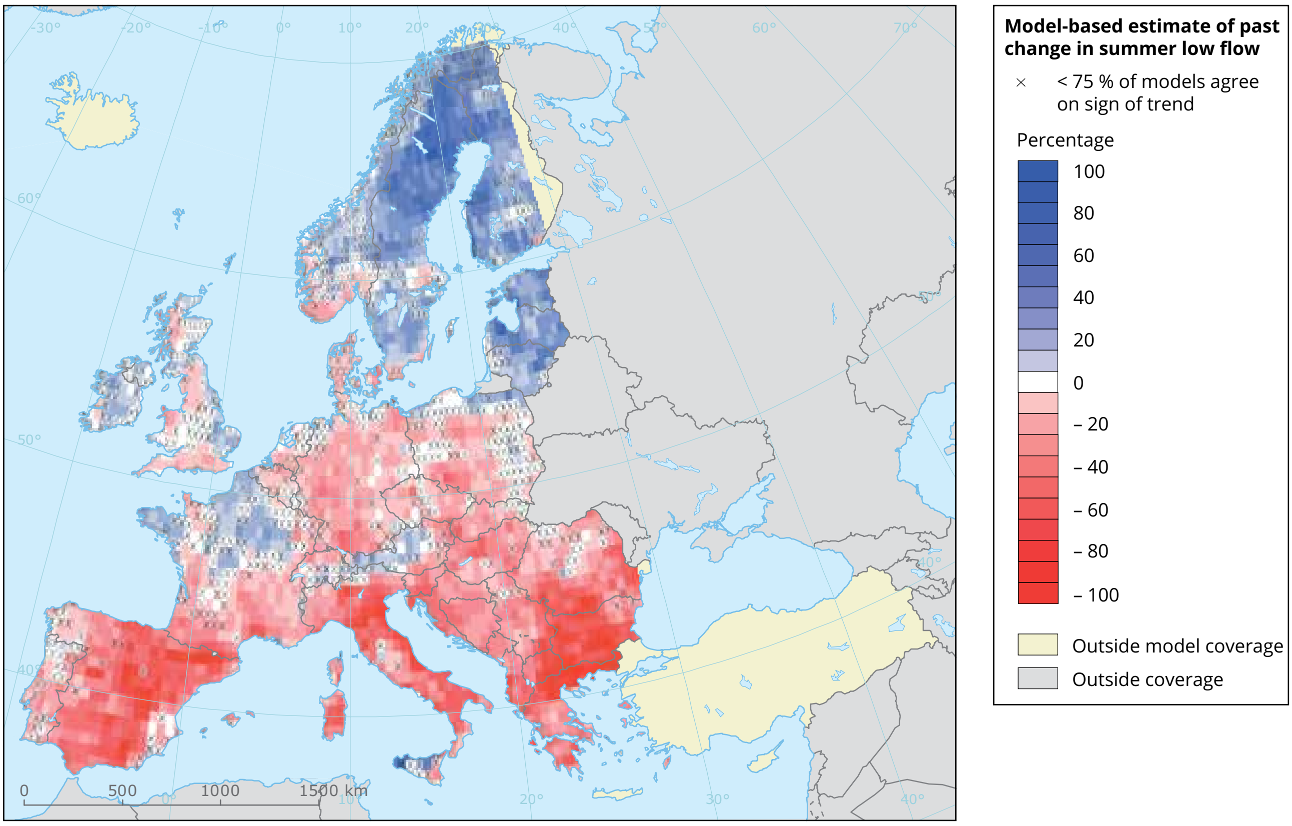
Map 4.9 Observed trends in frequency and severity of meteorological droughts



Note: This map shows the trends in drought frequency (number of events per decade; left) and severity (score per decade; right) of meteorological droughts between 1950 and 2012. The severity score is the sum of absolute values of three different drought indices (SPI, SPEI and RDI) accumulated over 12-month periods. Dots show trends significant at the 5 % level.

Source: Adapted from Spinoni, Naumann, Vogt et al., 2015.

Map 4.10 Model-based estimate of past change in summer low flow



Note: This map shows the ensemble mean trend in summer low flow from 1963 to 2000. 'x' denotes grid cells where less than three-quarters of the hydrological models agree on the direction of the trend.

Source: Adapted from Stahl et al., 2012.

Projections

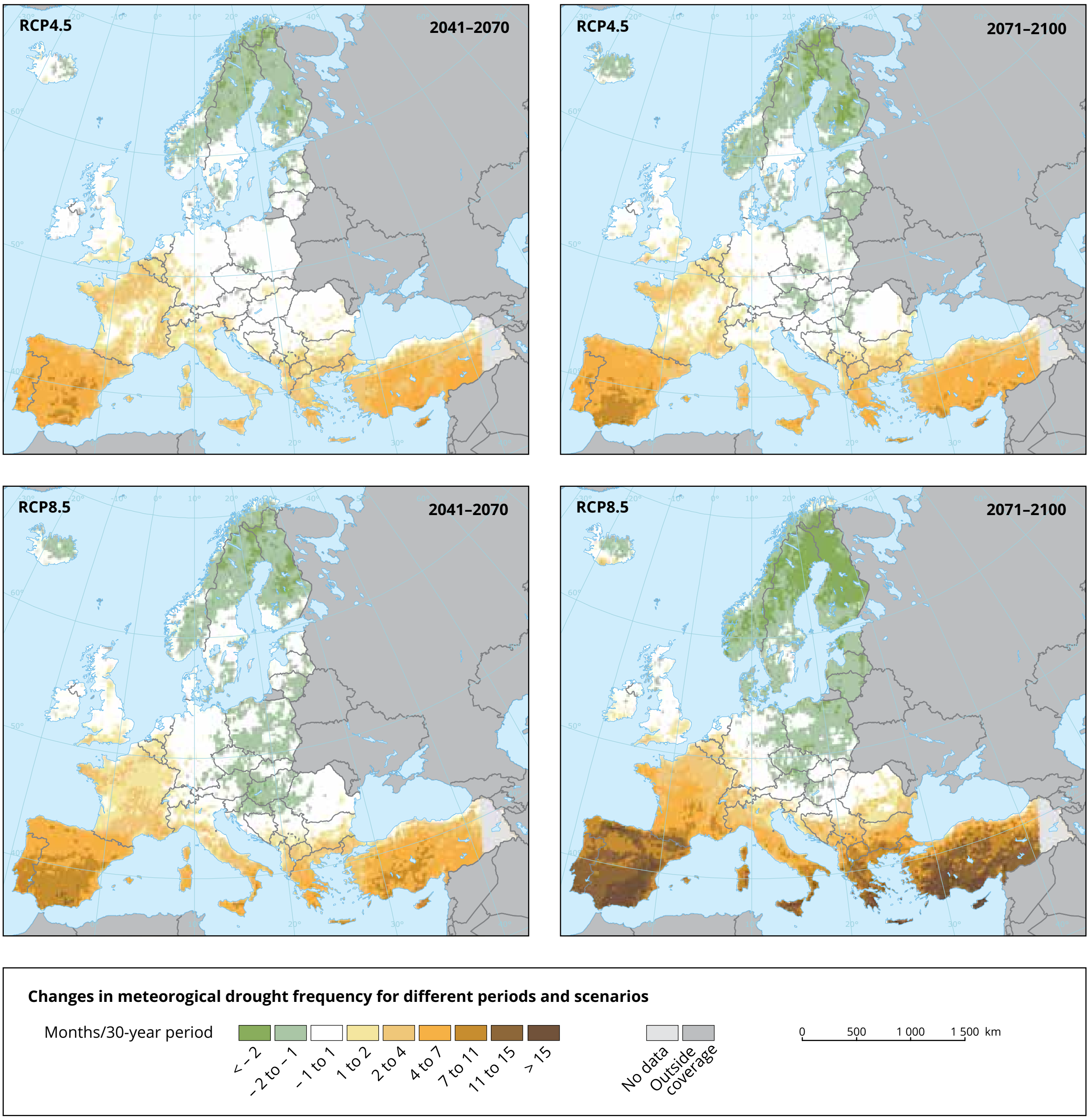
An assessment of European meteorological droughts based on different drought indices and an ensemble of RCMs has projected drier conditions for southern Europe for the mid-21st century, with increases in the length, magnitude and area of drought events (van der Linden and Mitchell, 2009). In contrast, drought occurrence was projected to decrease in northern Europe (Henrich and Gobiet, 2011). Similar results were obtained in later studies based on different indices and climate projections (e.g. Orlowsky and Seneviratne, 2013; Giorgi et al., 2014; Spinoni, Naumann, and Vogt, 2015; Touma et al., 2015).

A model ensemble from the EURO-CORDEX community projects that the frequency and duration of extreme meteorological droughts (defined as having a value below – 2 of the SPI-6) will significantly increase in the future (Stagge et al., 2015). These projections showed the largest increases in frequency for extreme droughts in parts of the Iberian Peninsula, southern Italy and the eastern Mediterranean, especially at the end of the century with respect to the baseline period 1971–2000 (Map 4.11). The changes are most pronounced for the RCP8.5 high emissions scenario and slightly less extreme for the moderate (RCP4.5) scenario.

Drought projections that also consider potential evapotranspiration (e.g. based on the SPEI, the Standardized Runoff Index (SRI) or the Supply–Demand Drought Index (SDDI)) showed substantially greater increases in the areas affected by drought than those based on the precipitation-based SPI alone. For example, the fraction of the Mediterranean region under drought was projected to increase by 10 % by the end of the 21st century based on RCP8.5 using the SPI, whereas an increase of 60 % was projected using the SPEI (Touma et al., 2015).

The projected increases in droughts in large parts of southern Europe would increase competition between different water users, such as agriculture, industry, tourism and households (see also Section 5.3.5).

Map 4.11 Projected change in frequency of meteorological droughts for different periods and scenarios



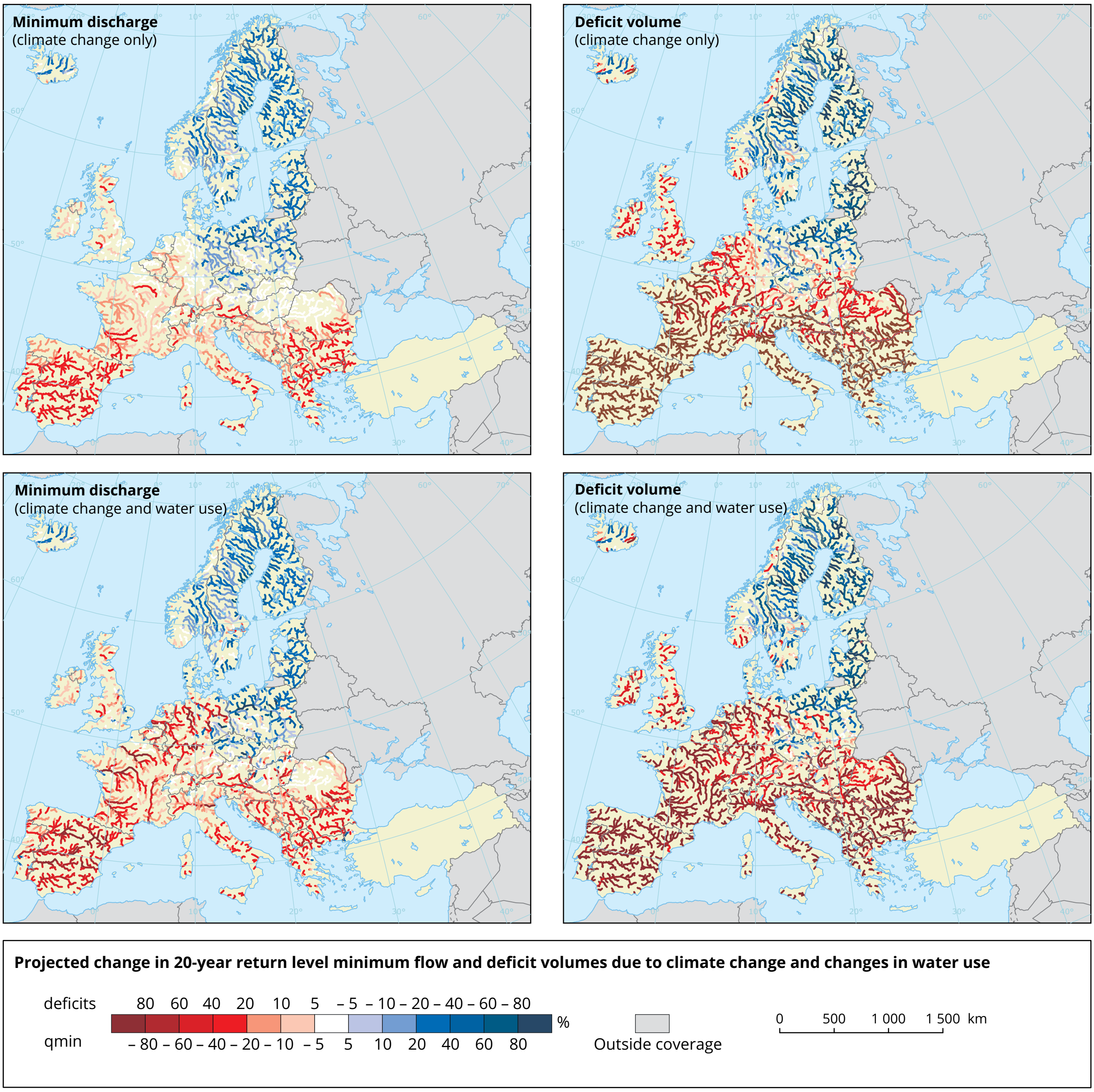
Note: This map shows the projected change in the frequency of extreme meteorological droughts (number of months in a 30-year period where the SPI accumulated over six-month periods (the SPI-6) is below – 2) between the baseline period 1971–2000 and future periods 2041–2070 (left) and 2071–2100 (right) for the RCP4.5 (top) and RCP8.5 (bottom) scenarios.

Source: Adapted from Stagge et al., 2015.

The top panels of Map 4.12 depict the projected impact of climate change on the 20-year return level minimum river flow (also known as minimum discharge; left) and deficit volumes (right), which are two measures for water availability and drought intensity. An increasing severity of river flow droughts is projected for most European regions, except for northern and north-eastern Europe. The greatest increase in drought risk is projected for southern Europe, but mean increases are also projected for large parts of central and north-western Europe. However, these increases show large seasonal variations and also depend on how the models represent evapotranspiration and soil moisture (Wong et al., 2011).

The bottom panels of Map 4.12 show the combined impact of climate change and changes in water consumption (based on the 'Economy First' water use scenario) on the same drought indices. In most regions, projected increases in water consumption further aggravate river flow droughts (Forzieri et al., 2014, 2016). Water use and abstraction will exacerbate minimum low-flows in many parts of the Mediterranean region, leading to increased probabilities of water deficits when maximum water demand overlaps with minimum or low availability (EEA, 2012c).

Map 4.12 Projected change in 20-year return level minimum flow and deficit volumes due to climate change and changes in water use



Note: This map shows the differences between the end of the 21st century (2071–2100; SRES A1B scenario) and the control period (1961–1990) for minimum flow (left) and deficit volume (right) for climate change only (top) and a combination of climate change and water use (bottom).

Source: Adapted from Forzieri et al., 2014.

4.3.5 *Water temperature*

Key messages

- Water temperatures in major European rivers have increased by 1–3 °C over the last century. Several time series show increasing lake and river temperatures all over Europe since the early 1900s.
- Lake and river surface water temperatures are projected to increase further with projected increases in air temperature.
- Increased water temperature can result in marked changes in species composition and functioning of aquatic ecosystems.

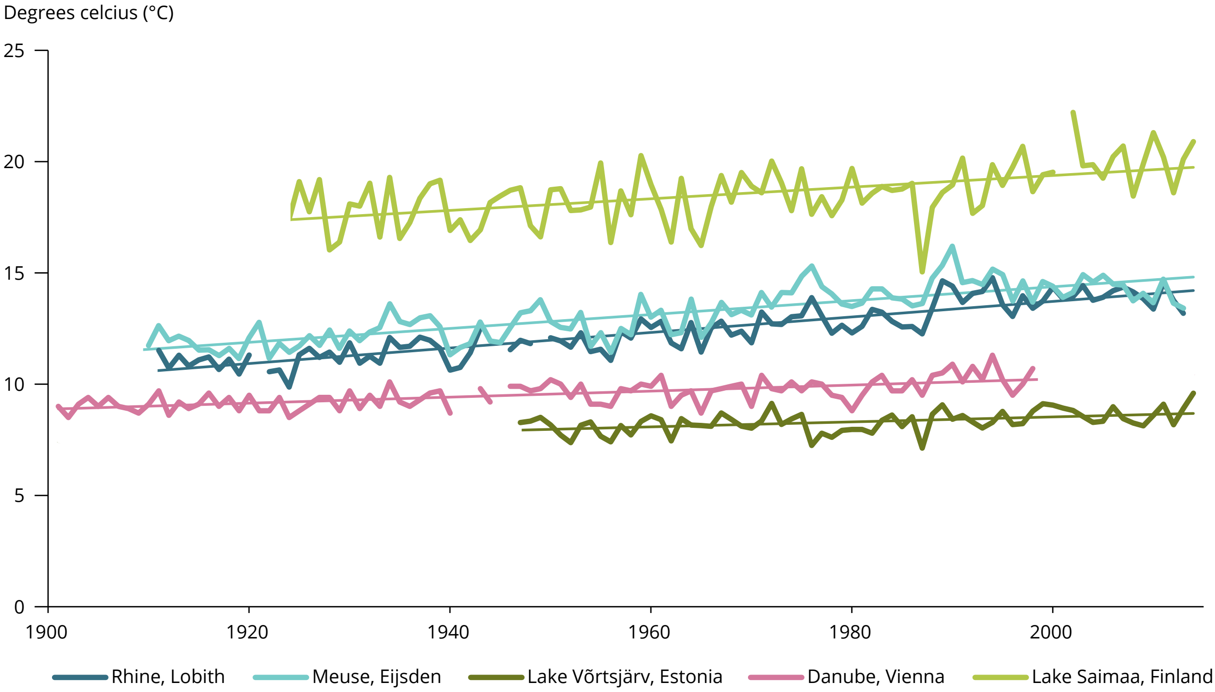
Relevance

Water temperature is one of the parameters that determine the overall health of aquatic ecosystems. Most aquatic organisms have a specific range of temperatures that they can tolerate, which determines their spatial distribution. Changes in temperature also determine ice cover periods, thermal stratification of lakes, nutrient availability and the duration of growing seasons that in turn affect species composition and food web structures (e.g. Moss et al., 2009; Markovic et al., 2014).

Past trends

The surface water temperatures of major rivers in Europe have increased by 1–3 °C over the last century (Figure 4.14). For example, the average temperature in the Rhine near Basel, Switzerland, has risen by more than 2 °C since the 1960s (FOEN, 2015). The temperature of the downstream part of the Rhine increased by nearly 3 °C between 1910 and 2013. A similar increase of 2.4 °C has been observed in the Meuse. Two-thirds of the increase of the downstream part of the Rhine is attributed to the increased use of

Figure 4.14 Observed trends in water temperature of large European rivers and lakes



Note: This figure shows the annual average water temperature in the Rhine and the Meuse (1911–2013), the Danube (1901–1998) and Lake Võrtsjärv (1947–2014), and the average water temperature in August in Lake Saimaa, Finland (1924–2014).

Source: Rhine and Meuse (CBS et al., 2014); Danube (Hohensinner, 2006, personal communication); Lake Saimaa (Johanne Korhonen, 2015, personal communication); Lake Võrtsjärv (Peeter Nõges, 2015, personal communication).

cooling water and one-third is attributed to the increase in air temperature as a result of climate change (CBS et al., 2014). The annual average temperature of the Danube increased by around by 1 °C during the 20th century (Webb and Nobilis, 1994).

Increases in surface water temperature were also found in lakes. Lake Võrtsjärv in Estonia had a 0.7 °C increase between 1947 and 2014, and the summer (August) water temperature of Lake Saimaa, Finland, increased by more than 1 °C over the last century (Figure 4.14). Many other time series indicate a general trend of increasing water temperature in European rivers and lakes in the range of 0.05 to 0.8 °C per decade, with some water bodies warming by more than 1 °C per decade (Dokulil, 2013; CBS et al., 2014; FOEN, 2015; Orr et al., 2015; Sharma et al., 2015).

Projections

Inland surface water temperatures are projected to increase further, in parallel with the projected increases in air temperature. The exact amount of warming depends on the magnitude of air temperature increase, on the region, on the season and on lake properties and river catchment.

An average increase in summer surface water temperature of 2 °C (1.2–2.9 °C) by 2050 has been estimated for 15 Austrian lakes, depending on the present thermal regime and geographical region (Dokulil, 2013). A global study estimated that mean river water temperatures of major European rivers will increase by 1.6–2.1 °C during the 21st century (2071–2100 relative to 1971–2000, mean of a GCM ensemble driven by SRES A2 and B1 scenarios) (van Vliet et al., 2013). A detailed assessment for the Rhine gives an estimated increase in mean annual and August temperature in the range of 3.0–3.5 °C during the 21st century, due to climate change. The number of days with water temperatures above 25 °C, which is the threshold for significant stress to river fauna and flora, would increase at least five-fold (e.g. from 2–15 days in the reference period 2001–2010 to 32–75 days in 2071–2100) (ICPR, 2014).

Further effects of increased lake and river water temperature are described in Box 4.5.

Box 4.5 Lake and river ice cover

Water temperature affects the ice cover and the timing of ice break-up in lakes and rivers. Ice cover in turn influences the vertical mixing and the light conditions in lakes, which are important factors for phytoplankton production.

The duration of ice cover in the northern hemisphere has shortened at a rate of 7 to 17 days per century over the last 100–150 years, resulting from ice cover beginning between 3 and 11 days later and ice break up beginning between 5 and 9 days earlier, on average, than previously (Benson et al., 2011). At the Hungarian section of the river Danube, the date of the first ice appearance has shifted 19–29 days later over the 1876–2011 period, while the date of the final ice disappearance has shifted 18–23 days earlier (Takács, 2011). In Lake Kallavesi (eastern Finland), the freezing date has shifted to 15 days later in the period 1833–2011, while the break-up date has shifted to 12 days earlier in the period 1822–2011 (SYKE, 2011). The ice break-up date in the Lake St. Moritz (Swiss Alps) has shifted to 15–20 days earlier since 1832 (Naturwissenschaften Schweiz, 2016). In the two large Estonian lakes, Peipsi and Võrtsjärv, trends in ice phenology were weak or absent, despite a marked increase in water temperature, in particular since 1961. These findings imply that the processes governing ice phenology are more complex than those governing lake surface water temperature (Nõges and Nõges, 2013).

Simulated changes in lake ice cover throughout the northern hemisphere (40–75 °N) based on one global climate model driven by the SRES A2 emissions scenario indicate an overall decrease in the duration of lake ice cover of 15–50 days across regions by 2040–2079, compared with the baseline period 1960–1999 (Dibike et al., 2011). In the two Estonian lakes, an increase of the average winter air temperature of 2 °C would presumably halve the ice cover duration in Peipsi but shorten it by only about 20 % in Võrtsjärv (Nõges and Nõges, 2013). The ice cover of lakes in regions where the ice season is already short or where ice cover occurs only in cold winters is generally more strongly affected by increasing temperature than that of lakes in colder regions (Weyhenmeyer et al., 2011).

4.3.6 Freshwater ecosystems and water quality

Key messages

- Coldwater species have been observed to move northwards or to higher altitudes in response to increased temperatures.
- Increasing water temperatures can lead to earlier and larger phytoplankton blooms and to species invasions. For example, the recent rapid spread of the highly toxic cyanobacterium *Cylindrospermopsis raciborskii* throughout Europe and into other temperate regions has caused international public health concerns.
- A warmer and wetter climate can lead to increased nutrient and dissolved organic carbon concentrations in lakes and rivers, but management changes can have much larger effects than climate change.

This section presents selected information on the impacts of changes in the indicators presented above for freshwater ecosystems and water quality. This information is not presented in the indicator format because several different impacts are foreseen for aquatic species and ecosystems, and the message cannot be conveyed simply in one indicator. More information can be found in the many reviews of climate change impacts on freshwater (see, for example, Kernan et al., 2011; Dokulil, 2013; Jeppesen et al., 2014; Vaughan and Ormerod, 2014; Arnell et al., 2015).

Changes in the river flow regime

River flow regimes, including long-term average flows, seasonality, low flows, high flows and other types of flow variability, play an important role in freshwater ecosystems. Thus, climate change affects freshwater ecosystems not only through increased temperatures but also through altered river flow regimes (van Vliet et al., 2013).

Changes in phenology

Increasing temperatures will change the life-cycle events and stimulate an earlier spring onset of various biological phenomena, such as phytoplankton spring bloom, clear water phase, the first day of flight for aquatic insects and the time of spawning of fish. Prolongation of the growing season can have major effects on species. For example, British *Odonata* dragonflies and damselfly species have changed their first day of flight by 1.5 days per decade on average over the period 1960 to 2004 (Hassall et al., 2007), and there is growing evidence for an advancement of phenological events in zooplankton (Vadadi-Fülöp et al., 2012).

Changes in species distribution

Increased water temperatures will favour warmwater species, whereas coldwater species will become more limited in their range. Examples of northwards-moving species are non-migratory British dragonflies and damselflies (Hickling et al., 2005) and south European dragonflies (INBO, 2015). Species have also been observed to move to higher altitudes, such as the brown trout in Alpine rivers (Hari et al., 2006).

Facilitation of species invasions

Climate change is facilitating biological invasions of species that originate in warmer regions. For example, the sub-tropical cyanobacterium *Cylindrospermopsis raciborskii* thrives in waters that have high temperatures, a stable water column and high nutrient concentrations. This highly toxic species has recently spread rapidly in temperate regions and is now commonly encountered throughout Europe (Haande et al., 2008; Antunes et al., 2015). Its spread into drinking and recreational water supplies has caused international public health concerns (see also Section 5.2.6).

Changes in algal blooms and water quality

Climate change is affecting water quality in various ways. Higher temperatures stimulate mineralisation of soil organic matter, which leads to increased leaching of nutrients, especially nitrogen and phosphorus (Battarbee et al., 2008; Jeppesen, Kronvang et al., 2010). Decreases in stream flow, particularly in summer, will lead to higher nutrient concentrations owing to reduced dilution (Whitehead et al., 2009), whereas increases in floods and extreme precipitation events can increase the nutrient load to surface waters because of increased surface run-off and erosion (Fraser et al., 1999; Battarbee et al., 2008).

Climate change can enhance harmful algal blooms in lakes, both as a direct result of temperature increase and as a result of climate-induced increases in nutrient concentrations. Increased lake temperature will generally have a eutrophication-like effect (Schindler, 2001; Jeppesen, Moss et al., 2010), with enhanced phytoplankton blooms (Wilhelm and Adrian, 2008) and increased dominance of cyanobacteria in phytoplankton (Kosten et al., 2012). These changes may restrain the use of lake drinking water and recreation, and they may increase the associated health risks (Mooij et al., 2005; Jöhnk et al., 2008; Paerl and Huisman, 2008) (see also Section 5.2.6).

4.4 Terrestrial ecosystems, soil and forests

Key messages

- Observed climate change has had many impacts on terrestrial ecosystems, such as changes in soil conditions, advances in phenological stages, altitudinal and latitudinal migration of plant and animal species (generally northwards and upwards), and changes in species interactions and species composition in communities, including local extinctions.
- The relative importance of climate change as a major driver of biodiversity and ecosystem change is projected to increase further in the future. In addition to climate change, human efforts to mitigate and adapt to climate change can both positively and negatively affect biodiversity and other ecosystem services.
- In Europe, 14 % of habitats and 13 % of species of interest have been assessed to already be under pressure because of climate change. The number of habitats threatened by climate change is projected to more than double in the near future. Many species in the Natura 2000 network are projected to lose suitable climate niches.
- Modelled and projected changes in soil moisture, such as significant decreases in the Mediterranean region and increases in parts of northern Europe, are having a direct effect on terrestrial ecosystems.
- Forest ecosystems and their services are affected by range shifts of tree species towards higher altitudes and latitudes, by increases in forest fire risk, in particular in southern Europe, and by an increased incidence of forest insect pests. Cold-adapted coniferous tree species are projected to lose large fractions of their ranges to broadleaf species. In general, forest growth is projected to decrease in southern Europe to increase in northern Europe, but with substantial regional variation.
- Climate change is likely to exacerbate the problem of invasive species in Europe.

4.4.1 Overview

Climate change is already affecting terrestrial ecosystems and biodiversity and is projected to become an even more important driver of biodiversity and ecosystem change in the future (Kovats et al., 2014; Urban, 2015). Climate change will have a broad range of positive and negative impacts on biodiversity at genetic, species (e.g. plant and animal species) and ecosystem levels, including shifts in the distribution of species and ecosystems, changes in species abundance, changes in species phenology (i.e. timing of annual events) and an increased risk of extinctions for some species. Soil organic carbon is potentially affected by climate change, and changes in soil organic carbon in turn have an impact on climate change. Soil erosion by water and wind is already affecting soils across Europe, thereby jeopardising many of the services that soils provide (see also Box 4.6). Changes in temperature, precipitation, and atmospheric CO_2 concentration will have impacts on the physical and chemical properties of the habitat (e.g. through changes in soil moisture), on individual species, and on ecological interactions between species (e.g. competition, symbiosis or food webs) (see Figure 4.15). Furthermore, climate change usually acts not in isolation but together with other stressors, such as human land use and management. Human efforts to mitigate (e.g. biofuel production, hydropower) and adapt (e.g. land-use changes or coastal defences) to climate change could also exacerbate the direct impacts (Paterson et al., 2008; Turner et al., 2010). Climate change will also affect the ability of ecosystems to deliver ecosystem services to humans (see Section 4.5 for further information).

The principal response mechanisms of species to climate change depend on their adaptive capacity and include phenological and/or physiological adaptation, altered migration and colonisation from locations and habitats. All these mechanisms are likely to face constraints in terms of timing and/or effectiveness. For example, migration may be constrained by the speed of dispersal mechanisms and by migration barriers, including habitat fragmentation induced by human activities. If all these response mechanisms fail, the species may gradually disappear from its current range and eventually become extinct.

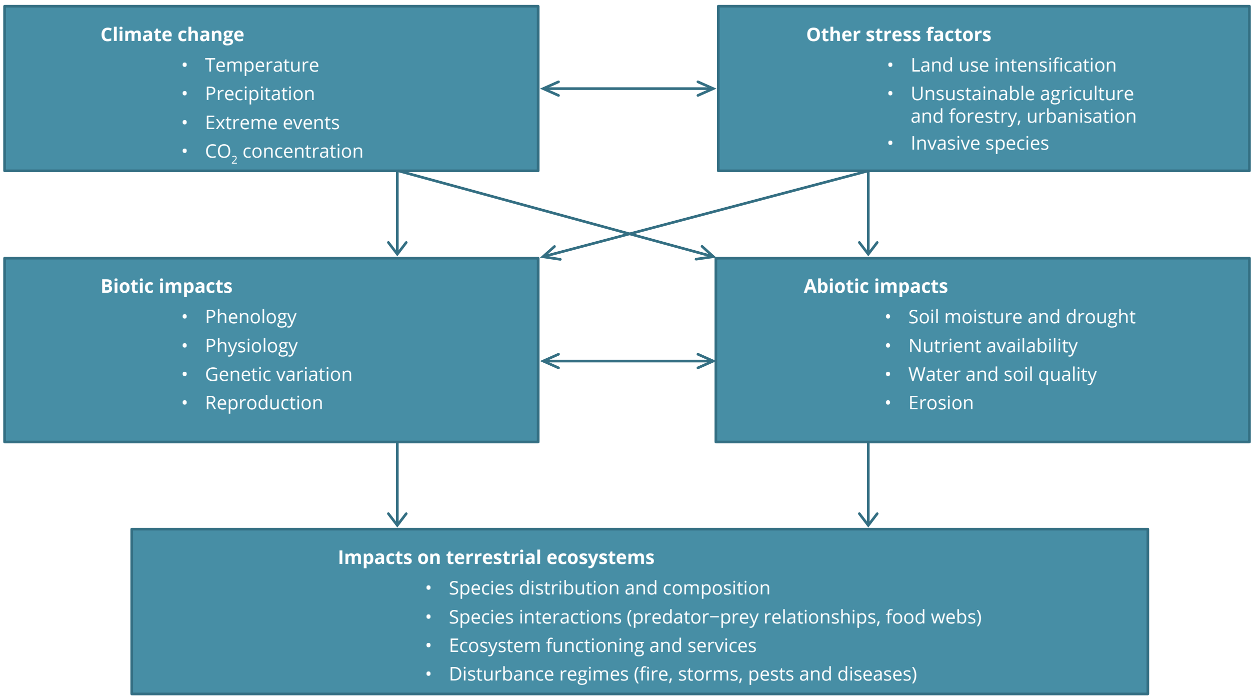
In its AR5, the IPCC highlights the importance of species interactions and states that '[…] climate-related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (low confidence)] […]' (Settele et al., 2014). Changing climatic conditions can lead to a mismatch between species' life-cycle events and food sources (Schweiger et al., 2012) or to decoupled predator-prey relationships, for example through influences on the activity of predators or on trophic interactions between species, such as the association between the timing of budburst (food supply), the emergence of insect larvae and the egg laying date of birds (Both et al., 2009). In spite of their critical role in mediating the impacts of future climate change, species interactions are still poorly understood with a lack of modelling. However, with respect to different phenological shifts, the IPCC is highly confident that climate change will continue to alter the interactions between species in Europe (Kovats et al., 2014).

The attribution of observed changes in biodiversity to climate change is sometimes difficult because of the importance of other drivers, such as habitat fragmentation, degradation and loss (Mantyka-Pringle et al., 2012), invasive alien species, human management and land-use change. Nevertheless, several comprehensive studies have identified climate change as the main driver for changes in the phenology and distribution of plant and animal species in Europe and across the world (Root et al., 2003; Parmesan, 2006; Amano et al., 2010; Singer and Parmesan, 2010; Chen et al., 2011; Delzon et al., 2013).

Policy context

The EU Habitats Directive (EC, 1992) calls for the regular assessment and reporting of the conservation status of the 1 500 species and the habitats of special European interest listed in Annexes I, II, IV and V of the Directive. During the second reporting period, 2007–2012, Member States collected a diverse range of data and provided expert opinion. The reports contain information on the conservation status of species and habitats. They also give an indication of whether or not climate change is considered as an important pressure ([56]) and threat ([57]) to change in conservation status. The national reports suggest that 14 % of habitats and 13 % of species of European interest are already under pressure because of climate change over their natural European range, including 43 % of dunes habitats. In the near future, 33 % of habitats and 18 % of species are projected to be threatened by climate change (Table 4.1). Bogs, mires and fens are considered to be the most vulnerable habitat types, with up to 75 % potentially negatively affected in the near future. This is particularly worrying because bogs and mires are important carbon stores and their degradation releases greenhouse gases into the atmosphere.

Figure 4.15 Selected effects of climate change on terrestrial ecosystems



Note: This figure shows selected effects of climate change on terrestrial ecosystems, focusing on the effects and relationships that are covered in this report.

Source: ETC-CCA.

([56]) Reported pressures are considered to be factors acting now or during the six-year reporting period.
([57]) Reported threats are factors expected to be acting in the near future (i.e. 12 years into the future).

The Natura 2000 network in Europe, designated under the Habitats Directive and the Birds Directive, is — by the number of sites — the most extensive network of conservation areas worldwide and, as such, the most important instrument for maintaining biological diversity within the European Union. The principle objective of the EU Habitats Directive (i.e. maintaining certain species and habitats) is static and does not recognise dynamic influences of environmental changes such as climate change. Nevertheless, Natura 2000 includes a lot of potential and chances to maintain biodiversity even under conditions of a changing climate (Ellwanger et al., 2012).

Owing to the high rate of change in climatic conditions and the predicted wide range of changes in species distribution and composition, the extent to which Natura 2000 might be able to fulfil its function of maintaining biological diversity also in the future has to be discussed, as well as the measures that should be taken to enhance its resilience. Some recent research shows that the Natura 2000 network is, in principle, able to cope with climate change and even to buffer some of the effects. However, strengthening the fitness of habitats and species, adaptive management, actions to enhance coherence and better awareness of climate change effects will be needed to support the crucial role of Natura 2000 under climate change conditions. Because of the complex and dynamic nature of habitats, particularly when considering the impacts of climate change, modelling the future distribution of habitat types should be based not exclusively on their current definitions and mapped distributions, but also on their constituent elements, and in particular their characteristic plant species.

An assessment of the effectiveness of sets of protected areas in conserving European plant and terrestrial vertebrate species under climate change estimates that, by 2080, 58 ± 3 % of the species would lose suitable climate niches in protected areas. In Natura 2000 areas, the losses were even higher, at 63 ± 2 %. The difference between protected areas and Natura 2000 sites is partly related to topography. While most protected areas are designated in the mountains or rugged environments, Natura 2000 also prioritises farmlands, which are often located in lower and flatter lands. Because proportional range losses arising from climate change are usually more pronounced in flatlands than in rugged terrains, Natura 2000 is more vulnerable to climate change (Araújo et al., 2011).

Several studies show that climate change should be considered in the selection and management of conservation areas (Filz et al., 2013; Virkkala et al., 2013; Watson et al., 2013). The EU Invasive Species Regulation also requires consideration of 'foreseeable' climate change in the risk assessment of potential invasive species (EU, 2014). Despite those threats, existing protected areas play an important role in the conservation of biodiversity under climate change,

Table 4.1 Habitats and species groups negatively affected by climate change in at least one EU Member State

Habitat type	**% of habitats considered …**		**Number of habitats …**	**Species group**	**% of species considered …**		**Number of species …**
	under pressure	**under threat**	**under pressure or threat**		**under pressure**	**under threat**	**under pressure or threat**
Coastal habitats	21	43	28	Amphibians	20	21	47
Dunes habitats	43	48	21	Arthropods	11	16	114
Freshwater habitats	11	30	18	Fish	11	16	105
Heath and scrub	9	9	11	Mammals	14	18	108
Sclerophyllous scrub	25	25	12	Molluscs	37	45	38
Grasslands	7	15	28	Reptiles	13	15	55
Bogs, mires and fens	25	75	12	Non-vascular plants	24	36	33
Rocky habitats	17	23	13	Vascular plants	10	16	352
Forests	6	30	63				
All habitats	**14**	**33**	**206**	**All species**	**13**	**18**	**852**

Note: The table gives the proportion of habitat types and species groups listed in the Habitats Directive for which at least one Member State has identified climate change as a high-rank pressure on and/or threat of unfavourable trends in the area covered or across the natural range as reported by the Member States for the 2007–2012 reporting period.

Source: ETC-BD, 2015.

because most sites that are currently important should remain important in the future (e.g. Johnston et al., 2013; Virkkala et al., 2014; Gillingham et al., 2015).

The fact that terrestrial ecosystems are affected by climate change is also recognised in the EU's CAP. Member States have to establish a comprehensive farm advisory system offering advice to beneficiaries, including on the relationship between agricultural management and climate change. The CAP's cross-compliance system related to direct payments incorporates basic standards comprising climate change aspects. More attention should perhaps be paid to how these aspects are being monitored. One of the priorities under the support for rural development is promoting resource efficiency and supporting the shift towards a low-carbon and climate-resilient economy in agriculture, food and forestry sectors (with a focus on increasing efficiency in water use). 'Climate change mitigation and adaptation and biodiversity' is explicitly mentioned as a thematic sub-programme. Accordingly, Member States have to specify agri-environment-climate measures and forest-environment and climate commitments that go beyond the basic standards. These measures often include provisions for soil (EU, 2013).

Indicator selection

The subsequent sections cover the following indicators:

- soil moisture;
- phenology of plant and animal species;
- distribution shifts of plant and animal species;
- forest composition and distribution;
- forest fires.

Climate change directly influences physiological processes of animal and plant species, especially energy and water budgets, and can, in extreme cases, lead to death by desiccation or freezing. Climate changes affect ecosystems indirectly through soil condition and interaction with stressors, some of which are steered through land use and land management, equally affecting soil characteristics and processes. *Soil moisture* is a key factor for ecosystems, which is determined by soil characteristics, vegetation and climatic factors. To adapt to changes in these aspects, species have several options: (1) adapting temporally, i.e. changing their life cycle within a year (their *phenology*) according to altered climatic conditions throughout the year; (2) adapting spatially, i.e. changing their *distribution* ranges to follow suitable climatic conditions; and (3) microevolution by adapting physiologically. Overall, a species' adaptive potential is the sum of the changes due to genetic adaptation and changes due to phenotypic plasticity (i.e. the capacity of an organism to change its phenotype in response to a change in environment, which is not always hereditary). Changes in plant and animal phenology have been shown to be good indicators of climate change impacts, but other pressures (such as nitrogen input) may also have an impact on phenology. Directly or indirectly, climate change can affect species populations in a number of ways, including species distribution changes (e.g. due to habitat loss, or contraction and expansion, relating to their dispersal ability). Novel non-native species are also expanding their ranges as a result of climate change. For example, birds and invertebrates from mainland Europe are extending their distribution ranges and are now being found in southern England and moving north. *Forest composition and distribution* may influence mitigation and the provision of ecosystem services. Furthermore, they have large economic relevance. *Forest disturbances* are experienced in many European countries, in particular forest fires in southern Europe. Climate change may lead to more forest fires because of warmer and drier weather, and possibly increases in lightning storms (a natural cause of fires).

Information on forest pests and diseases is presented in the concluding section, but this is not an EEA indicator. Invasive alien species have been recognised as one of the most important threats to biodiversity at the global level. The available information is insufficient for creating an EEA indicator, but key information on alien invasive species and climate change is presented in Box 4.7.

Data quality and gaps

Quantitative information, from both observations and modelling, on the past trends and impacts of climate change on soil and the various related feedbacks is very limited. For example, data have been collected in forest soil surveys, but issues with survey quality — at least in the first European forest soil survey — makes comparison between countries (and between surveys) difficult (Hiederer and Durrant, 2010). To date, assessments have relied mainly on local case studies that have analysed how soil reacts under changing climate in combination with evolving agricultural and forest practices. Thus, Europe-wide soil information to help policymakers identify appropriate adaptation measures is absent. There is an urgent need to establish harmonised monitoring networks to provide a better and more quantitative understanding of this system. Currently, EU-wide soil indicators are (partly) based on estimates and modelling studies, most of which have not yet been validated. It is still common to use precipitation (sometimes combined with evaporation-based indicators, such as the SPI or the Palmer Drought Severity Index) to describe changes in soil moisture, despite the high sensitivity of the assessment to the specific method used (Samaniego et al., 2013).

Generally, observations for popular species groups such as vascular plants, birds, other terrestrial vertebrates and butterflies are much better than for less conspicuous and less popular species. Similarly, owing to (1) extensive existing networks, (2) a long tradition and better means of detection of rapid responses of the organisms to changes, and (3) general knowledge, phenological changes are better observed and recorded than range shifts. Projections of climate change impacts on phenology rely crucially on the understanding of current processes and responses. For most cases, only a few years of data are available and they do not cover the entire area of the EU but are restricted to certain well-monitored countries with a long tradition, for example, in the involvement of citizen scientists. Based on the short time series, the quantification of impacts and their interpretation thus has to rely on assumptions (Singer and Parmesan, 2010). One of the greatest unknowns is how quickly and closely species will alter their phenology in accordance with a changing climatic regime (van Asch et al., 2007; Singer and Parmesan, 2010). Even experimental studies seem to be of little help, as they notoriously tend to underestimate the effects of climate change on changes in phenology (Wolkovich et al., 2012).

Observing range shifts (and projecting responses to climate change) crucially depends on good distributional data, which is better for popular groups of species than for other species. There are also large regional differences in the quality of observational data, with better data generally available in northern and western Europe than in southern Europe. As neither data quality nor lack of data is properly recorded, the true quality of projections of range shifts, as well as the likelihood of unobserved range shifts, is largely unknown (Rocchini et al., 2011). Some studies found unexpected results, such as range shifts of terrestrial plants towards lower elevations, which may be explained by the characteristics of local climate change or by taxonomic and methodological shortfalls identified in the simulation of range shifts (Lenoir and Svenning, 2015).

Species distribution models (also known as habitat models, niche models or climate envelope models) suffer from a variety of limitations because species are currently not in equilibrium with climate, and because species dispersal and biotic interactions are largely ignored (Bellard et al., 2012; Zarnetske et al., 2012). Furthermore, climate change projections for Europe include climate conditions for which no analogue climate was available for the model calibration. Some models still do not include such climates, which may lead to misinterpretations of projected changes.

When documenting and modelling changes in soil, biodiversity and forest indicators, it is not always feasible to track long-term changes (signal) given the significant short-term variations (noise) that may occur (e.g. seasonal variations of soil organic carbon as a result of land management). Therefore, detected changes cannot always be causally attributed to climate change. Human activity, such as land use and management, can be more important for terrestrial ecosystem components than climate change, both for explaining past trends and for future projections.

4.4.2 Soil moisture

Key messages

- Harmonised *in situ* data on soil moisture are not available across the EU. Modelled soil moisture content has significantly decreased in the Mediterranean region and increased in parts of northern Europe since the 1950s, as a result of past warming and precipitation changes.
- Significant decreases in summer soil moisture content in the Mediterranean region and increases in north-eastern Europe are projected for the coming decades.

Relevance

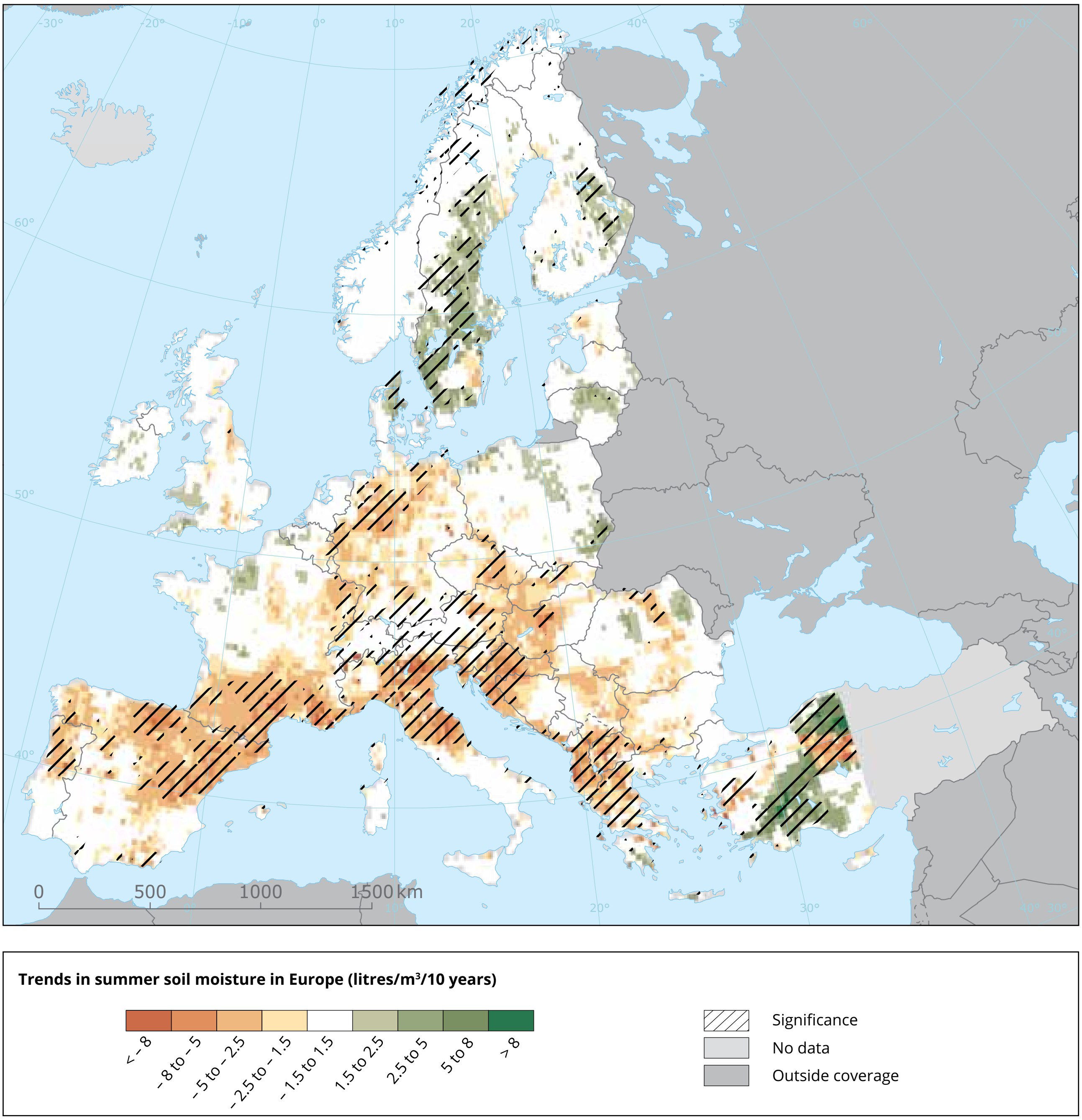
Water retention is a major hydrological property of soil that governs soil functioning in ecosystems. Maintaining water retention capacity and porosity in soils can also reduce the effects of extreme precipitation events. While water retention capacity is an intrinsic soil property based on clay content, structure and organic matter levels, soil moisture content is highly dynamic and is, if based on natural factors only, the balance between rainfall, evapotranspiration, surface run-off and deep percolation. Changes in temperature as well as precipitation patterns and intensity will affect evapotranspiration and infiltration rates, and thus soil moisture.

Although soil moisture constitutes only about 0.005 % of global water resources, it is an important part of the water cycle (see also Section 4.3) and a key variable controlling numerous processes and feedback loops within the climate system (Seneviratne et al., 2010). When depleted owing to a lack of precipitation, increased evapotranspiration or increased run-off, soil moisture starts to constrain plant transpiration, growth and, thus, productivity of natural and managed ecosystems. Therefore, information on soil moisture content can be used as a proxy for agricultural droughts.

Past trends

As a spatially and temporally comprehensive set of harmonised soil moisture data over a sufficient soil depth is not available, assessments of past trends in soil moisture rely on hydrological models driven by data on climate, soil characteristics, land cover and phenological phases. These simulations take account of changes in available energy, humidity and wind speed, but disregard artificial drainage and irrigation practices. Modelling of soil moisture content over the past 60 years suggests that there has been little change at the global and pan-European levels (Sheffield et al., 2012; Kurnik et al., 2015). At the sub-continental scale, however, significant trends in summer soil moisture content can be observed (Map 4.13). Soil moisture content has increased in parts of northern Europe, probably because of increases in precipitation amounts. In contrast, soil moisture has decreased in most of the Mediterranean region, particularly in south-eastern Europe, south-western Europe and southern France. The substantial increases in soil moisture content modelled over western Turkey should be considered with caution because of the limited availability of climate and soil data in the region, which affects the accuracy of the modelled trends (see Kurnik et al., 2015, for details).

Map 4.13 **Past trends in summer soil moisture content**



Note: Trends refer to the period 1951–2012; soil moisture content was modelled using a soil moisture balance model in the upper soil horizons; summer means June to August.

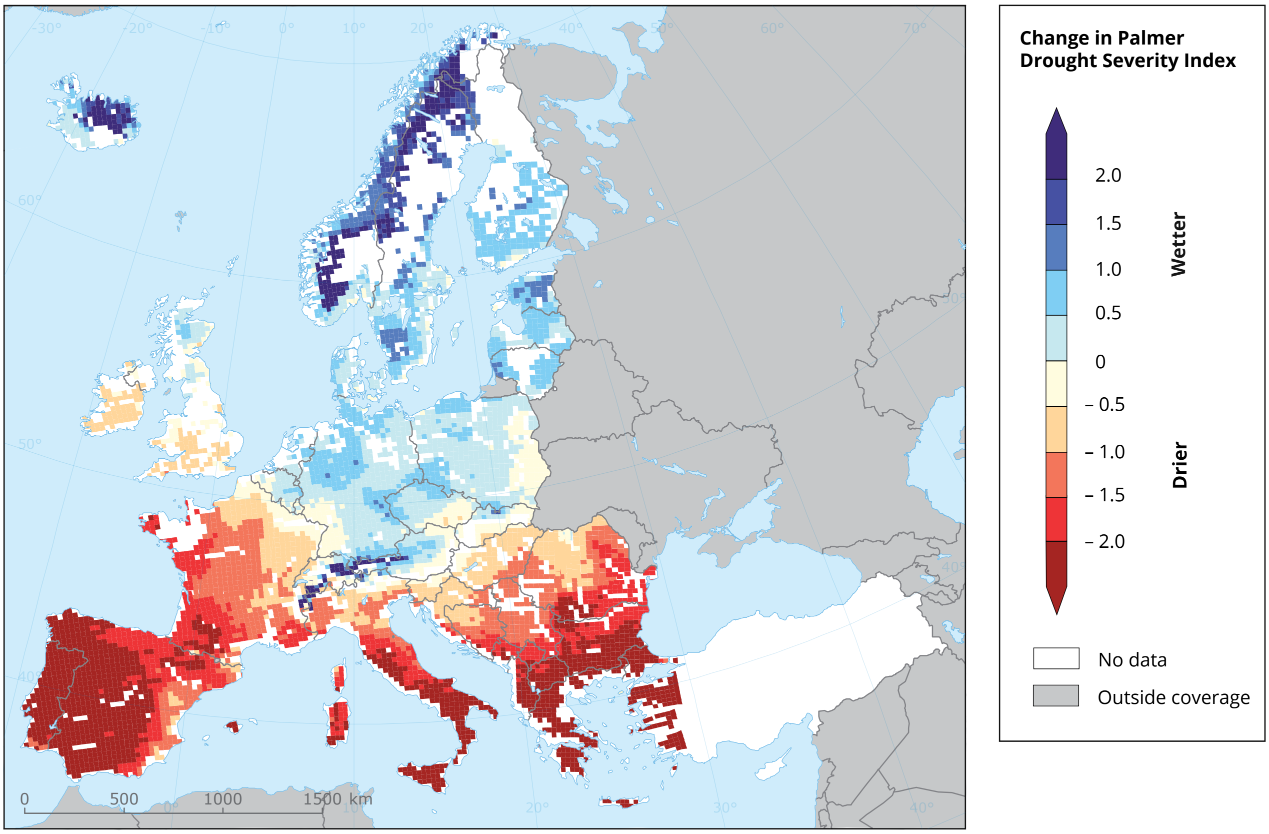
Source: Adapted from Kurnik et al., 2014, 2015.

Projections

Based on the results of 12 RCMs, the projected changes in soil moisture anomaly (Palmer Drought Severity Index) show a strong latitudinal gradient, from pronounced drier conditions in southern Europe to wetter conditions in northern European regions in all seasons (Map 4.14). The largest changes in the soil moisture index between 2021–2050 and the baseline period (1961–1990) are projected for the summer period in the Mediterranean, especially in north-eastern Spain and south-eastern Europe (Heinrich and Gobiet, 2012).

Projections for the end of the 21st century show significant decreases in summer soil moisture content in the Mediterranean region and central Europe, and increases in the north-eastern part of Europe (Calanca et al., 2006; López-Moreno et al., 2009; Orlowsky and Seneviratne, 2013).

Map 4.14 Projected changes in summer soil moisture



Note: Changes are based on the self-calibrated Palmer Drought Severity Index and presented as mean multi-model change between 1961–1990 and 2021–2050 using the SRES A1B emissions scenario and 12 RCMs; red indicates drier and blue indicates wetter conditions.

Source: Adapted from Heinrich and Gobiet, 2012.

Box 4.6 Soils under climate change: carbon storage and soil erosion

Climate is one of the factors that determines soil formation and soil processes. Soil functions are equally critical in the soil system's resilience to climate change effects. Soils can offset other greenhouse gas emissions by capturing and storing carbon, and the soil's flood regulation function (owing to the structuring effect of soil organic matter) can help in the adaptation to climate change. Furthermore, soils also help regulate temperature, as the water present in the soil has a cooling effect. Soils are subject to a range of degradation processes, some of which are strongly influenced by climate change. For example, erosion by water and wind are affected by extreme climate events (intense rainfall, droughts, heat waves, storms). In particular, erosion of the upper part of the soil (topsoil) leads to declining soil organic carbon and nutrient stocks, which influences fertility and has further knock-on effects. Soil organic matter loss leads to a breakdown of the soil structure and reduced soil water storage, which can lead to an enhanced risk of flooding and landslides in adjacent areas. Soil organic matter can be a strong indicator of soil biodiversity, which plays a crucial role in carbon and nutrient cycling. In addition, both soil organic matter and soil organism diversity and activity are affected by temperature and moisture changes. The interlinkages between the climate and soil system, along with the interaction between humans and these natural systems, define the degree to which soil can deliver services to society. Land use and land management (supported by conducive policies) responsive to the challenges of climate change and its impact are thus crucial for the resulting services.

Soil organic carbon

Estimates derived from the European Soil Database indicate that around 45 % of the mineral soils in Europe have a topsoil organic carbon content that is very low to low (0–2 %) and 45 % have a medium content (2–6 %) (Rusco et al., 2001). Soil organic carbon (SOC) stocks in the EU-27 were estimated at 73–79 billion tonnes using the Topsoil Organic Carbon Content for Europe (OCTOP) model (Jones et al., 2005, 2012). Comparisons of this modelled data with alternative approaches suggest that the SOC stock may have been both underestimated and overestimated. On the one hand, Baritz et al. (2014) suggest that the OCTPOP model has underestimated SOC (e.g. in Norway). On the other hand, estimates for north-eastern Europe, comprising countries with a high proportion of organic topsoils, are presumably overestimated (country data, Panagos et al., 2013; GEMAS ([58]) dataset, Baritz et al., 2014). Modelling results from the CAPRESE ([59]) project show a topsoil (0–30 cm) SOC pool of 17.6 billion tonnes (or Gt) ([60]) in agricultural soils at pan-European level ([61]) (17.0 Gt for the EU-28) (Lugato, Panagos et al., 2014). These data suggest that the OCTOP assessment may have overestimated the SOC pool in agricultural soils by around 24 %. Values for forest SOC stocks in Europe (on a reference forest area of 163 million hectares (ha)) were estimated at 3.50–3.94 Gt in forest floors (organic sub-layers), and 11.4–12.2 Gt (0–30 cm) or 21.4–22.5 Gt (upper 1 m) in mineral and peat soils (De Vos et al., 2015). These new data point at an underestimation of most existing estimates for European forest soils, and highlight that a substantial amount of SOC is stored in forest floors.

A recent assessment (using the LUCAS ([62]) database along with SOC predictors) shows that predicted SOC contents are lowest in Mediterranean countries and in croplands across Europe, whereas the largest predicted SOC contents are in wetlands, woodlands and mountainous areas (de Brogniez et al., 2015). This is in line with the notion that croplands generally act as a carbon source, while forest soils generally provide a sink (Schils et al., 2008). Nevertheless, some cropping practices can lead to sequestration in arable soils if given time (see below), while CH_4 emissions from livestock and N_2O emissions from arable agriculture may be fully compensated by the CO_2 sink provided by forests and grasslands (Schulze et al., 2009).

Possible pathways for SOC and CO_2 development in temperate mineral soils involve many possible interrelationships, making the effects of climate change on SOC stocks and greenhouse gas emissions complex (EEA, 2012). The organic carbon pool of soils (including deeper layers) in the northern permafrost region is estimated to account for approximately 50 % of the estimated global belowground organic carbon pool (Tarnocai et al., 2009). There, higher temperatures could increase the activity of microbial decomposers and indirectly affect organic matter decomposition through other feedbacks, of which thawing of permafrost (covering about 50 % of the boreal zone) and increased fire frequency are expected to create the strongest effects (positive and negative, respectively) on microbial CO_2 production (Allison and Treseder, 2011).

([58]) GEMAS: 'Geochemical Mapping of Agricultural and Grazing Land Soil'.
([59]) CAPRESE: 'CArbon PREservation and SEquestration in agricultural soils: Options and implications for agricultural production'.
([60]) Allocated as 7.6 and 5.5 Gt in arable and pasture lands, respectively.
([61]) EU-28 + Serbia, Bosnia and Herzegovina, Montenegro, Albania, former Yugoslav Republic of Macedonia and Norway.
([62]) LUCAS: 'Land Use/Cover Area frame Statistical Survey'.

Box 4.6 Soils under climate change: carbon storage and soil erosion (cont.)

In Europe, the CAPRESE projections using two climate scenarios (Lugato, Bampa et al., 2014) show that, compared with a baseline stock of 17.6 Gt, conversion of grassland to arable land can rapidly lead to consistent SOC losses (up to 2 Gt of SOC by 2100), while the conversion of arable land to grassland can lead to the most rapid and absolute SOC gain (with sequestration rates of 0.4–0.8 tonnes SOC/ha/year). Among the arable practices, ley in rotation and cover crops performed better than straw incorporation and reduced tillage. The same model was used to assess the effect of crop residue removal for ethanol production (Lugato and Jones, 2015). Such dry matter removal consistently resulted in SOC losses, which could not — at least for large-scale applications with up to 90 % removal of the residues — be totally offset by mitigation practices (such as ryegrass cover crop or biodigestate return).

Soil erosion

According to the revised water erosion model RUSLE2015, developed by the JRC in 2015 (Panagos, Ballabio et al., 2015; Panagos, Borrelli et al., 2015), around 11.4 % of the EU-28 territory is estimated to be affected by a moderate to high-level soil erosion rate (> 5 tonnes/ha/year). About 0.4 % of EU land suffers from extreme erosion (> 50 tonnes/ha/year). The mean erosion rate is estimated to be 2.46 tonnes/ha/year. Nevertheless, soil loss rates show high regional variability, with land use being one of the decisive parameters. Higher than average annual rates of water erosion are estimated for sparsely vegetated areas (40.1 tonnes/ha) and arable land (2.67 tonnes/ha), while lower than average rates are estimated in forests (0.065 tonnes/ha) and pastures (2.02 tonnes/ha). These estimates comprise soil loss caused by raindrop impact, overland flow (or sheet wash) and rill erosion, but do not account for gully or stream-channel erosion. Despite the remaining uncertainties and a lack of validation, these model results are more accurate than previous outputs, mainly owing to increased accuracy of the input data. Modelling of the wind-erodible fraction of soil shows that Mediterranean countries, such as Cyprus, Italy, Malta and Spain, have the lowest average erodible fraction values (around 20 %), whereas the highest values appear in the areas surrounding the North Sea and the Baltic Sea, with Denmark, the Netherlands, Poland and northern Germany showing average values of above 40 %. However, high regional variability applies, particularly in southern countries (Borrelli et al., 2014).

Soil erosion rates and extent are expected to reflect changing patterns of land-use and climate change. Variations in rainfall patterns and intensity, as well as in storm frequency and intensity, may affect erosion risk either directly, through the physical displacement of soil particles, or indirectly, through removing protective plant cover. Available case studies for Europe suggest that climate change may increase as well as decrease soil erosion, depending on local climatological and environmental conditions (Märker et al., 2008; Scholz et al., 2008; Thodsen et al., 2008). To predict the future rainfall erosivity, the JRC used the Hadley Centre Global Environment Model version 2 (HadGEM2) under the RCP4.5 scenario, combined with a geo-statistical model to estimate a Rainfall Erosivity Database at European Scale (REDES). An average increase of 10–15 % in rainfall erosivity is estimated until 2050. The major increase is predicted in northern Europe (coasts of the North Sea and the English Channel), the Alps, north-western France and eastern Croatia. The Nordic countries (specifically Finland and Sweden), the Baltic states and eastern Poland are expected to show a decrease in rainfall erosivity. Small changes in rainfall erosivity are expected in central Europe (specifically Slovakia and western Poland) and other parts of Europe, while the Mediterranean basin shows mixed trends. Projected wind erosion estimates are not available for Europe. Nevertheless, drier regions are likely to be more susceptible to wind erosion than wetter regions.

4.4.3 Phenology of plant and animal species

Key messages

- The timing of seasonal events has changed across Europe. A general trend towards earlier spring phenological stages (spring advancement) has been shown in many plant and animal species, mainly due to changes in climate conditions.
- As a consequence of climate-induced changes in plant phenology, the pollen season starts on average 10 days earlier than it did and is longer than it was in the 1960s.
- The life cycles of many animal groups have advanced in recent decades, with events occurring earlier in the year, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies. This advancement is attributed primarily to a warming climate.
- The breeding season of many thermophilic insects (such as butterflies, dragonflies and bark beetles) has been lengthening, allowing, in principle, more generations to be produced per year.
- The observed trends are expected to continue into the future. However, simple extrapolations of current phenological trends may be misleading because the observed relationship between temperature and phenological events may change in the future.

Relevance

Phenology is the timing of seasonal events such as budburst, flowering, dormancy, migration and hibernation. Some phenological responses are triggered by mean temperature, while others are more responsive to day length or weather (Menzel et al., 2006, 2011; Urhausen et al., 2011). Altitude and the amount of urbanisation have an effect on temperature and, consequently, on phenology (Jochner et al., 2012). Generally, so-called 'spring advancement' is seen in hundreds of plant and animal species in many world regions (Peñuelas et al., 2013). Changes in phenology affect the growing season and, thus, ecosystem functioning and productivity. Changes in phenology are having an impact on farming (see Section 5.3), forestry, gardening and wildlife. Changes in flowering have implications for the timing and intensity of the pollen season and related health effects.

Climate warming affects the life cycles of all animal species. Populations at the northern range margins of a species' distribution may benefit from this change, whereas populations at the southern margins may encounter increasing pressure on their life cycles. Mild winters and the earlier onset of spring allow for an earlier onset of reproduction and, in some species, the development of extra generations during the year. However, under unfavourable autumn conditions, the attempted additional generation can result in high mortality. This developmental trap has been suggested as the cause for the dramatic decline of the wall brown, a butterfly with non-overlapping, discrete generations, in Europe (Van Dyck et al., 2015). In the case of a phenological decoupling of species interactions in an ecosystem (e.g. reduced pressure from parasitoids and predators), certain populations may reach very high abundances that attain or exceed damage thresholds in managed ecosystems (Baier et al., 2007). Desynchronisation of phenological events, such as shortened hibernation times, may deteriorate body condition, and interactions between herbivores and host plants could be lost (Visser and Holleman, 2001), and may also negatively affect ecosystem services such as pollination (Hegland et al., 2009; Schweiger et al., 2010). There is robust evidence that generalist species with a high adaptive capacity are favoured, whereas specialist species will be affected mostly negatively (Schweiger et al., 2008, 2012; Roberts et al., 2011).

Past trends

A variety of studies show that there has been a general trend for plant, fungi and animal species to advance their springtime phenology over the past 20–50 years (Cook et al., 2012). An analysis of 315 species of fungi in England showed that, on average, they increased their fruiting season from 33 to 75 days between 1950 and 2005 (Gange et al., 2007). Furthermore, climate warming and changes in the temporal allocation of nutrients to roots seem to have caused significant numbers of plant species to begin fruiting in spring as well as autumn. A study on 53 plant species in the United Kingdom found that they have advanced leafing, flowering and fruiting on average by 5.8 days between 1976 and 2005 (Thackeray et al., 2010). Similarly, 29 perennial plant species in Spain have advanced leaf unfolding on average by 4.8 days, with first flowering having advanced by 5.9 days and fruiting by 3.2 days over the period 1943–2003, whereas leaf senescence was delayed on average by 1.2 days (Gordo and Sanz, 2006b). For plants, a medium spring advancement of four to five days per 1 °C increase has been observed in Europe (Bertin, 2008; Estrella et al., 2009; Amano et al., 2010). Short warm and cold spells also can have a significant effect on phenological events, but this depends strongly on their timing and the species (Koch et al., 2009; Menzel et al., 2011).

Remote sensing data can support the estimation of the trend of phenological phases over large areas. Continental-scale change patterns have been derived from time series of satellite-measured phenological variables (1982–2006) (Ivits et al., 2012). North-eastern Europe showed a trend towards an earlier and longer growing season, particularly in the northern Baltic areas. Despite the earlier leafing, large areas of Europe exhibited a rather stable season length, indicating that the entire growing season has shifted to an earlier period. The northern Mediterranean displayed on average a shift in the growing season towards later in the year, while some instances of earlier and shorter growing seasons were also seen. The correlation of phenological time series with climate data shows a cause-and-effect relationship over the semi-natural areas. In contrast, managed ecosystems have a heterogeneous change pattern with less or no correlation with climatic trends. Over these areas, climatic trends seemed to overlap in a complex manner, with more pronounced effects of local biophysical conditions and/or land management practices. One study demonstrated that the growing season was starting earlier between 2001 and 2011 for the majority of temperate deciduous forests in western Europe, with the most likely cause being regional spring warming effects experienced during the same period (Hamunyela et al., 2013).

A combination of ground observations and the Normalized Difference Vegetation Index (NDVI) both indicated that spring phenology significantly advanced during the period 1982–2011 in central Europe. The average trend of 4.5 days advancement per decade was not uniform and weakened over the last decade investigated, where ground observations and NDVI observations showed different trends (see Figure 4.16). One possible explanation for the weakening trend from 2000 to 2010 is the response of early spring species to the cooling trend in late winter during that time frame (Fu et al., 2014). However, while individual studies find good agreement between *in situ* observations and experimental warming, a meta-analysis (Wolkovich et al., 2012) suggests that experiments can substantially under predict advances in the timing of flowering and leafing of plants in comparison with observational studies.

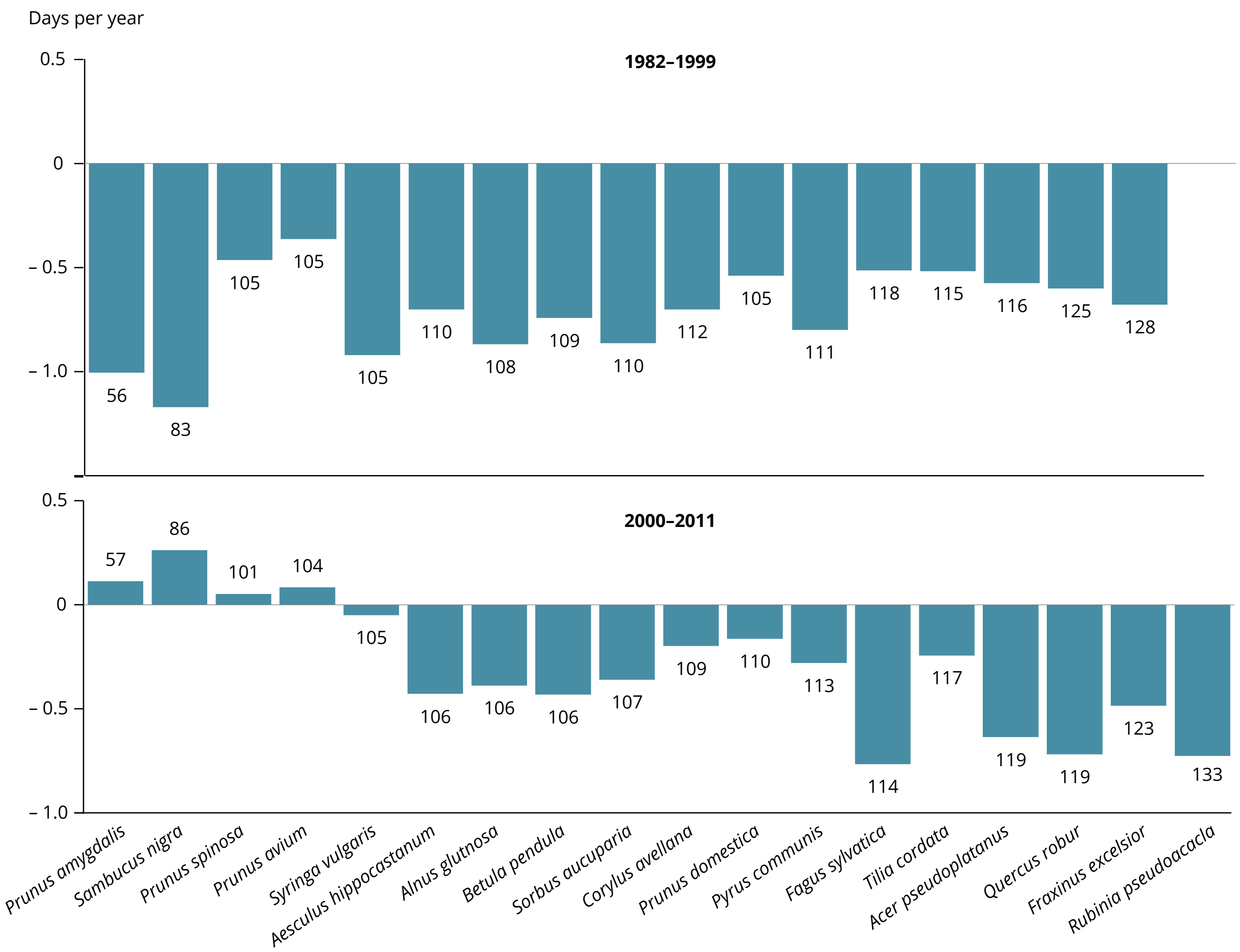
The phenology of numerous animals has advanced significantly in response to recent climate change (Dunn and Møller, 2014). Several studies have convincingly demonstrated that the life-cycle traits of animals are strongly dependent on ambient temperatures, in both terrestrial and aquatic habitats (e.g. Robinet and Roques, 2010; Schlüter et al., 2010; Tryjanowski et al., 2010; Cook et al., 2012; Bowler et al., 2015). Mostly, the observed warming leads to an advanced timing of life history events. For example, temporal trends for the appearance dates of two insect species (honey bee, *Apis mellifera*, and small white butterfly, *Pieris rapae*) in more than 1 000 localities in Spain have closely followed variations in recorded spring temperatures between 1952 and 2004 (Gordo and Sanz, 2006b).

The predicted egg-laying date for the pied flycatcher (*Ficedula hypoleuca*) showed significant advancement between 1980 and 2004 in western and central Europe, but delays in northern Europe, both trends depending on regional temperature trends in the relevant season (Both and Marvelde, 2007). Data from four monitoring stations in south to mid-Norway of nest boxes of the pied flycatcher from 1992 to 2011 show, contrary to the regional temperature estimated trends, that there were no significant delays in the egg-laying date for the pied flycatcher, but there was an annual fluctuation, making a rather flat curve for the median over these years (Framstad, 2012).

Two studies on Swedish butterfly species showed that the average advancement of the mean flight date was 3.6 days per decade since the 1990s (Navarro-Cano et al., 2015; Karlsson, 2014). Of the 66 investigated butterfly species, 57 showed an advancement of the mean flight date, which was significant for 45 species. A study from the United Kingdom found that each of the 44 species of butterfly investigated advanced its date of first appearance since 1976 (Diamond et al., 2011). A study indicated that average rates of phenological change have recently accelerated in line with accelerated warming trends (Thackeray et al., 2010). There is also increasing evidence about climate-induced changes in spring and autumn migration, including formerly migratory bird species becoming resident (Gordo and Sanz, 2006a; Jonzén et al., 2006; Rubolini et al., 2007; Knudsen et al., 2011).

Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer*), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors, including day length and food quality, may complicate this prediction (Kollberg et al., 2013). Warmer temperatures also extend the growing season. This means that plants need more water to keep growing or they will dry out, increasing the risk of

Figure 4.16 Species-specific trends of spring leaf unfolding during the two periods 1982–1999 and 2000–2011



Note: This figure shows species-specific trends of spring leaf unfolding (in days per year) during the two periods 1982–1999 and 2000–2011. The numbers above or below the column are the average dates (calendar day) of species-specific phenological events for the study period.

Source: Adapted from Fu et al., 2014.

failed crops and wildfires. The shorter, milder winters that follow might fail to kill dormant insects, increasing the risk of large, damaging infestations in subsequent seasons. For climate change factors other than temperature, the phenology of emissions of volatile compounds from flowers' seems affected not only by warming or drought but also by the phenological changes in the presence of pollinators. Nevertheless, experimental evidence suggests that phenological effects on pollinator–plant synchrony may be of limited importance (Willmer, 2012; Peñuelas et al., 2013).

Projections

Phenology is primarily seen as an indicator to observe the impacts of climate change on ecosystems and their constituent species. However, an extrapolation of the observed relationship between temperature and phenological events into the future can provide an initial estimate of future changes in phenology. Plants and animal species unable to adjust their phenological behaviour will be negatively affected, particularly in highly seasonal habitats (Both et al., 2010). Obviously, there are limits to possible changes in phenology, beyond which ecosystems have to adapt by changes in species composition. For six dominant European tree species, flushing is expected to advance in the next decades, but this trend substantially differed between species (from 0 to 2.4 days per decade) (Vitasse et al., 2011). Interestingly, the projected advancement is quite similar to the recently observed rates and does not increase, as could have been expected from increasingly rising temperatures. This might indicate some physiological limitations in temporal adaptation to climate change. Leaf senescence of two deciduous species, which is more difficult to predict, is expected to be delayed by 1.4 to 2.3 days per decade. Earlier spring leafing and later autumn senescence are likely to affect the competitive balance between species. Species unable to adjust their phenological behaviour will be negatively affected, particularly in highly seasonal habitats. For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, as the relative importance of influencing factors can change (Cook et al., 2012).

Projections for animal phenology are mainly carried out for species of high economic interest (Hodgson et al., 2011). Quantitative projections are hampered by the high natural variability in phenological data, particularly in insects (Baier et al., 2007). The projected future warming is expected to cause further shifts in animal phenology, with both positive and negative impacts on biodiversity. For example, increasing spring temperatures may have positive fitness effects in sand lizard populations in Sweden (Ljungström et al., 2015). Nevertheless, climate change can lead to an increase of trophic mismatching, unforeseeable outbreaks of species, a decrease of specialist species and changes in ecosystem functioning (van Asch et al. 2007; Singer and Parmesan 2010). A recent study suggests that many pollinator species are not threatened by phenological decoupling from specific flowering plants (Benadi et al., 2014). Other studies simulated the consequences of the phenological shifts in plant–pollinator networks and found that the breadth of the diet of pollinators might decrease because of the reduced overlap between plants and pollinators and that extinctions of plants, pollinators and their crucial interactions could be expected as consequences of these disruptions. Empirical evidence shows that climate change over the last 120 years has resulted in phenological shifts that caused interaction mismatches between flowering plants and bee pollinators. As a consequence, many bee species were extirpated from this system, potentially as a result of climate-induced phenological shifts. Although the plant–pollinator interaction networks are quite flexible, redundancy has been reduced, interaction strengths have weakened and pollinator service has declined (Memmott et al., 2007; Burkle et al., 2013).

4.4.4 Distribution shifts of plant and animal species

Key messages

- Observed climate change is having significant impacts on the distribution of European flora and fauna, with distribution changes of several hundred kilometres projected over the 21st century. These impacts include northwards and uphill range shifts, as well as local and regional extinctions of species.
- The migration of many species is lagging behind the changes in climate owing to intrinsic limitations, habitat use and fragmentation, and other obstacles, suggesting that they are unable to keep pace with the speed of climate change. Observed and modelled differences between actual and required migration rates may lead to a progressive decline in European biodiversity.
- Climate change is likely to exacerbate the problem of invasive species in Europe. As climatic conditions change, some locations may become more favourable to previously harmless alien species, which then become invasive and have negative impacts on their new environments.
- Climate change is affecting the interaction of species that depend on each other for food or other reasons. It can disrupt established interactions but also generate novel ones.

Relevance

Climate change affects ecosystems in complex ways. Many sites will experience a change in the composition and abundance of species. This change does not necessarily translate into species loss, but generalist species appear to be favoured over specialists. The composition of many plant communities is changing, often to such an extent that completely new assemblages are appearing (Urban et al., 2012). The extinction risk is particularly large at the trailing edge (i.e. southern or lower altitudinal range margins) of a species (Dirnböck et al., 2011). The ecological implications of these changes and their effects on the provision of ecosystems services are difficult to assess and quantify. However, it is clear that climate change is an important threat for long-term biodiversity conservation. It threatens the ability of meeting the EU policy target to halt biodiversity loss by 2020. In the longer term, the favourable status of Natura 2000 sites is also in danger (Thuiller et al., 2011; Hickler et al., 2012). The negative effects of climate change not only are having an impact on habitats that already have an unfavourable conservation status, but also are likely to cause changes in habitats that presently have a favourable conservation status (EC, 2013b).

Shifts in the distribution of plant and animal species can have consequences for agriculture (crops and livestock), forestry, human health, biodiversity and its conservation, and ecosystem functions and services (see Section 4.5). The distribution of many animal species will be particularly affected by climate change if habitat fragmentation impedes their movement to more suitable climatic conditions. Northwards and uphill movements are taking place two to three times faster than previously reported (Chen et al., 2011). An increased extinction risk compared with previous findings is predicted, and is supported by observed responses to climate change (Maclean and Wilson, 2011). A 'biotic homogenisation' of specific ecological communities of European flora and fauna (i.e. losing regional uniqueness and characteristics) is projected (Davey et al., 2012). Looking at the Natura 2000 terrestrial species, amphibians are considered to be most vulnerable to climate change. For many invertebrates (with the exception of butterflies), not much is known about their response to climate change, as there is limited knowledge about their ecology or their present distribution (EC, 2013b).

The impacts of climate change on a single species can lead to disruptions or alterations of currently existing species interactions such as competition, herbivory, predation, parasitism, pollination and symbiosis. These interactions are affected because different species adapt their phenology (i.e. the timing of annual events) and their distributional range differently in response to climate change (Kovats et al., 2014; Settele et al., 2014). Species interactions can further be disrupted by invasive species introduced as a result of human interference. Climate change can also affect disturbance regimes, such as wildfires and storms. Biodiversity is increasingly acknowledged as providing indispensable ecosystem services, such as increasing the resistance of ecosystem productivity to climate extremes (Isbell et al., 2015). Therefore, the 'EU Biodiversity Strategy to 2020' regards biodiversity as 'our collective life insurance' (EC, 2011).

An improved understanding of how climate change will affect species interactions in novel communities established under a novel climate can be utilised to assess the extinction risk of species of particular conservation concern. It will also enhance our ability to assess and mitigate potential negative effects on ecosystem functions and services. Despite increasing knowledge of the effects of climate change on pairwise species interactions and on complete ecological networks, quantitative assessments of these effects are still lacking.

Past trends

A wide variety of plant and animal species in Europe have moved northwards and uphill during recent decades. Mountain top floras across Europe have shown significant changes in species composition between 2001 and 2008, with cold-adapted species decreasing and warm-adapted species increasing in number (Gottfried et al., 2012). On average, most species have moved uphill. These shifts have had opposing effects on the species richness of summit floras in boreal-temperate mountain regions (+ 3.9 species on average) and Mediterranean mountain regions (– 1.4 species) (Pauli et al., 2012). Data from Switzerland collected over an altitudinal range of 2 500 m over a short period of eight years (2003–2010) revealed significant shifts in communities of vascular plants towards warm-dwelling species at lower altitudes. However, rates of community changes decreased with altitude (Roth et al., 2014). There is further evidence of increases in the distribution range due to climate change for several plant species (Berger et al., 2007; Walther et al., 2007; Pompe et al., 2011).

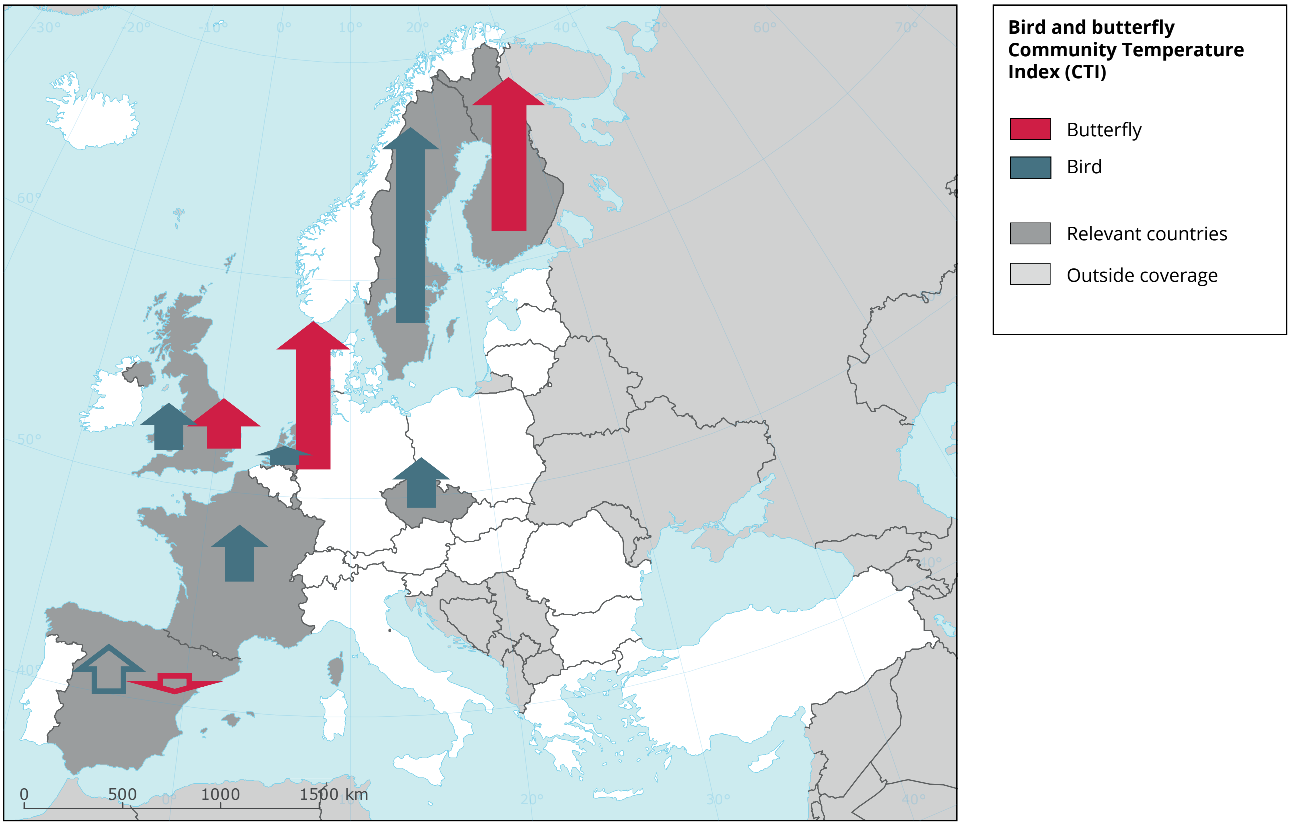
The distributions of many terrestrial animals have recently shifted to higher elevations. In Britain, the distributions of spiders, ground beetles, butterflies, grasshoppers and allies have shifted to higher elevations at a median rate of 11 m per decade, and to higher latitudes at a rate of 17 km per decade, but with substantial variability across and within taxonomic groups (Chen et al., 2011). These range shifts are partly attributable to observed changes in climatic conditions, but land-use and other environmental changes also play a role (Schweiger et al., 2010, 2012). A study in the Netherlands covering the period between 1932 and 2004 found that half of the investigated bird species were overwintering significantly closer to their breeding site than in the past, most likely due to warmer winters (Visser et al., 2009). A long-term trend analysis of 110 common breeding birds across Europe (1980–2005, 20 countries) showed that species with the lowest thermal maxima showed the sharpest declining trends in abundance (Jiguet et al., 2010). In other words, cold-adapted species are losing territory most quickly.

Observations for most species show an expansion at the leading edge (i.e. by expanding the range northwards and/or uphill), whereas there is less evidence for contractions at the trailing edge (i.e. at the southern margins). However, bumblebees, which are an important pollinator for agricultural and natural ecosystems, showed a different response to the observed warming in recent decades. They suffered from strong range contractions at their southern margins of up to 300 km in southern Europe during the last 40 years, but failed to expand northwards, thereby experiencing a substantial compression of their range (Kerr et al., 2015). The Community Temperature Index (CTI) is a measure of the rate of change in community composition in response to temperature change. As the CTI increases, butterfly communities become increasingly composed of species associated with warmer temperatures. For example, the CTI of butterfly communities across Europe has increased by 0.14 °C per decade from 1970 to 2007. However, temperature has increased by 0.39 °C per decade in the same period, that is, almost three times faster than the butterfly community could move northwards (van Swaay et al., 2008). The finding that the movement of animal species is unable to keep pace with climate change has been confirmed in an analysis of the CTI of several thousand local bird and butterfly communities across Europe (see Map 4.15) (Devictor et al., 2012).

A comprehensive review study on amphibians and reptiles found that 20 out of the 21 amphibian and four out of the five reptilian species assessed in Europe were already affected by climate change. The reported effects were negative, mainly through population declines, reductions in habitat suitability, and reduced survival and range sizes, in more than 90 % for amphibians and in more than 60 % for reptiles (Winter et al., 2016). A review study on ducks (*Anatidae*), which are major elements of wetland biodiversity, reports shifts in winter distribution range and phenology. Nevertheless, a phenological mismatch between the periods of peak energy requirements for young and peak seasonal food availability was not found in general with regard to ducks (Guillemain et al., 2013).

The contribution of the Arctic to global biodiversity is substantial, as the region supports globally significant populations of birds, mammals and fish. The Arctic Species Trend Index (ASTI) has been tracking trends in 306 Arctic species. An analysis of the ASTI over 34 years (1970–2004) has shown that the abundance of High Arctic vertebrates declined by 26 % whereas Low Arctic vertebrate species increased in abundance. Sub-Arctic species did not show a trend over the whole time period, but seem to have declined since the mid-1980s (McRae et al., 2010).

Map 4.15 Trend in thermophilic species in bird and butterfly communities



Note: The map shows the temporal trend of the Community Temperature Index (CTI) of birds and butterflies for each country. A temporal increase in CTI directly reflects that the species assemblage of the site is increasingly composed of individuals belonging to species dependent on higher temperatures. The height of each arrow is proportional to the temporal trend and its direction corresponds to the sign of the slope (from south to north for positive slopes). The arrow is opaque if the trend is significant.

Source: Adapted from Devictor et al., 2012.

There is some evidence that climate change has already played a role in the spread of alien animal species in Europe (see Box 4.7).

Projections

The observed northwards and uphill movement of many plant and animal species is projected to continue in the current century. Threatened endemic species with specific requirements of the ecotope or a small distribution range will generally be at greatest risk, in particular if they face migration barriers (Dirnböck et al., 2011).

A modelling study comprising 150 high-mountain plant species across the European Alps projects average range size reductions of 44–50 % by the end of the 21st century (Dullinger et al., 2012). An assessment of the impacts of climate change on 2 632 plant species across all major European mountain ranges under four future climate scenarios projected that habitat loss by 2070–2100 will be greater for species distributed at higher elevations (Engler et al., 2011). Depending on the climate scenario, up to 36–55 % of Alpine plant species, 31–51 % of sub-Alpine plant species and 19–46 % of montane plant species are projected to lose more than 80 % of their suitable habitat. Nevertheless, at the finer scale, microclimate heterogeneity may enable species to persist under climate change in so called micro-climatic refugia (Scherrer and Körner, 2011). A Europe-wide study of the stability of 856 plant species under climate change indicated that the mean stable area of species decreases significantly in Mediterranean scrubland, grassland and warm mixed forests (Alkemade et al., 2011). The rate of climate change is expected to exceed the ability of many plant species to migrate, especially as landscape fragmentation may restrict movement (Meier et al., 2012). A recent study has analysed the likely shifts in distribution for 3 048 plants and animals in England. Of those species, 640 (21 %) were classified as being at high risk owing to the loss of substantial parts of their current distributions as a result of a 2 °C rise in global temperatures (Pearce-Higgins et al., 2015).

Animals generally have a greater capacity than plants to escape unfavourable climatic conditions because of their greater mobility, but they are also affected by climate change. A study based on bioclimatic envelope modelling for 120 native terrestrial European mammals under two climate scenarios showed that 1 % or 5–9 % of European mammals risk extinction (Levinsky et al., 2007). Another study simulated phylogenetic diversity for plants, birds and mammals in an ensemble of forecasts for 2020, 2050 and 2080 (Thuiller et al., 2011). The results show that the tree of life faces a homogenisation across the continent as a result of a reduction in phylogenetic diversity in southern Europe (where immigration from northern Africa was not considered) and gains in high latitudes and altitudes. The limited dispersal ability of many reptiles, amphibians and butterflies, combined with the fragmentation of habitats, is very likely to reduce and isolate the ranges of many of those species (Araújo et al., 2006; Hickling et al., 2006; Settele et al., 2008). A study on the effects of projected climate change on 181 terrestrial mammals in the Mediterranean region projected average declines in species' ranges between 11 and 45 %, depending on the climate scenario and assumptions regarding dispersal (Maiorano et al., 2011). Under a scenario of 3 °C warming above pre-industrial levels by 2100, the ranges of European breeding birds are projected to shift by about 550 km to the north-east, whereby average range size would be reduced by 20 %. Arctic, sub-Arctic and some Iberian species are projected to suffer the greatest range losses (Huntley et al., 2008).

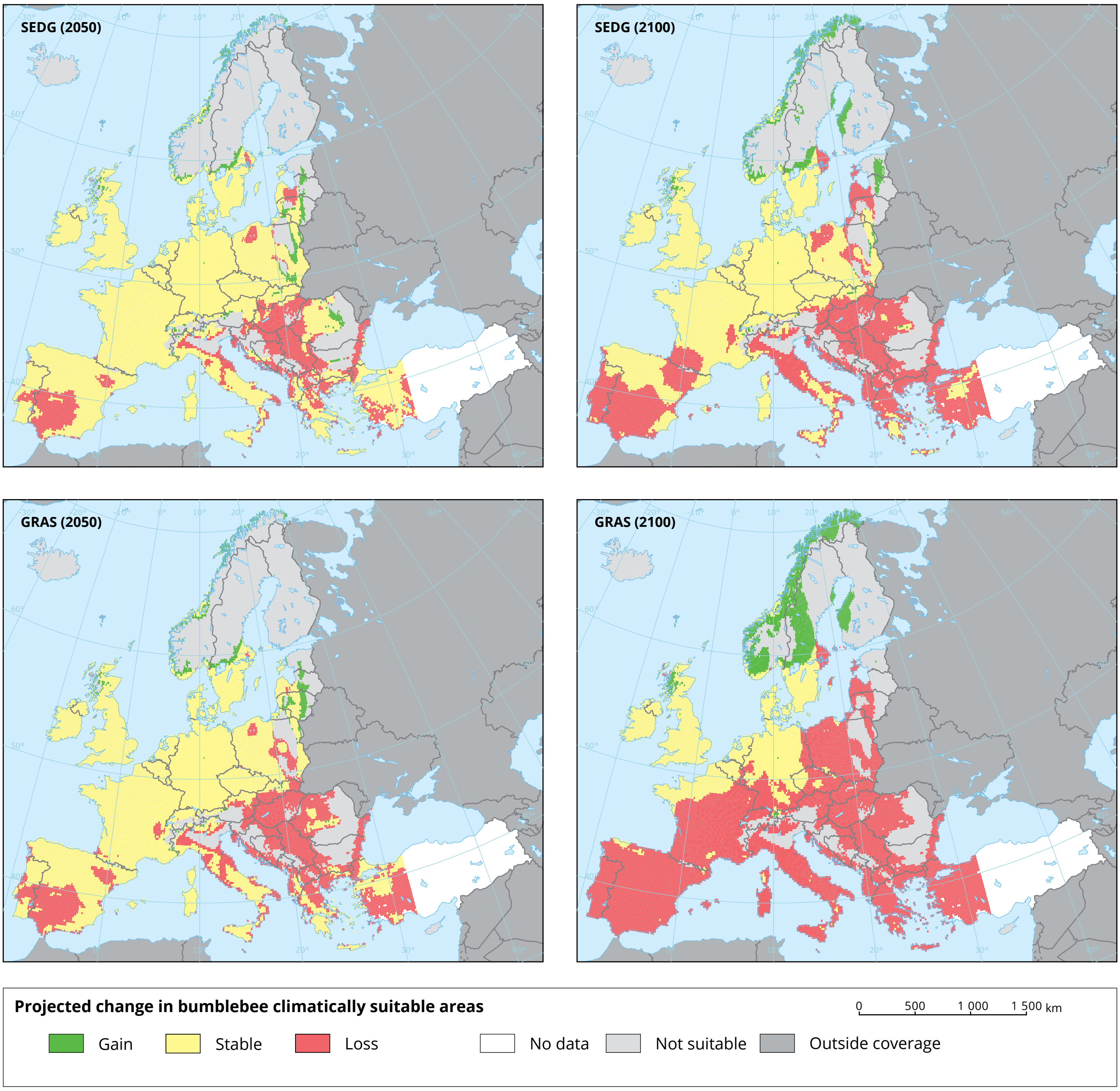
A comprehensive assessment simulated the current climatic niche and future climatically suitable conditions for almost all European bumblebee species based on over one million records from the STEP project ([63]) and three climate change scenarios for the years 2050 and 2100 (see Map 4.16). The number of species on the verge of extinction by 2100 ranges from three (5 % of assessed species) under the lowest climate scenario to 25 (45 % of species) under the highest scenario; under the highest scenario, 53 out of 56 assessed species (95 %) would lose the main part of their suitable habitat (Rasmont et al., 2015). The risk of exposure to extreme climates was investigated using four global circulation model outputs and three emissions scenarios. In total, 1 149 species were simulated (104 amphibians, 248 reptiles, 288 mammals and 509 breeding birds). The results showed that the main hotspots of biodiversity for terrestrial vertebrates may be significantly influenced by climate change, with a regional hotspot in the Mediterranean (Maiorano et al., 2013).

In the Arctic and sub-Arctic, warmer and wetter future conditions allow a considerable number of mammals, reptiles, amphibians and birds to expand their distribution range. However, various species (especially habitat specialists) are expected to contract their range over time. Furthermore, a number of new species are predicted to be able to invade the region, altering community composition and biotic interactions in ways difficult to anticipate (Hof et al., 2012).

As the climatic conditions of some locations in Europe change, they may become more favourable to the establishment and survival of alien species, making native species, communities and ecosystems more vulnerable (see Box 4.7) (EC, 2014a). On the other hand, climate change may also offer some opportunities to control alien species that are predicted to suffer from climate change. Whereas some components of global change, such as rising CO_2, usually promote invasion, other components, such as changing temperature and precipitation, can help or hinder plant invasion. Therefore, in some cases climate change can offer unprecedented opportunities for restoration of species distribution.

([63]) For more information on the Status and Trends of European Pollinators (STEP) project, see http://www.step-project.net.

Map 4.16 Projected change in climatically suitable areas for bumblebees



Note: The map shows the projected change in the climatically suitable area for the bumblebee *Bombus terrestris* (the largest and one of the most numerous bumblebee species in Europe) for two time horizons and under the combined climate–land use scenarios SEDG (Sustainable European Development Goal, based on SRES B1) and GRAS (Growth Applied Strategy, based on SRES A2).

Source: Adapted from Rasmont et al., 2015.

Box 4.7 Alien species and climate change: new establishments and new ranges?

It is difficult to predict how global environmental changes such as climate change and biological invasions will affect ecological systems. Because alien species are mostly opportunistic and generalists, they tend to perform better under a rapidly changing climate than native species (Hellmann et al., 2008). There is growing concern that invasive alien species may benefit from climate change and further deterioration in the environment, allowing them to increasingly compete (i.e. increase their establishment and reproduction rates and their niche breadth) with native species to the latter's disadvantage (Walther et al., 2009; EEA, 2010; Kleinbauer et al., 2010a; EC, 2014a). Invasive alien species may affect and reduce native biodiversity in various ways, such as through competition for food and space, predation, disease transfer, and changing habitat structure and functions. They have negative consequences for their new environment and significant adverse impacts on the goods and services provided by ecosystems, on the economy and on human health (Millennium Ecosystem Assessment, 2005; Vilà et al., 2010, 2011; Blackburn et al., 2014; Rabitsch et al., 2016). In response to these increasing pressures, the European Union has recently adopted a dedicated legislation on invasive alien species (IAS), which aims to reduce the future impacts of alien species (EU, 2014).

According to the DAISIE ([64]) project, there are more than 12 000 non-native species in Europe. An estimated 1 200–1 800 of them are invasive, and this figure is predicted to rise with the growth in global trade and travel (EC, 2014a). Some recent trends in alien species introductions to Europe are shown in Figure 4.17. The positive trend in the establishment of new species indicates that the problem is far from under control, with impacts on biodiversity expected to increase because of the growing number of species involved, and an increasing vulnerability of ecosystems to invasions, which results from other pressures such as habitat loss, degradation, fragmentation, overexploitation and climate change. The situation is particularly worrying in marine and island ecosystems (EEA, 2010).

According to the most recent global analysis of the Red List (IUCN, 2012), IAS constitute a severe threat to various taxonomic groups of plants and animals. The Red List Index allows the impacts of alien species on the conservation status of native species to be quantified and indicates the rates at which affected species are moving towards or away from extinction. Amphibians are known to be particularly affected by IAS and their associated pathogens and diseases. A recent analysis regarded IAS as a threat to 8 out of the 11 species of amphibians whose Red List status deteriorated between 2004 and 2009 (Rabitsch et al., 2016).

Horticulture and ornamental plant trade are by far the most important pathways of plant introductions to Europe (Keller et al., 2011). According to the data from EASIN ([65]), stowaway (introductions through shipping, aviation and land transport) is the main pathway for introductions of both terrestrial and aquatic alien species (Katsanevakis et al., 2015). It is difficult to identify and quantify the role of climate change in species invasions. However, a recent modelling study on '100 of the world's worst invasive alien species' indicates that, besides habitat characteristics and socio-economic variables such as the distance to airports, seaports and human population density, climate variables were the main predictors of the distribution of the studied invasive species (Bellard et al., 2013). Climate change mitigation and adaptation measures may also contribute to the introduction of new species, for example through cultivation of energy plants and increasing use of dry-adapted species in forestry (IUCN, 2009).

It is important to note that, while improved border control regulations at Europe's external borders might limit new invasions, many alien species are already in Europe. Many of these species are currently limited by various environmental factors, but they might become invasive at some point in the future and no control measures are currently in place to limit invasions from such species.

An increasing number of warm-adapted alien plant species have recently become established in central Europe, such as palms, cacti and evergreen tree species (Berger et al., 2007; Walther et al., 2007; Essl and Kobler, 2009). One example is the windmill palm (*Trachycarpus fortunei*), which was introduced more than a century ago, but became established in the wild only recently after the average winter temperature increased and the severity of cold spells decreased (Berger et al., 2007). Alien plant species have also increased their range by moving uphill (Pauchard et al., 2009). Most alien plant species originate from warmer regions and will therefore benefit from the projected climate change in Europe (Walther et al., 2009; Schweiger et al., 2010; Hulme, 2012). For example, future climate will become more suitable for 30 major invasive alien plant species in large parts of Austria and Germany under different climate change scenarios (Kleinbauer et al., 2010b).

([64]) Delivering Alien Invasive Species Inventories for Europe (DAISIE) is a research project funded by the European Commission through the Sixth Framework Programme, and by the Centre for Ecology and Hydrology (CEH); see http://www.europe-aliens.org.

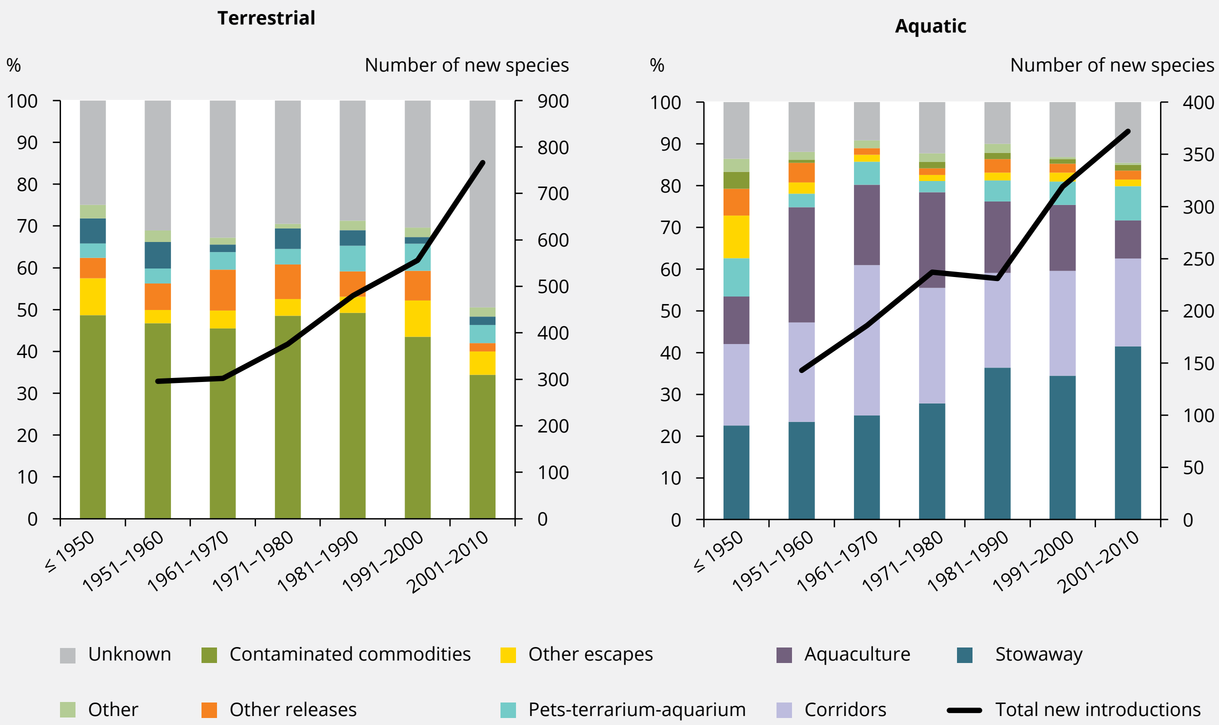
([65]) The European Alien Species Information Network (EASIN) was launched in 2012 by the European Commission to facilitate the exploration of information on existing alien species and to assist the implementation of European policies on biological invasions; see http://easin.jrc.ec.europa.eu.

Box 4.7 Alien species and climate change: new establishments and new ranges? (cont.)

The red-eared slider turtle (*Trachemys scripta elegans*) is native to eastern North America and was introduced to Europe as a pet in the 1960s (ISSG, 2011). In Europe, it can currently only reproduce in the Mediterranean, but this range is projected to shift further northwards with climate change (Ficetola et al., 2009). The spread of alien animal species into new regions is favoured by the impact of climate change on ecosystems and landscapes (e.g. rapid climatically driven change in ecosystem composition), by a weakening resistance of native species to alien predators and parasites, and by decreasing climatic constraints on warm-adapted alien species (e.g. research findings suggest that the pumpkinseed (*Lepomis gibbosus*), a freshwater fish, will become more invasive under warmer climatic conditions) (Copp and Fox, 2007).

Indicators of alien species can provide vital information on the trends of biological invasions and on the efficacy of response measures put in place for use in biodiversity policy. Based on the current policy needs and previous work on the global scale, a recently published paper has suggested a set of six indicators for invasive species in Europe, which capture complementary facets of biological invasions in Europe: (1) a combined index of invasion trends, (2) an indicator on pathways of invasions, (3) the Red List Index of IAS, (4) an indicator of the impacts of IAS on ecosystem services, (5) trends in the incidence of livestock diseases and (6) an indicator on the costs for management of and research on alien species (Rabitsch et al., 2016).

Figure 4.17 Trends and temporal variation of the importance of the main pathways of introduction in Europe of terrestrial and aquatic alien species



Note: The figures show the overall trends in the number of terrestrial (left) and aquatic (right) alien species introductions to Europe (black line, right scale) as well as the relative importance of main pathways over time (coloured bars, left scale).

Source: Adapted from Katsanevakis et al., 2015.

4.4.5 Forest composition and distribution

Key messages

- Range shifts in forest tree species due to climate change have been observed towards higher altitudes and latitudes. These changes considerably affect the forest structure and the functioning of forest ecosystems and their services.
- Future climate change and increasing CO_2 concentrations are expected to affect site suitability, productivity, species composition and biodiversity. In general, forest growth is projected to increase in northern Europe and to decrease in southern Europe, but with substantial regional variation. Cold-adapted coniferous tree species are projected to lose large fractions of their ranges to more drought-adapted broadleaf species.
- The projected changes will have an impact on the goods and services that forests provide. For example, the value of forest land in Europe is projected to decrease between 14 and 50 % during the 21st century.

Relevance

Forests and other wooded land cover approximately 182 million ha (1.82 million km^2) in the EU-28 region; this area has increased by more than 4 million ha in the last 15 years (UNECE and FAO, 2015). Forests and woodlands are key providers of timber, wood fuel and energy, water, food, medicines, recreation and other ecosystem services. Forests are habitats for a large fraction of biological diversity. The pervasive influence of climate on forests is obvious. Climate affects the composition, structure, growth, health and dynamics of forest ecosystems. At the same time, forests also influence local, regional and even global climate through carbon removal from the atmosphere, absorption or reflection of solar radiation (albedo), cooling through evapotranspiration, and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011). Changes in temperature and the availability of water will affect the relative health and productivity of different species in complex ways, thereby influencing the range of most species and forest composition. These shifts may have severe ecological and economic consequences (Hanewinkel et al., 2012). Generally, European forests have been becoming older and they have been close to carbon saturation point (Nabuurs et al., 2013). More information on the state and trends of European forest ecosystems can be found in EEA (2016).

Short- and long-term managing strategies are needed to mitigate and adapt to the impacts of climate change on European forests and forestry. Strategies should focus on enhancing forest ecosystems' resistance and resilience, and on addressing potential limits to carbon accumulation (Kolström et al., 2011; EC, 2013a). Maintaining and restoring biodiversity in forests promotes their resilience and therefore can buffer climate change impacts (Thompson et al., 2009). Specific strategies may include planting species that are better adapted to warm conditions and more resistant to pests and diseases, landscape planning and forest management oriented towards decreasing fuel loads in fire-prone areas, the promotion of carbon storage, the consideration of renewable energy and the introduction of payments for services from forests (Fares et al., 2015). Nevertheless, introduced alien species may have negative effects on the native flora, e.g. through competition with native species or by modifying the physical condition of the sites (Kjær et al., 2014).

Past trends

Trees are slow-migrating species. Range expansion occurs primarily into newly suitable habitats at their (generally northern) latitudinal or (upper) altitudinal limit. Range contraction occurs primarily at the rear edge, which is often the most southern or the lowest lying part of their distribution range. These areas can become unsuitable for tree species as a result of direct effects (e.g. drought) or indirect effects (e.g. drought-induced pests or diseases) of climate change. In France, the altitudinal distribution of 171 forest plant species along the elevation range 0–2 600 m was studied using a 101-year data record starting in 1905. Climate warming has resulted in a significant upwards shift in species optimum elevation averaging 29 m per decade, but with a wide range from + 238 to – 171 m per decade (Lenoir et al., 2008). Land-use changes are the most likely explanation of the observed significant downwards shifts in some regions (Lenoir et al., 2010). In the Montseny mountain range in north-east Spain, the altitude range of beech extended by about 70 m upwards according to different data sources from the 1940s to 2001 (Penuelas and Boada, 2003). A study comparing data from the 1990s with data from the 2000s in the Spanish Pyrenees and the Iberian Peninsula found an average optimum elevation shift of 31 m upwards per decade for five tree species, ranging between − 34 and + 181 m per decade (Urli et al., 2014). Nevertheless, not all studies found clear climate signals, partly because tree species can experience time lags in their migration response to climate change (Rabasa et al., 2013; Renwick and Rocca, 2015).

In addition to range shifts, changes in forest composition have been observed in the past. In a Swedish spruce-beech forest, a long-term study covering the period since 1894 showed that spruce has been losing its competitive advantage over beech since 1960 (Bolte et al., 2010). In north-east Spain, beech forests and heather heathlands have been replaced by holm oak forest at medium altitudes (800–1 400 m), mainly as a result of the combination of warming temperatures and land-use change (Penuelas and Boada, 2003). Field-based observations from a forest inventory providing presence and absence information from 1880 to 2010 for a Mediterranean holm oak species (*Quercus ilex*) have been used to investigate the migration speed in the past. In four studied forests in France along the Atlantic coast, *Quercus ilex* has colonised a substantial amount of new space, but the northwards movement occurred at an unexpected low maximum rate of 22 to 57 m/year across the four forests (Delzon et al., 2013).

Extreme climate and weather events such as droughts can have negative effects on food webs and regional tree dieback For the Iberian Peninsula, the defoliation of trees due to a water deficit rose significantly between 1987 and 2007 in all 16 examined tree species. Defoliation doubled on average, and this trend was paralleled by significant increases in tree mortality rates in drier areas (Carnicer et al., 2011). Furthermore, droughts can lead to secondary impacts on forests through pests and pathogens (Jactel et al., 2012).

Projections

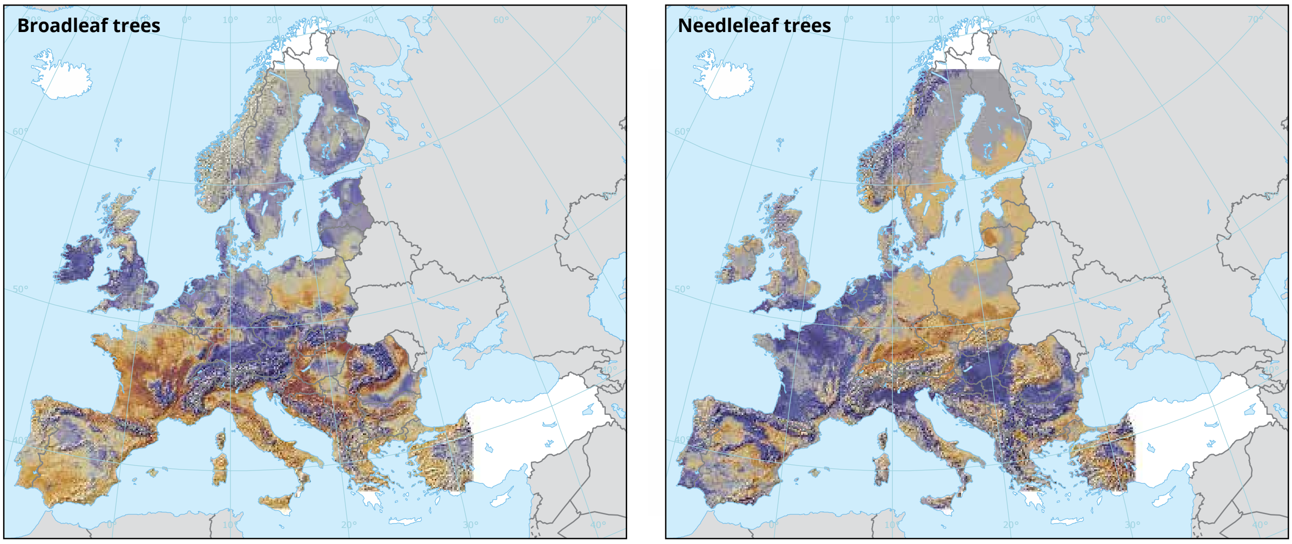
Climate change is expected to strongly affect the biological and economic viability of different tree species in Europe, as well as competition between tree species. A study in Finland showed that climate change may lead to a local reduction of forest growth but total forest growth nationwide may increase by 44 % during the 21st century (Kellomäki et al., 2008). Observations and simulations of tree mitigation rates suggest that only fast-growing, early successional tree species will be able to track climate change (Delzon et al., 2013; Fitzgerald and Lindner, 2013). Recent studies that simulated forest composition and range shifts in Europe and at the global level using different climate and land-use scenarios suggest upwards shifts in the tree line and northwards migration of boreal forests (Lindner et al., 2014; Betts et al., 2015). Broadleaf tree cover in Europe is projected to increase during the 21st century under all climate scenarios, whereas needleleaf tree cover decreases, despite a northward extension in northern Europe (Map 4.17).

A large-scale integrated project on adaptive forest management (MOTIVE) ([66]) applied an array of models (empirical as well as hybrid and process-based) in the analysis of the impacts of climate change on 38 European tree species. The results show that more drought-tolerant species such as sessile oak (*Quercus petraea*), pubescent oak (*Quercus pubescens*) and Scots pine (*Pinus sylvestris*) can be expected to become more abundant at lower altitudes throughout Europe, while other species such as beech (*Fagus sylvatica*), sycamore maple (*Acer pseudoplatanus*), lime (*Tilia*), elm (*Ulmus*) or silver fir (*Abies alba*) are likely to see further reductions in their ranges. Species from (sub-)Mediterranean regions such as holm oak (*Quercus ilex*), hop hornbeam (*Ostrya carpinifolia*) and cork oak (*Quercus suber*) are expected to extend their ranges to the north. Different pine species are also expected to extend their ranges quite considerably. Some species, such as Scots pine (*Pinus sylvestris*), might face indirect threats from insects and other pest outbreaks, rather than direct threats from climate change alone. In summary, the projected range shifts will affect the forest structure quite considerably. Such changes will also affect the functioning of forest ecosystems and the services these ecosystems could provide (Fitzgerald and Lindner, 2013).

Another modelling study assessed the impacts of projected climate change on forest composition across Europe and the economic consequences in terms of annual productivity and land value (Hanewinkel et al., 2012). It projected that the major commercial tree species in Europe, Norway spruce, will shifts northwards and to higher altitudes. It will lose large parts of its present range in central, eastern and western Europe under all scenarios (SRES A1B, A1FI and B2). Depending on the emissions scenario and climate model, between 21 and 60 % (mean: 34 %) of European forest lands were projected to be suitable only for a forest type of Mediterranean oak, with low economic returns by 2100, compared with 11 % in the baseline period 1961–1990. As a result of the decline of economically valuable species, the value of forest land in Europe is projected to decrease between 14 and 50 % (mean: 28 % for an interest rate of 2 %) by 2100. The economic loss in land estimation value is estimated at several hundred billion euros.

([66]) MOTIVE: 'Models for Adaptive Forest Management'; see http://motive-project.net.

Map 4.17 Projected change in climatic suitability for broadleaf and needleleaf trees



Projected changes in broadleaf (left) and needleleaf (right) tree composition from species habitat suitability changes

High: 13
Low: – 13

No data
Outside coverage

0 500 1 000 1 500 km

High: 4
Low: – 5

Note: The two maps indicate to what degree broadleaf (left) and needleleaf (right) tree species are expected to increase (blue) or decrease (brown) in numbers by 2100. The results represent ensemble species distribution modelling simulations, using climate projections from six RCMs under the A1B scenario.

Source: Adapted from Lindner et al., 2014.

4.4.6 Forest fires

Key messages

- Fire risk depends on many factors, including climatic conditions, vegetation, forest management practices and other socio-economic factors.
- The number of forest fires in the Mediterranean region increased from 1980 to 2000; it has decreased thereafter. The burnt area shows a decreasing trend over the period 1980–2013, but with strong interannual variability.
- In a warmer climate, more severe fire weather and, as a consequence, an expansion of the fire-prone area and longer fire seasons are projected across Europe. The impact of fire events is particularly strong in southern Europe.

Relevance

Forest fires are an integral part of forest ecosystem dynamics in many ecosystems, as they are an essential element of forest renewal. They help control insect and disease damage and eliminate litter that has accumulated on forest floors. At the same time, forest fires are a significant disturbance agent in many forested landscapes. Fire risk depends on many factors such as weather, vegetation (e.g. fuel load and condition), topography, forest management practices and socio-economic context, to mention the main ones. The extreme fire episodes and devastating fire seasons of recent years in Europe were, in most cases, driven by severe fire weather conditions. Although most of the wild fires in Europe are ignited by humans (either accidently or intentionally), it is widely recognised that weather conditions and the accumulation of fuel play dominant roles in affecting the changes in fire risk over time (Camia and Amatulli, 2009). Thus, climate change is expected to have a strong impact on forest fire regimes in Europe.

Past trends

The number and extent of forest fires vary considerably from one year to the next, depending on the seasonal meteorological conditions. Some multi-annual periodicity in the burned area trend can also be partially attributed to the dead biomass burning/accumulation cycle typical of the fire-prone regions. The historical trend of the number of fires is difficult to analyse because fire frequency is strongly affected by the significant changes that occurred in past years in the statistical reporting systems of the countries.

Historical fire series are available in Europe and are regularly updated within the European Forest Fire Information System (EFFIS) ([67]). Data availability in EFFIS is not the same for all countries, and time series longer than 25 years are available for only a few countries. Figure 4.18 shows that the reported fire frequency in the five southern European countries for which long time series are available increased during the 1990s, then stabilised for around one decade, and slightly decreased during recent years. The burnt area shows a decreasing trend over the period 1980–2013, but with strong interannual variability. Note that these values cannot be compared across countries because of large differences across countries in the total area and the area at risk.

In 2014, a large forest fire severely damaged more than 15 000 ha of forest land in Västmanland County, Sweden (EC, 2014b). Forest fires are also affecting new areas. For example, in 2007, wildfires moved to previously non-fire-prone ecosystems in southern Greece (Koutsias et al., 2012).

Past trends of fire danger have also been analysed by processing series of meteorological fire danger indices, which are routinely used to rate the fire potential owing to weather conditions. The Canadian Fire Weather Index (FWI) is used in EFFIS to rate the daily fire danger conditions in Europe (Van Wagner, 1987). Daily severity values can be averaged over the fire season obtaining a Seasonal Severity Rating (SSR) index. The index is dimensionless and allows objective comparison of fire danger from year to year and from region to region; SSR values above six may be considered in the extreme range.

Map 4.18 shows the current state, past trend and projections for forest fire danger based on annual SSR values, which have been computed using daily weather data including air temperature, relative

([67]) http://forest.jrc.ec.europa.eu/effis.

humidity, wind and precipitation from the European Centre for Medium-Range Weather Forecasts (ECMWF). Other driving factors of fire regimes, such as land-use changes or fuel dynamics, are not taken into account by the SSR. The upper left map shows the average SSR values during the period 1981–2010; the lower left map shows the linear trends over this period, which indicate that there has been a significant increase in forest fire danger in several regions in Europe.

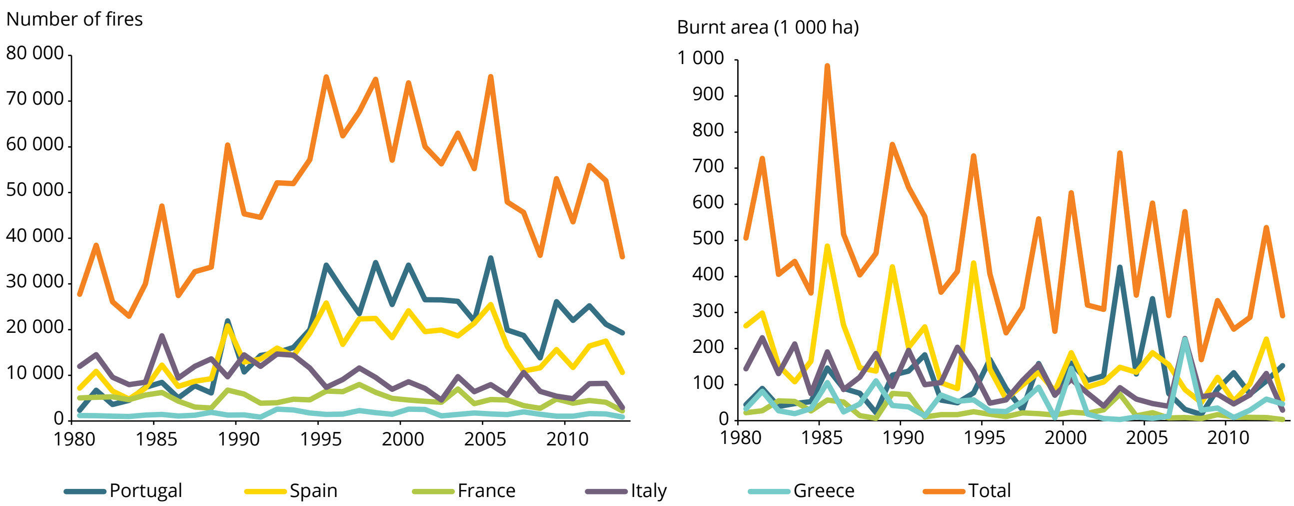
Projections

Climate change projections suggest substantial warming and increases in the number of droughts, heat waves and dry spells across most of the Mediterranean area and more generally in southern Europe (see Sections 3.2.3 and 4.3.4). These projected changes would increase the length and severity of the fire season, the area at risk and the probability of large fires, possibly enhancing desertification (Moreno, 2014).

Map 4.18 also includes fire danger projections for projected climate conditions in 2071–2100 (upper right map: projected state; lower right map: projected change). The results suggest that climate change would lead to a marked increase of fire potential in south-eastern and south-western Europe; in relative terms, the increase in SSR would be particularly strong in western-central Europe (Khabarov et al., 2014). Similar results were obtained for other forest fire indices, such as the FWI (Bedia et al., 2013).

The PESETA II study ([68]) has estimated that the burnt area in southern Europe would more than double during the 21st century for a reference climate scenario and increase by nearly 50 % for a 2 °C scenario (Ciscar et al., 2014). Another study has estimated a potential increase in burnt areas in Europe by about 200 % during the 21st century under a high emissions scenario (SRES A2) assuming no adaptation. The forest fire risk could be substantially reduced by additional adaptation measures, such as prescribed burning, fire breaks and behavioural changes (Khabarov et al., 2014).

Figure 4.18 Number of forest fires and burnt area in five southern European countries

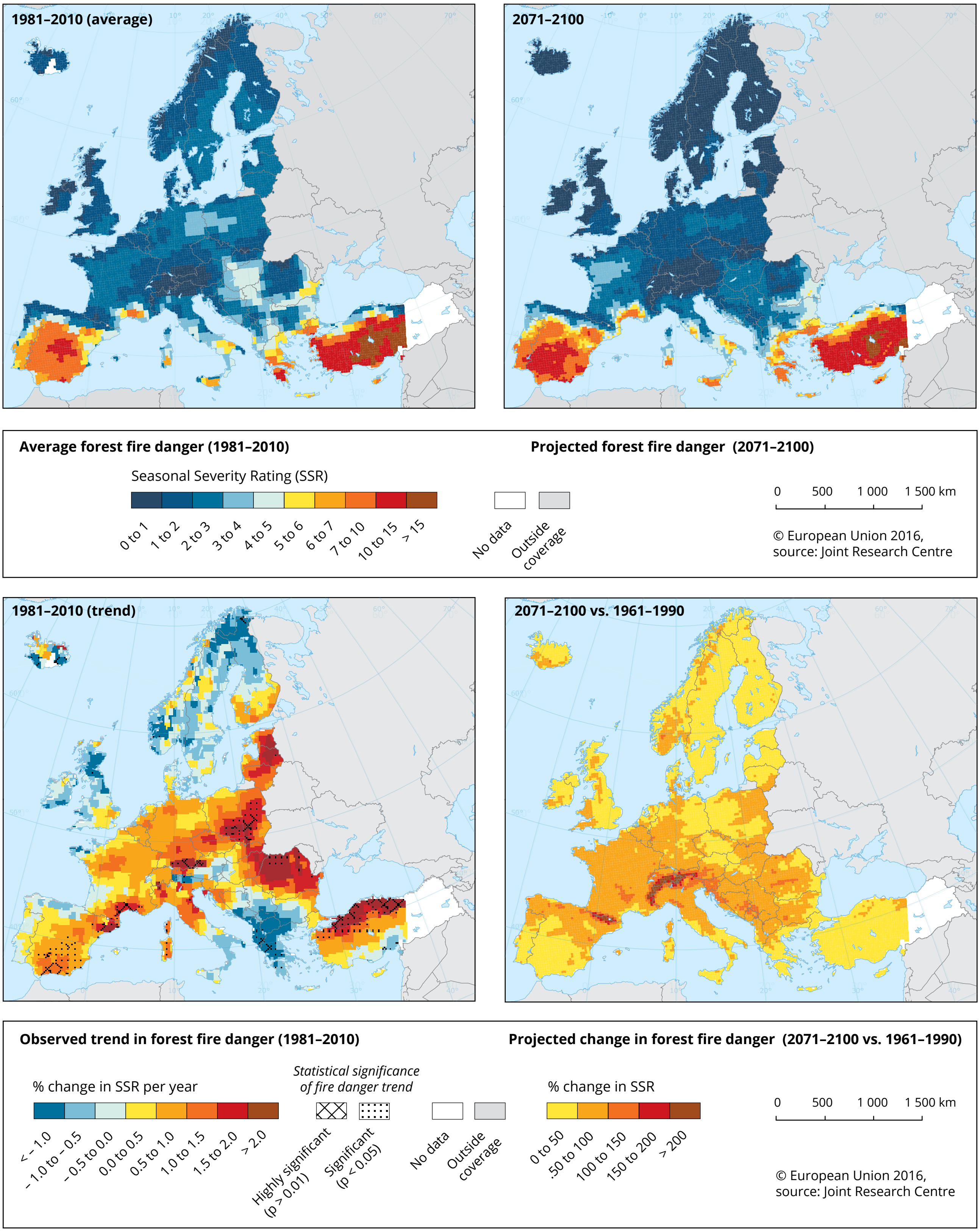


Note: Number of forest fires (left) and burnt area (right) in five southern European countries from 1980 to 2013.

Source: Adapted from San-Miguel-Ayanz et al., 2013 and Schmuck et al., 2015.

([68]) Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis, see https://ec.europa.eu/jrc/en/peseta.

Map 4.18 Current state, past trend and projections for forest fire danger



Note: Fire danger is expressed using the SSR. Daily severity values can be averaged over the fire season using the SSR index, which allows for objective comparison of fire danger from year to year and from region to region. The coarse scale of the map does not allow specific conditions of given sites to be accounted for, as, for example, in the Alpine region, where the complex topography may strongly affect local fire danger.

Source: Camia, 2012 (personal communication), based on Camia et al., 2008.

4.4.7 Forest pests and diseases

Key messages

- The incidence of forest insect pests, which represent a serious threat to forests, has increased across Europe.
- Climate change will have a major influence on the spatial and temporal distribution of forest insect pests in Europe, with increased risks projected in most regions.

Relevance

Forest insect and pathogen species are currently expanding their geographical ranges, in many cases owing to introductions facilitated by international trade. Several invasive alien species have damaging impacts on agricultural, forest and natural resources. Populations of forest insect pests can be influenced by climate change, as it leads to a longer growing season, variations in precipitation patterns, modifications in food availability, and qualitative and quantitative changes in their predator and parasite populations (Netherer and Schopf, 2010). There is evidence that these changes affect the distribution and relative abundance of pest species in forest ecosystems, thus changing the frequency of pest outbreaks (Marini et al., 2012; Spathelf et al., 2014; Barredo et al., 2015). In Europe, higher temperatures are likely to promote distributional shifts of forest insect pests towards northern latitudes and higher elevations.

In the southern Mediterranean region and in some continental zones, warmer temperatures and the increased frequency of droughts are likely to affect heat-sensitive insects, resulting in a northwards and upwards shift of their geographic range. Heat-tolerant species, on the other hand, such as the pine processionary moth (*Thaumetopoea pityocampa*) or the oak processionary moth (*Thaumetopoea processionea*), will probably benefit from warmer conditions and hence expand their geographical range beyond the Mediterranean region and expand into previously unaffected areas. However, temperature increase and drought could shrink the southern range of these species, resulting in some cases in range contraction (Netherer and Schopf, 2010; Battisti et al., 2014).

Past trends

Disturbances such as drought, windthrow, fires, and attacks by insect pests and pathogens of trees are naturally occurring in forests. Nevertheless, despite many uncertainties, there is consensus on an increased incidence of pests and diseases in European forests (Marcais and Desprez-Loustau, 2007; Moore and Allard, 2008) and on shifts in the spatial and temporal range of insects as a result of climatic change (Netherer and Schopf, 2010; Bebber et al., 2014; Seidl et al., 2014). In addition, some species of fungi and pests benefit from milder winter temperatures in temperate forests, facilitating the spread of pests formerly controlled by frost sensitivity (Settele et al., 2014), while other species spread during drought periods to northern latitudes (Drenkhan et al., 2006; Hanso and Drenkhan, 2007).

A review study concluded that several changes have already been observed in the occurrence of forest pests in Europe (Netherer and Schopf, 2010). The European spruce bark beetle (*Ips typographus*) has been reacting to warmer and drier spring and summer periods in recent decades by having a shorter development period, which enables multiple generations (Baier et al., 2007). The spread of insect outbreak zones has been observed in those regions with the greatest warming in boreal forests (Malmström and Raffa, 2000; Volney and Fleming, 2000). In temperate continental forests, tree defoliation by the gypsy moth (*Lymantria dispar dispar*) and the incidence of other insect pests are among the factors responsible for oak decline in central Europe (Balci and Halmschlager, 2003). In addition, altitudinal shifts of the moth have been observed in Slovakia (Hlásny and Turčáni, 2009). In the Mediterranean region, altitudinal range expansion of the pine processionary moth (*Thaumetopoea pityocampa*) has also been observed in mountain regions of the Sierra Nevada in the United States and the Sierra de Baza in Spain (Hódar et al., 2003) and in mountainous regions of Italy (Battisti, 2008; Petrucco-Toffolo and Battisti, 2008). In Britain, Dothistroma needle blight has spread rapidly since about 1995 (Forestry Commission, 2012).

Climate change has driven range shifts in tree species and increased drought effects resulting in forest dieback (Allen et al., 2010). In addition, forests are increasingly coping with human-related stressors that affect forest condition, either directly through logging and clearing or indirectly through air pollution and introduction of invasive species (Trumbore et al., 2015). These processes, in combination with changes in climatic parameters, could facilitate propagation and increase the number of forest insects and pathogens. However, the interaction between different impact factors, biotic and abiotic, is only partly understood. What is known is that changing environmental conditions will produce ambiguous consequences regarding forest pests, involving positive, indifferent and negative responses (Netherer and Schopf, 2010).

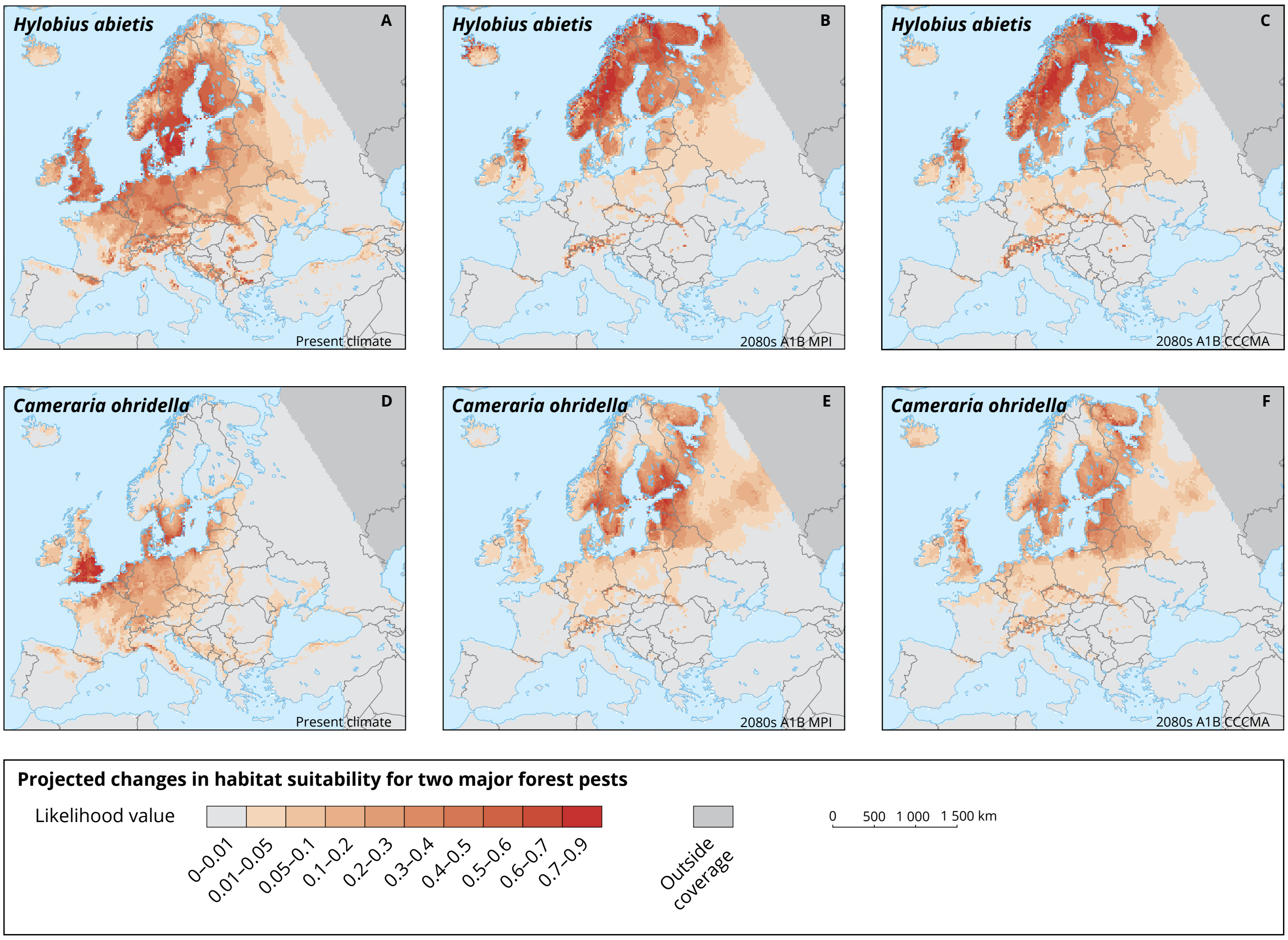
Dramatic changes have been observed over time in the sources of forest pathogens that have become established across Europe (Santini et al., 2013). The earliest known establishments of pathogen species were largely a result of intra-European spread. With increased trade activities, species from North America and, later, Asia became more important and even the dominant sources of pathogens. Historical evidence indicates that the import of live plants has facilitated the majority of forest insect and pathogen invasions. There is a strong trend of increasing trade in live plants, which could further facilitate the proliferation of forest insects and diseases (Liebhold et al., 2012).

Projections

Climate change can affect the distribution of insect pests by expanding or contracting their habitat range and by shifting it to regions beyond their current climatic range. This suggests that forest areas that are currently not vulnerable to a certain insect pest may become vulnerable under the future climate and vice versa. Species distribution modelling has been applied in several studies to assess the future vulnerability of forests to insect pests. One study has integrated insect pest distribution data, bioclimatic variables and host tree species maps illustrating the potential effects of climate change in the habitat distribution of two exemplar forest insect pests in Europe (Barredo et al., 2015). The results suggest that the suitable habitat of the large pine weevil (*Hylobius abietis*) will probably decrease by more than 20 % by the end of the century under the SRES A1B scenario, compared with the present situation (darker areas in Map 4.19A). The results indicate a shift in the distribution of suitable habitat for *Hylobius abietis* towards northern regions and regions at higher elevations (Map 4.19B and Map 4.19C). Results for another insect pest, the horse-chestnut leaf miner (*Cameraria ohridella*), project that there will be an increase in the total potential suitable habitat of more than 40 % resulting from a shift in the potential suitable habitat towards northern regions and higher elevations (Map 4.19E and Map 4.19F). The driver of the potential habitat maps shown in Map 4.19 is climate data. Note that other factors such as the presence of host tree species or land cover are not considered in these maps. Similar results were found by other studies for Europe and the United States (Netherer and Schopf, 2010; Evangelista et al., 2011).

Actions intended to mitigate the effect of forest pests should be targeted at specific pests and should consider the full range of environmental factors driving insect pest phenology and distribution. Forest mortality could be reduced by selecting tree species that are better adapted to relatively warm environmental conditions (Resco de Dios et al., 2006) or that are more resistant to damage by pests and diseases in pure stands (Jactel et al., 2012).

Map 4.19 Projected changes in habitat suitability for two major forest pests



Note: Habitat suitability maps of *Hylobius abietis* (large pine weevil) and *Cameraria ohridella* (horse-chestnut leaf miner) resulting from the Maxent model. A darker colour represents a higher probability of suitable habitat. (A) and (D) show habitat suitability maps of the present climate. (B) and (E) show projected (2080s) habitat suitability maps according to the Max Planck Institute (MPI) ECHAM5. (C) and (F) show projected (2080s) habitat suitability maps according to the Canadian Centre for Climate Modeling and Analysis (CCCMA) Coupled General Circulation Model version 3 (CGCM3).

Source: Adapted from Barredo et al., 2015.

4.5 Ecosystems and their services

Key messages

- Climate change significantly affects ecosystems, their biodiversity and consequently their capacity to provide services for human well-being; it may have already triggered shifts in ecological regimes from one state to another.
- Climate change is increasingly exacerbating the impact of other human stressors, especially in natural and semi-natural ecosystems.
- There is still limited knowledge about the combined effects of climate change and other pressures on ecosystems and their capacity to provide services, but the knowledge base is improving.
- The relative importance of climate change compared with other pressures depends on the environmental sector (terrestrial, freshwater, marine) and geographical region. Europe's marine and alpine ecosystems are assessed as being most sensitive to climate change.

4.5.1 Ecosystem services under pressure

Human well-being depends on the good condition of the planet's environmental systems, which provide vital goods and services such as food, clean water, clean air and physical, intellectual and cultural interaction with nature. These environmental systems are based on numerous regulating and maintaining services requiring clean and productive seas, fertile soils, a supply of good-quality fresh water, pollination of fruits and crops, natural flood protection and/or climate regulation. However, the ecosystems, habitats and species that provide these services are seriously under pressure and are being lost or degraded by human activity (EEA, 2015b, 2016a; Newbold et al., 2015).

The capacity of ecosystems to deliver ecosystem services for human well-being depends on the condition of ecosystems, i.e. the quality of their structure and functionality. There is growing understanding of the importance of biodiversity in ecosystem functioning and service delivery, which represents our natural capital (Harrison et al., 2014). Consequently, biodiversity is an important element in ecosystem and ecosystem service assessment, and this activity is implemented as part of the EU Biodiversity Strategy to 2020.

The European assessment of ecosystem conditions for the implementation of the EU Biodiversity Strategy to 2020 considers five major pressures, as identified in the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005; EEA, 2016a). As illustrated in Figure 4.19, these pressures are:

1. habitat change, including all structural changes, such as land and sea take, urbanisation, urban sprawl, fragmentation and land abandonment;

2. climate change, including changes in mean climate and extreme events (mainly temperature, precipitation, humidity), as well as atmospheric CO_2 concentration;

3. invasive alien species dispersal;

4. exploitation and management, including land-use intensification, unsustainable agriculture and forestry, natural resource consumption and technological adaptation;

5. pollution and nutrient enrichment, including atmospheric deposition, fertiliser and pesticide use, irrigation, and acidification of soil, freshwater bodies and seas.

In addition, the capacity of ecosystems to deliver services and their biodiversity depend on the 'natural conditions' (e.g. current climate) and site conditions (e.g. pH, nutrient content of soil and water, land elevation, bathymetry, slope, etc.), which are considered constant within the time horizon of years to decades. The concept of ecosystem services has recently been applied to suggest priority areas for green infrastructure development in Europe (Liquete et al., 2015). Several EU research projects focus on operationalising ecosystem services and putting the concept into practical use ([69]).

([69]) OPERAs (http://www.operas-project.eu/) and OpenNESS (http://www.openness-project.eu).

In addition to the direct effects of pressures on ecosystem structure and functioning, and the subsequent changes in capacity to deliver services, there are also more complex impacts, including effects on species interactions and cross-habitat linkages (e.g. between aquatic and riparian ecosystems).

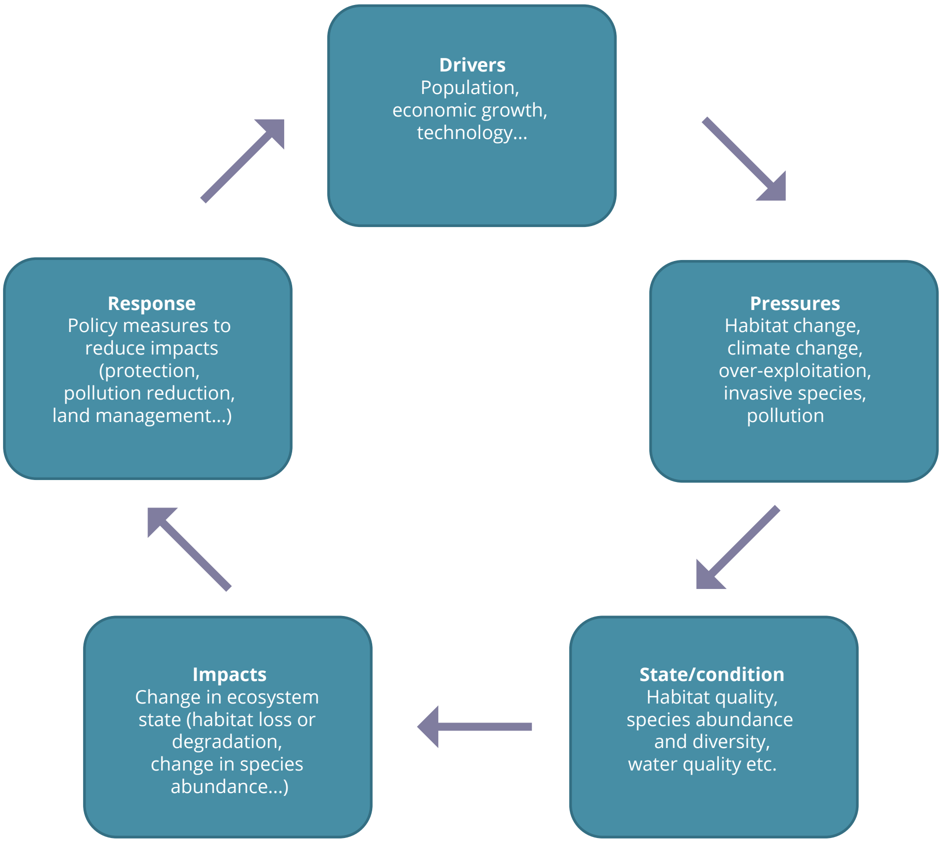
More information on the drivers of ecosystem change is available in a recent review of 27 global and European scenarios (Hauck et al., 2015). As a result of the interaction between various anthropogenic pressures, global species extinction rates (for mammals) in the last century have been between 8 and 100 times higher than the natural background rate (Ceballos et al., 2015). The term 'sixth mass extinction' is frequently used to describe this extinction crisis. These biodiversity losses affect many ecosystem services, including cultural and provisioning ecosystem services (Harrison et al., 2015).

4.5.2 *Ecosystem service assessment*

The Drivers–Pressures–State–Impacts–Response (DPSIR) approach (Figure 4.19) provides a conceptual framework for structuring the components of the assessment of ecosystem condition and its biodiversity. Human activities such as agriculture, forestry or water management are drivers that are inducing pressures on ecosystems, affecting their condition. These have an impact on species richness and abundance, water quality and other functions and, if undesired, these effects may trigger (policy) responses, with actions taken to tackle negative effects. The DPSIR approach can be applied to assess the effects of environmental changes on ecosystem services (Rounsevell et al., 2010).

The assessment of impacts of multiple pressures on ecosystem condition calls for a better understanding of the relative importance of the different pressures and their interactions (Harrison et al., 2015; EEA, 2016a). Only a few studies have addressed the combined effects of multiple pressures, such as climate change, land use and population change (e.g. CLIMSAVE; Dunford et al., 2015). The relative importance of climate change for service provision will become ever greater in the future in comparison with the current main pressures, such as nutrient and pollution load or land and sea management, especially if these pressures

Figure 4.19 The DPSIR framework for European ecosystem assessment



Source: EEA, 2016a.

remain constant or even are reduced, as is the case for atmospheric acidification and nitrogen loads (EEA, 2015a). The impacts comprise all dimensions of climate change, including rising temperature, changes in precipitation and changes in extreme events such as droughts, floods, storms and fires.

This report clearly shows that the impacts of climate change vary depending on the geographical region and on the different components of the Earth system. Many impacts have been reported for terrestrial and freshwater ecosystems, and knowledge about marine systems is rapidly growing. However, even if the impacts of climatic changes have become increasingly visible, other pressures are often as important as or even more important than climate change. It should be noted that the current knowledge about the impacts of climate change has not yet been fully integrated into ecosystem service assessments (EEA, 2015b).

Recently, the Group on Earth Observations Biodiversity Observation Network (GEO BON) developed an operational system to monitor nine ecosystem services at global and national levels (Karp et al., 2015). However, there is still considerable uncertainty in assessing the provision of some ecosystem services across Europe (Schulp et al., 2014). An overview of the state of ecosystem and ecosystem service assessments and their links to other methods, such as environmental accounting, has recently become available (Potschin et al., 2016).

4.5.3 Climate change impacts on ecosystem services

Terrestrial ecosystems that are managed less intensively, as well as Alpine, northern-latitude and Mediterranean areas, seem to be more affected by climate change than ecosystems that are intensively used and already affected by high loads of nutrients and pesticides (EEA, 2012). A changing climate in combination with land-cover change can trigger the dispersal of pests, diseases and invasive species (Bellard et al., 2013). There is also growing understanding of how extreme events affect the biosphere and ecosystem functioning (Bahn et al., 2014).

Freshwater ecosystems seem to be mostly affected by heat waves and droughts and, in some cases, by decreasing ice cover in winter. The availability of operational data for water quantity and water use (EEA, 2016b) will provide further insight into the interaction between climate and water balance. The indicator on soil moisture (see Section 4.4.2) projects that there will be increasing summer droughts for large parts of Europe, which affect river and groundwater recharge and subsequent water availability.

Marine ecosystems are generally sensitive to temperature changes and show more significant shifts in ecosystem condition and biodiversity than terrestrial ecosystems (Burrows et al., 2014; EEA, 2015c). These changes have further impacts on service provision, e.g. because of changes in the breeding behaviour of commercial fish and moving fish stocks (MCCIP, 2013).

A wide range of indicators describing the impacts of climate change on ecosystems have been developed, as illustrated in this report. This approach focuses on natural entities that are highly sensitive (such as protected natural areas or fire-prone forests), as well as relatively stable entities (such as soils) that underpin animal and plant ecosystems but have only limited capacities to adapt.

There is an increasing amount of systematic analysis being undertaken of the interlinkages between ecosystem functioning and ecosystem services, as well as of the role of biodiversity in ecosystem service delivery (Harrison et al., 2014). Increasing levels of knowledge about pressures and their effects on ecosystem condition allow the conceptual understanding of these interlinkages to be implemented in environmental assessments (EEA, 2016a). The constantly growing importance of the increased pressure climate change exerts on ecosystems and biodiversity is summarised in this report. Climate change affects all aspects of ecosystem functioning and service supply (see, for example, Nelson et al., 2013). The impacts of climate change are not exclusively negative, but they have to be better understood in the context of other environmental changes for adequate mitigation and adaptation strategies to be developed to sustain human well-being.

The authors of the chapter on Europe in the IPCC AR5 have performed a literature review of how various ecosystem services in European macro-regions will be affected by climate change (Kovats et al., 2014). Table 4.2 summarises the potential impacts of climate change on ecosystem services in Europe by sub-region, based on an assessment of the published literature (2004–2013). The direction of change (increasing, decreasing or neutral) is provided, as well as the number of studies/papers on which the assessment was based (in parentheses). Empty cells indicate the absence of appropriate literature. Unless otherwise stated, impacts assume no adaptation and are assessed for the mid-century (2050s). A decrease in natural hazard regulation (e.g. for wildfires) implies an increased risk of the hazard occurring.

Table 4.2 Projected impacts of climate change on ecosystem services in Europe by macro-region based on an IPCC literature review

			Southern	Atlantic	Continental	Alpine	Northern
Provisioning services	Food production		↓ (1)	↓ (1)	↓ (1)	No (1) ↓ (4)	↑ (1) ↓ (1)
	Livestock production					No (1) ↓ (1)	
	Fibre production					↓ (1)	
	Bioenergy production		↓ (1)			↑ (1)	↑ (1)
	Fish production		No (1) ↓ (2)	No (1) ↓ (1)	↓ (1)		No (1) ↓ (1)
	Timber production		↓ (2)	↑ (2) No (3)	↑ (1) No (2) ↓ (1)	↑ (5) No (2) ↓ (5)	↑ (6) No (1)
	Non-wood forest products		↓ (1)				↑ (1) No (1)
	Sum of effects on provisioning services		**No (1) ↓ (7)**	**↑ (2) No (4) ↓ (2)**	**↑ (1) No (2) ↓ (1)**	**↑ (4) No (6) ↓ (11)**	**↑ (9) No (3) ↓ (2)**
Regulating services	Climate regulation (carbon sequestration)	General/forests	↑ (3) ↓ (1)	↑ (4) No (1)	↑ (3) No (1)	↑ (4) No (3) ↓ (1)	↑ (4) No (1) ↓ (1)
		Wetland	No (1) ↓ (1)	No (1) ↓ (1)	↓ (1)		No (1) ↓ (1)
		Soil carbon stocks	No (1) ↓ (1)	No (1) ↓ (2)	No (1) ↓ (1)	No (1) ↓ (2)	↓ (3)
	Pest control		↓ (1)		↑ (1)	↑ (1)	↑ (1)
	Natural hazard regulation ([a])	Forest fires/wildfires	↓ (1)	↓ (1)	↓ (2)		
		Erosion, avalanche, landslide				↑ (2) ↓ (1)	
		Flooding				↓ (1)	
		Drought	No (1) ↓ (1)		↓ (1)		
	Water quality regulation			↓ (1)			↓ (1)
	Biodiversity		↑ (1) ↓ (8)	↑ (2) No (1) ↓ (4)	↑ (2) ↓ (4)	↑ (2) ↓ (4)	↑ (3) ↓ (2)
	Sum of effects on regulating services		**↑ (4) No (3) ↓ (14)**	**↑ (6) No (4) ↓ (9)**	**↑ (6) No (2) ↓ (9)**	**↑ (9) No (2) ↓ (11)**	**↑ (8) No (2) ↓ (8)**
Cultural services	Recreation (fishing, nature enjoyment)		↑ (1)	↓ (1)			↑ (1) ↓ (2)
	Tourism (skiing)					↑ (1)	↑ (1)
	Aesthetic/heritage (landscape character, cultural landscapes)		↓ (1)	↓ (1)	No (1) ↓ (1)	↑ (1)	
	Sum of effects on cultural services		**↓ (2)**	**↑ (1) ↓ (1)**	**No (1) ↓ (1)**	**↑ (1) ↓ (1)**	**↑ (1) ↓ (3)**

Note: ↓ = Climate change impacts are decreasing ecosystem services;
No = Neutral effect;
↑ = Climate change impacts are increasing ecosystem services.
(1) = Numbers in brackets refer to the number of studies supporting the change (increasing, decreasing, neutral) in ecosystem services.

([a]) A decline in ecosystem services implies an increased risk of the specified natural hazard.

Entries for biodiversity are those that were found during the literature search for climate change impacts on ecosystem services.

Source: Adapted from Kovats et al., 2014 (Box 23-1).

Biodiversity is included in the IPCC review as a service (for completeness), although it is debated whether biodiversity should be considered as a service or as part of the natural capital from which services flow. It is agreed, however, that biodiversity losses within an ecosystem will have deleterious effects on service provision.

According to Table 4.2, the provision of ecosystem services in southern Europe is projected to decline across all service categories in response to climate change. Other European macro-regions are projected to have both losses and gains in the provision of ecosystem services. The northern macro-region will have increases in provisioning services arising from climate change. Except for the southern macro-region, the effects of climate change on regulating services are balanced with respect to gains and losses. There are fewer studies for cultural services, and assessments of regional changes in cultural services have low confidence.

An independent assessment of the future impacts of climate change on eight ecosystem services was performed using an integrated modelling platform developed in the CLIMSAVE ([70]) project for the same macro-regions as in the IPCC review (Dunford et al., 2015). Table 4.3 presents a semi-qualitative summary of the results for different ecosystem services, regions, climate scenarios and socio-economic scenarios.

Table 4.3 Projected impacts of climate change on ecosystem services in Europe

	Food						Water						Timber						Atmospheric regulation					
	Extreme			Moderate			Extreme			Moderate			Extreme			Moderate			Extreme			Moderate		
	✹	W	S	✶	W	S	✹	W	S	✶	W	S	✹	W	S	✶	W	S	✹	W	S	✶	W	S
Europe		↑	↑		↑	↑	↓		↓			↓	↑	↑	⬇			⬇	⬆	⬆	⬇	↑	⬆	⬇
Continental	↓	↑	⬆	↑	⬆	⬆	⬇	↓	⬇	↓		↓	⬆	⬆	↓	⬆	⬆	↓		⬇	⬇	↓	↓	⬇
Alpine	⬆	⬆	⬆	⬆	⬆	⬆							↑		⬇	⬆	⬆		⬆	⬆		⬆	⬆	↑
Atlantic	⬇	↓	↓	⬇	↓	↓		↑	↓		↑	↓	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	↓	↓	⬇
Northern	⬆	⬆	⬆	⬆	⬆	⬆							⬆	⬆	↓	↑	↑	↓	⬆	⬆	↓	⬆	⬆	↓
Southern	↓	↑	↓	⬇	↓	⬇	⬇	⬇	⬇	↓	↓	↓	⬇	⬇	⬇	⬇	⬇	⬇	↑	⬆	⬇	⬆	⬆	↓

	Landscape experience						Land use diversity						Biodiversity (forest)						Biodiversity (arable)					
	Extreme			Moderate			Extreme			Moderate			Extreme			Moderate			Extreme			Moderate		
	✹	W	S	✶	W	S	✹	W	S	✶	W	S	✹	W	S	✶	W	S	✹	W	S	✶	W	S
Europe	⬆	⬆	↑	⬆	⬆	↑	↓	↓		↓	↓		⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	↓	↓	↓	↓
Continental	⬆	⬆	⬆	⬆	⬆	↑	↓	↓	↓			↓	⬇	⬇	⬇	⬇	⬇	⬇		↓	↓	↓	↓	↓
Alpine	↑	↑		↑	↑		↓	↓	⬆	⬇	⬇		⬇	⬇	⬇	⬇	⬇	↓	⬇	⬇	⬇	⬇	⬇	↓
Atlantic	⬆	⬆	⬆	⬆	⬆	⬆				↑			⬇	⬇	⬇	⬇	⬇	⬇		⬇	↓	↓	↓	↓
Northern	↑	↑		⬆	⬆	↑	↓	↓	↑	↓	⬇	↑		↓	↓	↓	↓	↓		⬇		⬇	⬇	↓
Southern	⬆	⬆	↑	⬆	⬆	⬆	↓	↓		⬇	⬇		⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇

Legend:

⬇	Decrease > – 20 %	✹	Extreme climate
↓	Decrease > – 5 %	✶	Moderate climate
↑	Increase > + 5 %	W	'We are the world' socio-economics
⬆	Increase > + 20 %	S	'Stay or go' socio-economics

Note: This table shows projected impacts of climate change on ecosystem services in Europe by macro-region for different scenarios based on the CLIMSAVE integrated assessment platform.

Source: Adapted from Dunford et al., 2015.

([70]) CLIMSAVE: 'Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe'.

The general pattern shows mostly positive impacts in northern and Alpine Europe (with the notable exception of biodiversity), predominantly negative impacts in southern Europe and mixed impacts in continental Europe. Interestingly, impacts for Atlantic Europe are assessed as predominantly negative. A more detailed discussion of this table is beyond the scope of the report, and the interested reader is invited to consult the original publication for detailed information on the underlying methods and assumptions, as well as an in-depth discussion of the results.

The results of the IPCC and CLIMSAVE assessments show similar patterns to those of the indicator-based climate impact assessments in this report: predominantly negative effects are projected for warmer regions in southern Europe, positive effects prevail in cooler regions in northern Europe and a balance of positive and negative effects is expected in temperate regions in continental and Atlantic Europe, with some disagreement for the latter region. Further information on cross-sectoral climate change assessments in Europe, including the CLIMSAVE assessment, is available in Section 6.2.

5 Climate change impacts on society

Changes in climatic conditions and their impacts on environmental systems have a wide range of effects on economic activities and on human health and well-being. This chapter presents selected observed and projected changes in certain climate-sensitive sectors and systems. Individual sections discuss the economic impacts of extreme climate and weather events (Section 5.1), the human health impacts of climate change and climate extremes (Section 5.2) and climate change impacts on agriculture (Section 5.3), energy production and demand (Section 5.4), transport infrastructure and operation (Section 5.5) and tourism (Section 5.6). Most of the information in Sections 5.1 to 5.4 is primarily based on indicators, whereas no indicators are available for Sections 5.5 and 5.6.

Information on fisheries is presented as part of the section on oceans and marine ecosystems (Section 4.1). Information on forests is presented as part of the section on terrestrial ecosystems (Section 4.4). Further information on climate change impacts and risks based on multi-sectoral climate change assessments is available in Chapter 6.

5.1 Impacts of climate-related extremes

Key messages

- The number of reported climate-related extremes and the economic losses caused by them have increased in recent decades, but this increase has been driven primarily by better reporting and by socio-economic factors.
- Attribution of the observed changes in the number of disaster events and the associated losses to specific causes is hampered by large inter-annual variability, changes in reporting, and the implementation of measures to reduce impacts.
- Future climate change will affect the frequency and intensity of climate-related extremes and the associated losses differently across Europe.
- Evidence-based disaster risk reduction and other public policy choices would be facilitated by better collection of data concerning the economic, social and environmental impacts of climate extremes.

5.1.1 Overview

The IPCC AR5 concludes that, globally and in Europe, climate change has led to detectable changes over the past decades in some extreme weather and climate-related events (hereafter climate extremes or extremes), including extreme temperatures and, in many regions, intense precipitation (Bindoff et al., 2013). The increasing exposure of people and assets to climate extremes is driving the observed increase in economic losses as a result of disaster events ('disaster losses') in Europe. Observed changes in climate extremes and possibly the deteriorated status of natural ecosystems may also have played a role (IPCC, 2012).

The terms 'disaster damages', 'disaster losses' and 'costs of disasters' are not always clearly distinguished. In this report, the term 'damage' is used to refer to *physical* damage (e.g. destroyed infrastructure), whereas the term 'loss' is used to refer to *economic* losses. Economic losses can be further categorised into *direct* losses (which largely correspond with the costs of physical damage) and *indirect* losses (such as the economic impacts of business interruption) (OECD, 2014; IRDR, 2015; JRC, 2015). The disaster loss data included in the global databases underpinning this section focus on direct economic losses as well as human impacts.

Despite progress in the statistical attribution of specific climate extremes to human-induced global climate change, it is currently not possible to attribute observed changes in economic losses to global climate change. The stochastic nature of disaster risk, with uncertain tail distributions and only partial observations of disaster impacts, make it difficult to estimate the extent to which observed climate change has already contributed to the growing trend in disaster losses. However, significant progress has been made in the statistical attribution of selected extreme climate events to anthropogenic climate change. This includes events with large economic and health impacts, such as the 2003 summer heat wave in large parts of Europe, which have been found to become much more likely as a result of anthropogenic climate change (see Sections 3.1 and 3.2.3 for details).

Policy context

A better understanding of the risk of natural hazards and the ensuing economic losses is important to prevent excessive macro-economic imbalances and to coordinate responses to shocks and crises within the European Economic and Monetary Union. It is also important for recovery after a disaster, and within the context of the internal market regulation on state aid conferred on business enterprises.

State aid given on a selective basis that distorts (or threatens to distort) free-market competition is incompatible with the EU internal (single) market, except for cases in which the aid is to make good the damage caused by natural disasters. Exposure to natural hazards exemplifies natural handicaps that hold up economic, social and territorial cohesion in the EU. As an expression of the European solidarity that is pinned down in the Treaty on the Functioning of the European Union, the EU Solidarity Fund (EU, 2002, 2014) was set up as a way to respond with financial assistance in the event of a major, or regionally important, natural disaster in a Member State or in a country negotiating membership.

Reliable assessment of past and future losses caused by climate extremes is essential for well-informed disaster policies and climate adaptation. The United

Nations Sendai Framework for Disaster Risk Reduction (UN, 2015), which has been endorsed by the EU and the EEA member and cooperating countries, requires structured evaluation, recording and sharing of data about economic impacts of natural hazards and disasters. The Framework entails a target of reducing direct disaster economic losses in relation to global GDP by 2030 compared with 2005–2015 baselines. In parallel, the European Union Civil Protection Mechanism (EU, 2013) compels the EU Member States to conduct risk assessments, and where possible also in economic terms, at national or appropriate sub-national level. For both purposes, the JRC is developing loss indicators that should be part of operational disaster loss databases (De Groeve et al., 2013, 2014; JRC, 2015).

The EU strategy on adaptation to climate change (EC, 2013) has called for better informed decision-making through, among other things, improved damage and risk assessment and a thorough assessment of adaptation costs and benefits. The adaptation strategies that are to be developed by Member States ought to be closely connected to disaster risk management plans and actions.

Indicator selection

The subsequent parts of this section present information on the following indicator: *economic losses from climate-related extremes*.

A review is also presented of data sources on the number of climate extremes for which economic and/or human impacts have been recorded. This information is provided primarily to contextualise information on the above-mentioned indicator, and it is not presented in indicator format.

Information on environmental, health and social impacts is also presented in various other parts of the report, e.g. in Section 4.4.6 (forest fires), Section 5.2 (health risks of climate extremes), Section 5.3.4 (effect of climate extremes on agricultural yield) and Section 6.2 (exposure to multiple climatic hazards).

Data quality and data needs

Europe-wide assessments of natural disasters and their impacts rely on global databases, in particular EM-DAT from CRED ([71]), the Dartmouth Flood Observatory (DFO) ([72]) and NatCatSERVICE of Munich RE ([73]). The databases are compiled from various sources; the differences in definitions, thresholds, classification criteria, reporting approaches, etc., are to be taken into account when interpreting the data. In general, larger disasters are captured well in these databases. However, they are less accurate for smaller events, which still may have a significant impact (WHO and PHE, 2013).

DFO considers only flood events or natural hazards where flooding has happened. Information for Europe on all types of natural hazards can be extracted from global disaster databases, such as the EM-DAT database, which places a particular focus on human fatalities and displaced and affected people, and the NatCatSERVICE database, which provides more comprehensive data on insured and overall losses. The 'disaster thresholds' for an event to be included in these global databases are as follows:

- EM-DAT: 10 or more people killed and/or 100 or more people affected and/or declaration of a state of emergency and/or call for international assistance;
- NatCatSERVICE: small-scale property damage and/or one fatality. In addition, Munich RE uses different classes to classify the events.

Over recent years, these global databases have been harmonised and better coordinated, but some differences remain and, although during the past decades both databases have improved their reporting, caution is still needed in formulating conclusions about observed changes. In addition, both databases are less suitable for analysing the impacts of smaller events or for analyses at the sub-national level. However, despite these considerations, both databases serve as a good starting point for getting an overview of the human impacts and economic costs of disasters in Europe.

The economic loss records reviewed in Section 5.1.3 have been converted to euros (2013 value). For the purpose of cross-country comparison, the loss records have been normalised using the Eurostat collection of economic indicators. Data from earlier years have been completed from the annual macro-economic database of the European Commission (AMECO), the International Monetary Fund (IMF) World Economic Outlook (WEO), the Total Economy Database (TED), and the World Bank's database ([74]).

([71]) http://www.emdat.be.
([72]) http://floodobservatory.colorado.edu.
([73]) http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx.
([74]) See http://ec.europa.eu/economy_finance/db_indicators/ameco/index_en.htm (AMECO), https://www.imf.org/external/pubs/ft/weo/2015/02/weodata/index.aspx (WEO), https://www.conference-board.org/data/economydatabase/ (TED) and http://data.worldbank.org (World Bank's database).

5.1.2 *Number of climate-related extremes with recorded impacts*

Key messages

- The number of reported climate extremes with relatively small damages has increased in recent decades, but this increase seems to be driven primarily by better reporting and by socio-economic factors.
- The number of extreme events for which economic impacts have been reported has increased over the period 1980–2013. This increase is driven by events with recorded losses of up to EUR 0.5 million, presumably as a result of better reporting.
- There is no apparent change in the number of extreme events in the analysed disaster database for events with recorded losses of above EUR 0.5 million.

The number of climate extremes that have demonstrably caused economic losses is sensitive to climatic changes but also to a number of confounding factors such as reporting bias, improvements in disaster risk management, wealth and population increase in hazard-prone areas. The potential for a hazard to cause a disaster mainly depends on how vulnerable an exposed community is to such hazards. Well-designed disaster risk management and proactive climate adaptation can reduce the impacts of climate extremes and prevent them turning into disasters. In recent years, policies for disaster risk reduction and management have shifted to a comprehensive multi-hazard approach that embraces prevention, protection, preparedness, response and recovery (EEA, 2011). Adaptation to climate change and disaster risk management provide a range of complementary approaches for managing the risks of climate extremes (IPCC, 2012). The greater uptake of disaster insurance has arguably improved the damage reporting for extensive hazards (i.e. relatively frequent events with limited damage).

The NatCatSERVICE database ([75]) comprises 4 443 records for climate-related disasters in Europe (in the period 1980–2013), each with a unique disaster event identification number, divided into three categories (meteorological, hydrological and climatological), with several sub-types within each category. A further 442 events have been classified as geophysical hazards, which are shown here for comparison. The most commonly observed category of disasters is meteorological (41 %), followed by hydrological (33 %), climatological (15 %) and geophysical (9 %) (see Figure 5.1, left). The difference between the NatCatSERVICE database and the EM-DAT database ([76]) (see Figure 5.1, right) in the total number of reported events and in their distribution over the years is caused by the different data sources and inclusion criteria used in the databases. The EM-DAT database applies much more stringent inclusion criteria.

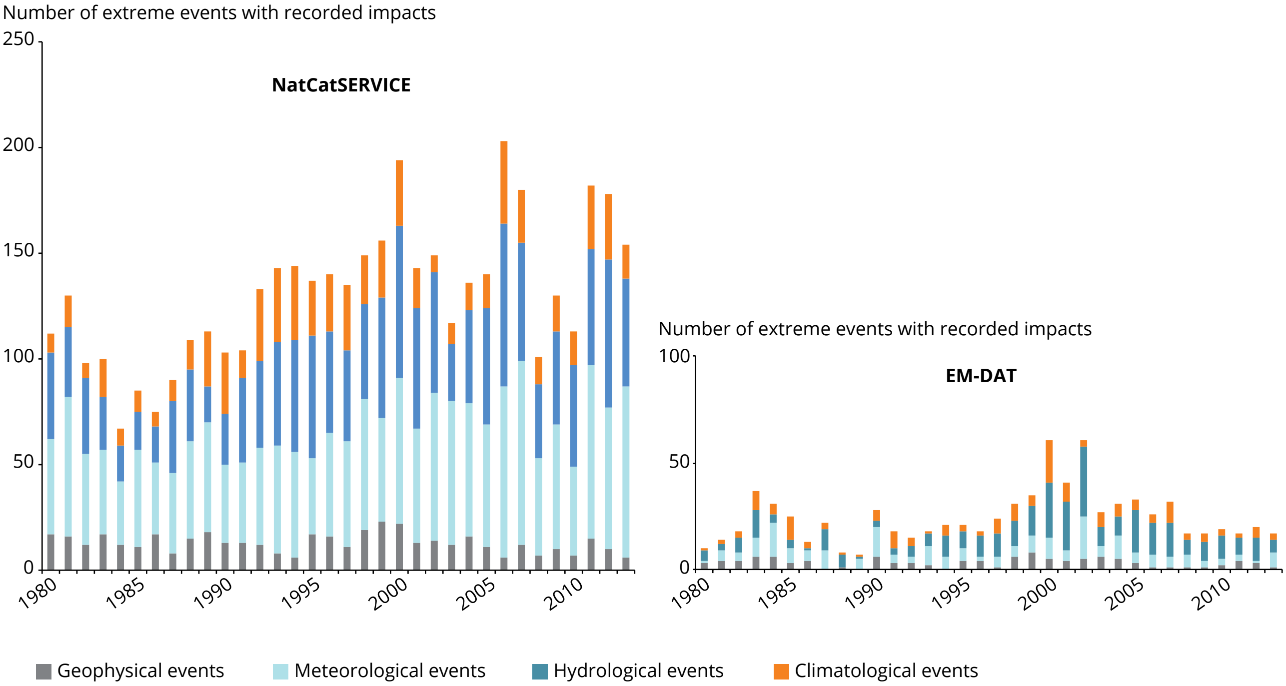
The number of climate extremes on record in the NatCatSERVICE database increased between 1980 and 2013, from around 80 per year in the 1980s to 120 in the 1990s and almost 140 in the 2000s. The contrast between the increasing incidence of climate extremes and the apparently constant number of reported geophysical events has been previously used to dismiss the possibility of reporting bias. However, the increase is driven by events with recorded losses of up to EUR 0.5 million. In contrast, the number of events with losses above this threshold, which are responsible for most of the overall losses, appears invariable since 1990 (see Figure 5.2).

Changes in recorded natural disasters need to be interpreted with caution. Disaster occurrence and disaster burden, in terms of people affected and economic losses, are results of several interlinked factors such as changes in wealth, changes in

([75]) NatCatSERVICE (http://www.munichre.com/natcatservice) is one of the most comprehensive natural catastrophe loss databases, managed by Munich Reinsurance Company (Munich RE), based in Munich, Germany. As a proprietary database, it is not publicly accessible. The entire Munich RE dataset, which covers the period 1980–2013, was provided to the EEA under institutional agreement (June 2014).

([76]) EM-DAT (http://www.emdat.be/database) is a natural catastrophe loss database, managed by CRED (School of Public Health, Université Catholique de Louvain), based in Brussels, Belgium. Most data are available via the internet. Based on a letter of understanding (June 2014), the EEA received the database covering the period 1980–2013.

Figure 5.1 Number of extreme events with recorded impacts in Europe by year and hazard category from two data sources



Note: This figure shows the number of unique extreme events with recorded impacts according to hazard category based on the NatCatSERVICE database (left) and the EM-DAT database (right). In contrast with the previous version of this report, events affecting several countries are counted only once. Hazard categories: geophysical events (earthquakes, tsunamis, volcanic eruptions); meteorological events (storms); hydrological events (floods, mass movements); climatological events (heat waves, cold waves, droughts, forest fires).

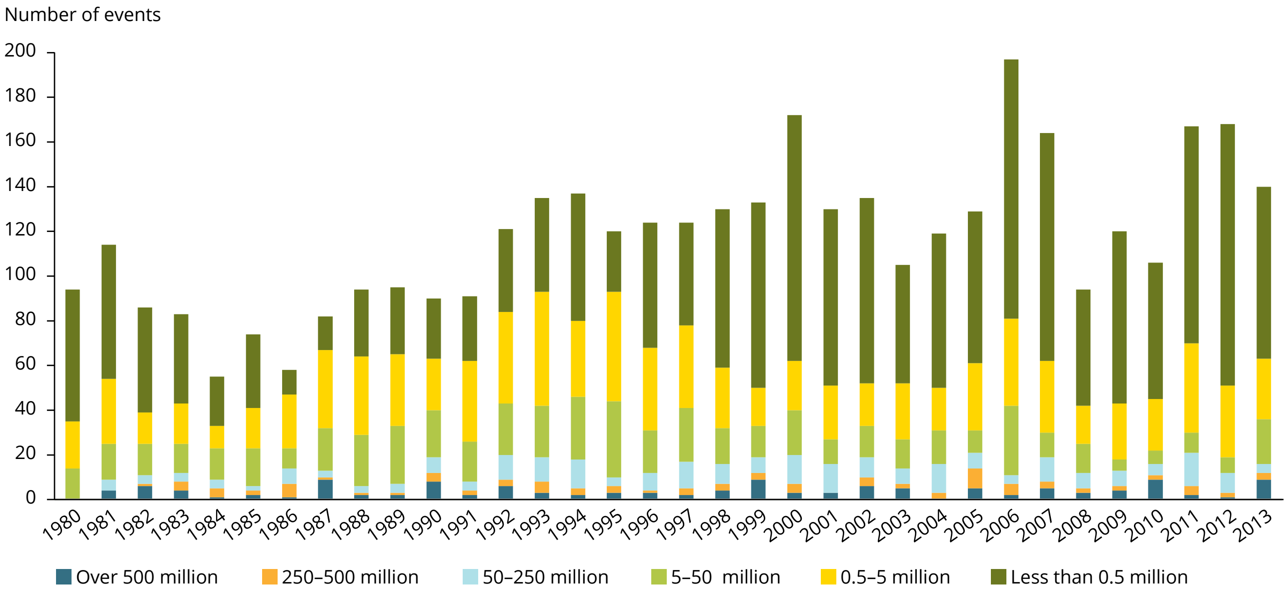
Source: Munich RE NatCatSERVICE (data received under institutional agreement) and CRED EM-DAT (data received based on a Letter of Understanding).

population, changes in intensity or frequency of climate extremes, and changes in vulnerability. Therefore, a direct attribution of changes in disaster burden to any specific factor, such as climate change, should be avoided (Visser et al., 2012).

Climate change will affect the frequency and severity of climate extremes. Among long-term climate extremes, heat waves are expected to increase across Europe (see Section 3.2.3), and droughts are expected to increase in most regions in southern Europe (see Section 4.3.4). The direction of future changes is uncertain for short-term meteorological extremes, such as wind and hail storms (see Sections 3.2.6 and 3.2.7). Model projections show a likely increase in hydrological extremes (i.e. floods). Such an increase is likely to occur across Europe for coastal floods owing to the projected sea level rise (see Section 4.2.2); projections for river floods differ for different parts of Europe (see Section 4.3.3). Further information on projected changes in climatic hazards in Europe based on a multi-hazard climate risk assessment supported by the Seventh Framework Programme (FP7) ENHANCE ([77]) project is provided in Section 6.2.

([77]) ENHANCE: 'Enhancing risk management partnerships for catastrophic natural hazards in Europe', http://enhanceproject.eu.

Figure 5.2 Number of climate extremes by loss category over time



Note: This figure shows the number of events per loss category based on NatCatSERVICE.

Source: Munich RE NatCatSERVICE (data received under institutional agreement).

5.1.3 Economic losses from climate-related extremes

Key messages

- The total reported economic losses caused by climate-related extremes in the EEA member countries over the period 1980–2013 were almost EUR 400 billion (2013 value). The average damage has varied between EUR 7.6 billion per year in the 1980s and EUR 13.7 billion in the 2000s.
- The observed changes in reported losses over time are difficult to interpret, as a large proportion of the total deflated losses has been caused by a small number of events. Specifically, more than 70 % of the damage was caused by only 3 % of all registered events.

Relevance

Economic losses from extreme climate events have increased, but with large spatial and interannual variability. Reported disaster losses often reflect only structural damages to tangible physical assets, neglecting the impacts on health, integrity of ecosystems and intangible cultural heritage. Hence, the reported economic losses focus on direct losses and should therefore be understood as lower-bound estimates. The changes in recorded losses are, to a large extent, influenced by increased economic wealth. Determining the effect of ongoing climate change in the pattern of loss data remains elusive.

Past trends

According to the data from NatCatSERVICE (Munich RE), climate extremes accounted for 82 % of the total reported losses in the EEA member countries ([78]) over the period 1980–2013, whereas geophysical events such as earthquakes and volcano eruptions are responsible for the remaining 18 %. The main hazards underlying economic losses and fatalities differ substantially from each other. In particular, heat waves represented only 1 % of all hazards and caused only 5 % of the reported losses, but they were responsible for 67 % of all fatalities (Figure 5.3). Further information on fatalities and other health effects from climate-related extremes is presented in Section 5.2.

Recorded losses from climate extremes in Europe amounted to EUR 393 billion (2013 value) ([79]), on average EUR 11.6 billion per year, EUR 69 000 per square kilometre or EUR 710 per capita (based on the average population over the entire period 1980–2013). The loss is equal to 0.1 % of cumulative deflated GDP over the analysed period. Around 33 % of the total losses were insured. The distribution of losses caused by climate extremes among the 33 EEA member countries is uneven. The highest losses in absolute terms were registered in the large countries Germany, Italy and France, in rank order. The highest losses per capita were recorded in Switzerland, Denmark and Luxembourg, in rank order; the highest losses expressed as a fraction of GDP over the period were registered in the Czech Republic, Croatia and Hungary, in rank order (see Table 5.1).

Losses from natural hazards in Europe have varied substantially over time. The average annual (inflation-corrected) losses from climate extremes have increased from EUR 7.6 billion in the 1980s to EUR 13 billion in the 1990s and EUR 13.7 billion in the 2000s (see Figure 5.4, which also includes losses from geophysical events for comparison). The changes over time that can be seen in the recorded losses are obfuscated by high variability and are strongly determined by a few exceptionally large events. Around 3 % of events, some of which affected more than one country, account for around 70 % of total inflation-adjusted losses. The most costly climate extremes were the 2002 flood in central Europe (EUR 20 billion), followed by the 2003 drought and heat wave (EUR 16 billion) and the 1999 winter storm 'Lothar' (EUR 14 billion). By contrast, some three-quarters of the registered events caused only half a percentage point of the total losses.

One important issue is the extent to which the observed increase in overall losses during recent decades is

([78]) http://www.eea.europa.eu/about-us/countries-and-eionet.

([79]) The exact estimate differs by several percentage points depending on the choices made, including the price indices chosen for accounting for inflation, the reference base (annual, monthly) for the conversion between losses expressed in US dollars and euros, etc.

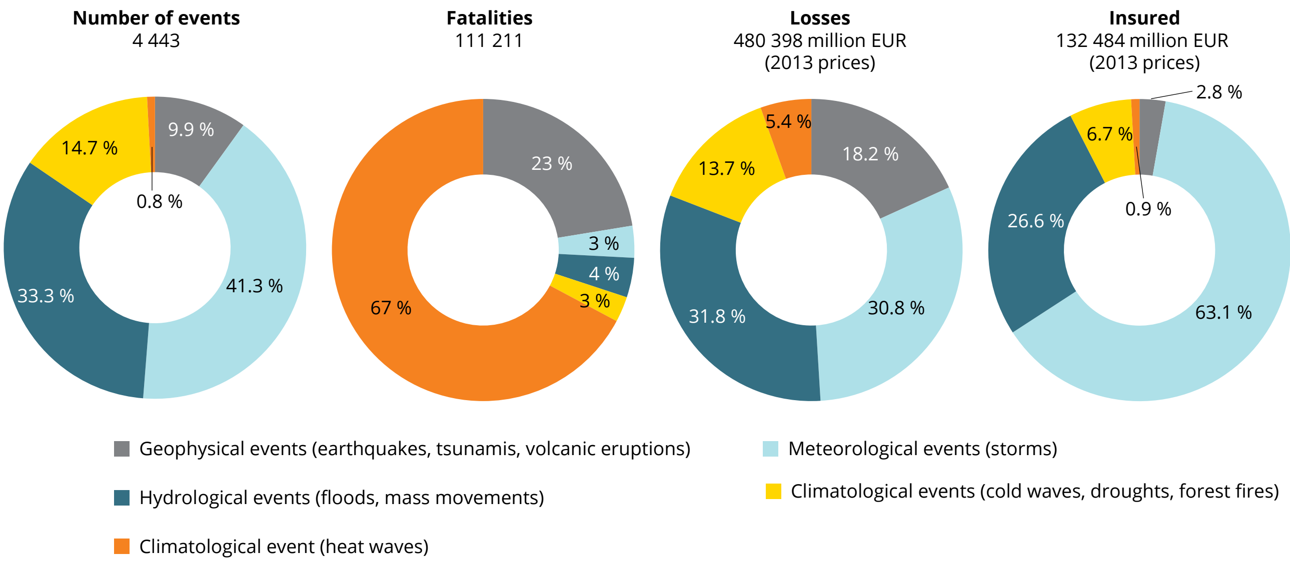
attributable to changing climatic conditions rather than other factors. According to the IPCC AR5 (IPCC, 2014a), the increasing exposure of people and economic assets to climate extremes has been the major cause of the global long-term increases in economic losses from climate-related disasters. Long-term changes in economic disaster losses adjusted for wealth and population increases have not been attributed to climate change, but a role for climate change has not been excluded either. Available studies for damages from river floods and storms in Europe suggest that the observed increases in losses are primarily due to increases in populations, economic wealth and developments in hazard-prone areas, but the observed increase in heavy precipitation in parts of Europe may have also played a role (e.g. Barredo, 2009, 2010; Maaskant et al., 2009; Bouwer et al., 2010; te Linde et al., 2011; Feyen et al., 2012; Visser et al., 2012; Rojas et al., 2013) (see also Section 3.2.5 and Section 4.3.3). There is evidence that improved flood protection and prevention contributed to reducing losses over time in some cases (e.g. Thieken et al., 2016).

Projections

The IPCC AR5 concludes that high temperature extremes, heavy precipitation events and droughts will markedly increase in all or most world regions, including in Europe. Furthermore, large parts of Europe will face an increasing drought risk (IPCC, 2013). There is medium confidence in the fact that climate change will increase the likelihood of systemic failures across European countries as a result of extreme climate events affecting multiple sectors (IPCC, 2014b; Kovats et al., 2014). Increasing extremes will presumably lead to greater losses. However, the future cost of climate-related hazards in Europe will depend on several factors, including the resilience and vulnerability of society, which are variable across hazards and regions.

Further information on projected changes in individual extreme events is provided in Sections 3.2, 4.2 and 4.3; projections based on multi-hazard assessments are presented in Section 6.2.3 and in recent JRC studies (Forzieri et al., 2015, 2016).

Figure 5.3 Number of events, fatalities, total losses and insured losses from all natural hazards



Note: This diagram shows the number of events, fatalities, total losses and insured losses (expressed in 2013 values) from all natural hazards in EEA member countries cumulated over the period 1980–2013. Hazard categories: meteorological events (storms); hydrological events (floods, mass movements); climatological events (heat waves, cold waves, droughts, forest fires); geophysical events (earthquakes, tsunamis, volcanic eruptions).

Source: EEA based on data from Munich RE NatCatSERVICE received under institutional agreement.

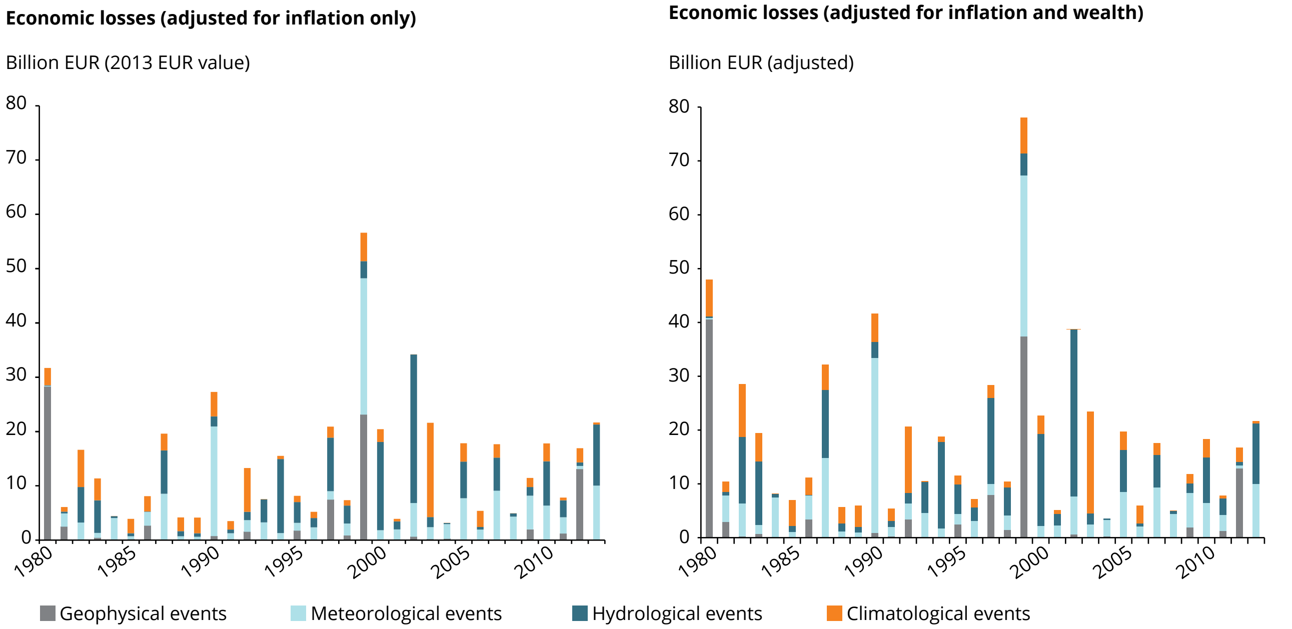
Table 5.1 Economic losses from climate extremes by country

	Losses (2013 EUR value)					
Country	**Total (million)**	**Insured (million)**	**% insured**	**Per capita**	**Per square kilometre**	**% GDP**
Austria	10 957	3 178	29	1 379	130 634	0.14
Belgium	3 016	1 603	53	294	98 806	0.03
Bulgaria	1 235	1	0	150	11 140	0.04
Croatia	2 248	4	0	499	39 714	0.20
Cyprus	357	9	2	537	38 562	0.09
Czech Republic	9 563	3 088	32	926	121 256	0.24
Denmark	9 432	5 598	59	1 781	219 776	0.13
Estonia	241	29	12	168	5 331	0.06
Finland	1 729	208	12	338	5 108	0.03
France	53 182	25 410	48	860	84 038	0.09
Germany	78 721	34 382	44	1 046	220 403	0.11
Greece	7 435	89	1	703	56 344	0.12
Hungary	5 521	69	1	535	59 347	0.18
Iceland	47	16	33	171	454	0.02
Ireland	2 984	1 569	53	774	42 756	0.09
Italy	59 624	1 945	3	1 039	197 383	0.12
Latvia	415	50	12	173	6 423	0.08
Liechtenstein	5	3	58	174	33 880	0.01
Lithuania	984	6	1	285	15 066	0.06
Luxembourg	700	432	62	1 645	270 834	0.07
Malta	62	24	38	167	197 426	0.04
Netherlands	6 147	2 768	45	396	147 983	0.04
Norway	3 587	1 922	54	806	11 079	0.04
Poland	13 935	859	6	367	44 566	0.13
Portugal	6 783	300	4	665	73 563	0.14
Romania	8 424	56	1	383	35 339	0.14
Slovakia	1 332	66	5	251	27 166	0.08
Slovenia	919	143	16	462	45 325	0.09
Spain	32 834	3 920	12	800	64 891	0.12
Sweden	3 630	1 032	28	412	8 277	0.04
Switzerland	17 812	8 425	47	2 517	431 444	0.14
Turkey	3 040	238	8	49	3 879	0.03
United Kingdom	46 046	31 372	68	782	185 274	0.10
Total	**392 949**	**128 813**	**33**	**710**	**68 755**	**0.10**

Note: This table shows recorded economic losses (2013 EUR value) from climate-related hazards cumulated for the period 1980–2013 in each EEA member country.

Source: EEA based on data from Munich RE NatCatSERVICE received under institutional agreement.

Figure 5.4 Trends in economic losses from all natural hazards



Note: This figure shows recorded economic losses in EEA member countries over the period 1980–2013 by hazard category: adjusted for inflation only (2013 EUR value) (left); adjusted for inflation and wealth (in terms of GDP changes) (right). Geophysical events are included for comparison.

Source: EEA based on data from Munich RE NatCatSERVICE received under institutional agreement.

5.2 Human health

Key messages

- Climate change is already contributing to the burden of disease and premature deaths in Europe. Its main health effects are related to extreme weather events, changes in the distribution of climate-sensitive diseases and changes in environmental and social conditions.
- Heat waves were the deadliest extreme weather event in the period 1991–2015 in Europe. They have caused tens of thousands of premature deaths in Europe.
- Adverse impacts of future climate change are projected to outweigh beneficial impacts on the global scale. The health impacts and associated economic costs are also estimated to be substantial in Europe. However, quantitative projections of future climate-sensitive health risks are difficult owing to the complex relationships between climatic and non-climatic factors, climate-sensitive disease and other health outcomes.

5.2.1 Overview

Relevance

Climate change is already contributing to the global burden of disease and premature deaths. Climate change affects our health and well-being in many ways, through direct physical impacts (most of them due to amplified extreme weather events) and indirect social and economic changes (Figure 5.5). Many of the indirect effects of climate change will be simultaneously influenced by other global changes and socio-demographic pressures that act in conjunction with climate change. These include several categories of indirect health impacts and the tertiary effects on health and survival that arise from more diffuse disruptions, dislocations and conflicts, which are likely to increase in future decades and are indicated by upward-pointing arrows in Figure 5.5 (McMichael, 2013). Climate change will act mainly by exacerbating health problems that already exist, and the largest risks will apply in populations that are currently most affected by climate-related diseases. The potential health benefits from milder winters in some regions are, however, not expected to outweigh the risk of negative health effects through direct and indirect, immediate and delayed risks of climate change (McMichael et al., 2012).

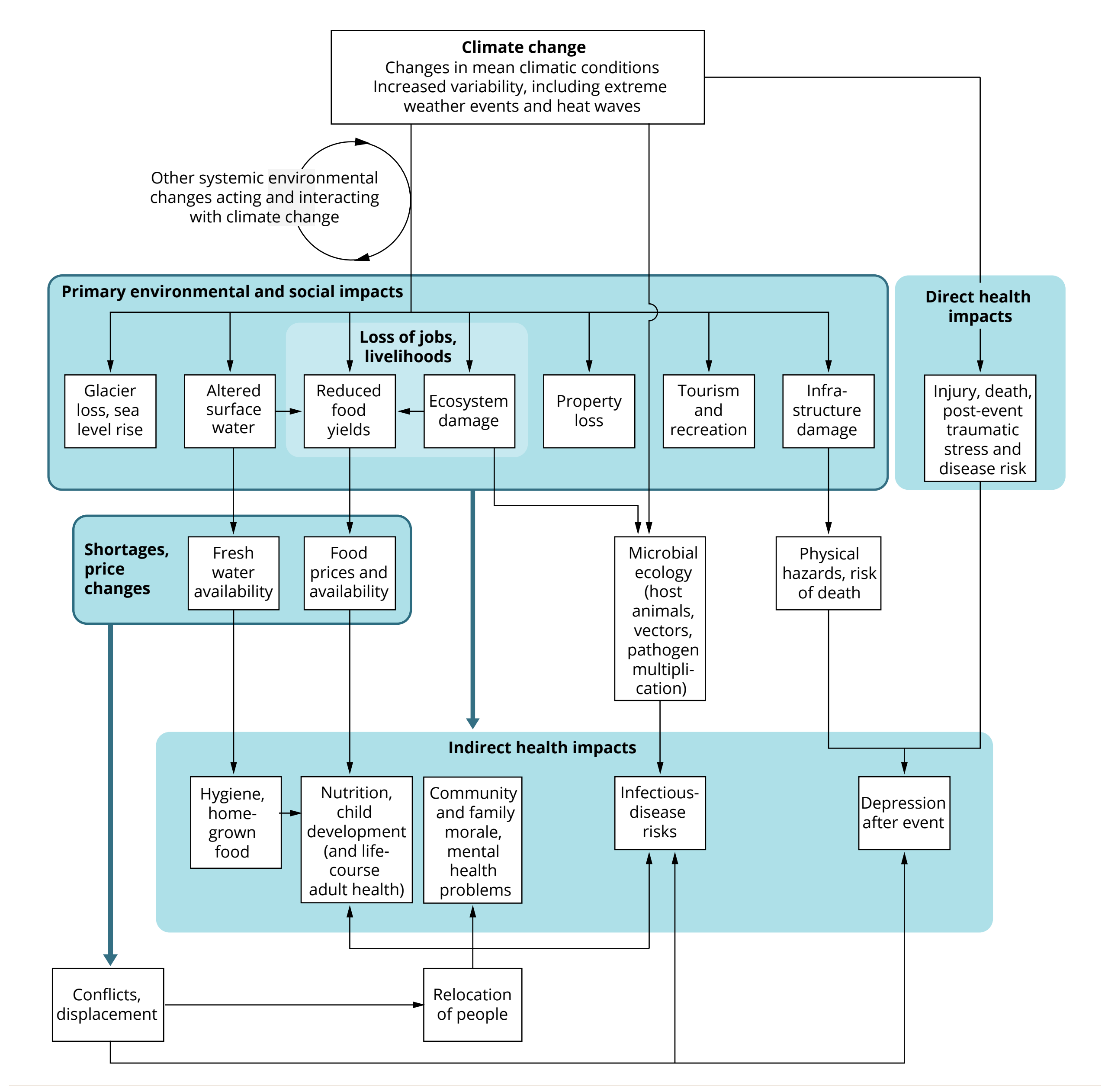
In Europe, climate change can increase water scarcity and quality, and can pose additional challenges for providing sustainable water and sanitation services (EEA, 2011b; Ludwig et al., 2011; Sinisi and Aertgeerts, 2011; IPCC, 2014a). Nearly half of over 50 infectious diseases that the EU Member States are currently required to report can be directly or indirectly affected by climate change; other climate-sensitive diseases, including many vector-borne diseases, are considered *priority* infectious diseases in relation to climate change in Europe (Lindgren et al., 2012).

All people are affected by climate change, but the effect of climate change on people's health depends largely on their vulnerability ([80]) (e.g. age, pre-existing diseases, exposure, location) and their ability to adapt, linked to ecological, social, economic and cultural factors, including education and access to health systems, among others (EEA, 2010). Vulnerable population groups include the elderly and children, the urban poor, traditional societies, subsistence farmers and coastal populations (WHO, 2011). Vulnerabilities vary both within and across European regions. Areas with high adaptive capacities may be able to mitigate some of the health-related risks of climate change. In the European Union, areas with projected high vulnerabilities to infectious disease transmission include regions in Bulgaria, Greece, southern Italy, and Romania (Suk et al., 2014).

Populations in some European areas are at a higher risk from climate change than others, depending on their exposure to climatic hazards and their vulnerability. Climate change will increase the frequency and intensity of heat waves, and can increase economic losses and the number of people affected by such extreme heat events, having impacts on health and well-being, labour productivity, crop production and air quality, and increasing the risk of wildfires in southern Europe (Kovats et al., 2014). Arctic populations are particularly

([80]) The term 'vulnerability' is being used in different ways in the climate change context (see Section 1.4 for a more detailed discussion). Its use in this section follows its general use in epidemiology and public health, where it describes the relationship between exposure to a health hazard and the health effect.

Figure 5.5 Impact pathways of climate change on human health



Source: McMichael, 2013. © 2013 Massachusetts Medical Society. Reproduced with permission.

at risk because of their reliance on the physical environment for food, water and infrastructure (IPCC, 2014b). In the Arctic, changes in temperature and precipitation (see Section 3.2), the melting of permafrost and decreasing sea ice (see Section 3.3), coastal erosion (see Section 4.2), landscape transformation and biodiversity change (see Section 4.4) can affect the lifestyle and culture of the indigenous people. Ice melting caused by climate change is expected to also influence exposures to some contaminants (mercury, radionuclides and persistent organic pollutants), which will create additional and/or synergistic impacts on the overall health and well-being of all Arctic communities (Armitage et al., 2011; Teran et al., 2012).

Policy context

Climate change is an emerging threat that rightly commands widespread policy and public attention. Along with other rapid changes associated with global population and economic growth, climate change creates additional stresses on existing weak points in health protection, and requires reconsideration of public health priorities. The most effective responses today, and while global warming stays below a 2 °C increase compared with pre-industrial levels, are likely to be strengthening of key functions such as environmental management, surveillance and response to safeguard health from natural disasters and changes in infectious disease patterns, and a more proactive approach to ensure that development decisions serve the ultimate goal of improving human health. Both climate-sensitive health risks and the health benefits of cutting greenhouse gas emissions should be central to any discussion on climate change (WHO, 2015). Many mitigation and adaptation responses to climate change are 'no-regret' options, which lead to direct reductions in the burden of ill-health, enhance community resilience, alleviate poverty and address global inequity (Watts et al., 2015). For example, further improvement, development and implementation of heat-wave preparedness, planning and response in European countries would lead to a reduction in heat-related mortality, and a focus should be placed on developing strong inter-sectorial coordination, effective early warning and health system response mechanisms, and surveillance and evaluation measures (Bittner et al., 2014). Long-term planning, including urban planning and housing, becomes even more relevant than before. The recent Sendai Framework on Disaster Risk Reduction 2015–2030 was adopted by representatives from 187 UN Member States in March 2015 (UN, 2015) with six priorities (see Section 2.1.2). Activities at national and local levels, as well as global and regional levels, were established for each of these priorities.

The current policy context is further set through European Union policies and the pan-European 'Commitment to Act' on environment and health. In March 2010, at the Fifth Ministerial Conference on Environment and Health in Parma, Italy, ministers of health and the environment of 53 European Member States and the European Commission declared their commitment to protecting health and well-being, natural resources and ecosystems and to promoting health equity, health security and healthy environments in a changing climate (WHO, 2010a, 2010b). This includes the promotion of climate change mitigation and adaptation measures that also improve human health. As a continuation of the engagement, the European Environment and Health Process will concentrate on activities in light of the Paris climate agreement, and in preparation for the Sixth Ministerial Conference on Environment and Health in 2017. The European Commission adopted, in April 2013, an EU strategy on adaptation to climate change, which has been welcomed by the EU Member States. The strategy aims to make Europe more climate resilient. It focuses on promoting action by Member States, climate-proofing action, and better informed decision-making (EC, 2013) (see Section 2.3 for details). Furthermore, the Decision of the Council and the EU Parliament on cross-border health threats will help Member States to prepare for and protect citizens against possible future pandemics and serious cross-border threats caused not only by communicable diseases, but also by chemical, biological or environmental events (EU, 2013).

Selection of indicators

The next section presents an overview of extreme weather events and health, which is not presented in indicator format and therefore is not merged with the more specific indicators on this topic. After the section on extreme weather events and health, the following indicators on key climate-sensitive health risks in Europe are presented:

- floods and health (addressing both coastal and river floods);
- extreme temperatures and health (focussing on extreme high temperatures);
- vector-borne diseases;
- water- and food-borne diseases.

Climate change can also affect ground-level ozone concentrations, which are a threat to human health. However, the projected increase in summertime ozone concentrations in Europe due to future warming is small compared with the background level and the effect of expected reductions in ozone precursors (EEA, 2015).

Data needs and uncertainty

The attribution of health effects to climate change is difficult owing to the complexity of interactions and the potential modifying effects of a range of other factors (such as land-use changes, public health preparedness and socio-economic conditions) (Wardekker et al., 2012). Criteria for defining a climate-sensitive health impact are not always well identified, and their detection sometimes relies on complex observational or prospective studies, applying a mix of epidemiological, statistical and/or modelling methodologies. Furthermore, these criteria, as well as the completeness and reliability of observations, may differ between regions and/or institutions, and they may change over time. Data availability and quality are crucial in climate change and human health assessments, both for longer term changes in climate-sensitive health outcomes and for health impacts of extreme events. The monitoring of climate-sensitive health effects is currently fragmentary and heterogeneous. All these factors make it difficult to identify significant trends in climate-sensitive health outcomes over time, and to compare them across regions. In the absence of reliable time series, more complex approaches are often used to assess the past, current and future impacts of climate change on human health.

The links between climate change and health have been the subject of intense research in Europe in the early 2000s (e.g. the projects cCASHh ([81]), EDEN ([82]), EDENext ([83]) and Climate-TRAP ([84])); more recently health has been incorporated, to a minor extent, into some cross-sectorial projects (e.g. CIRCE ([85]), PESETA II ([86]), IMPACT2C ([87]) and RAMSES ([88])). Furthermore, the World Health Organization (WHO) has a policy, country support and research mandate given by its 193 Member States through the World Health Assembly on all aspects of climate change and health (WHO, 2008, 2014). The European Centre for Disease Prevention and Control (ECDC) assesses the effects of climate change on infectious diseases and has also established a pan-EU network dedicated to vector surveillance (VBORNET) ([89]).

([81]) cCASHh — 'Climate change and adaptation strategies for human health in Europe' — is a European Commission FP5 project (http://cordis.europa.eu/project/rcn/56944_en.html).
([82]) EDEN — 'Emerging Diseases in a changing European eNvironment' — is a European Commission FP6 project (http://www.eden-fp6project.net).
([83]) EDENext — 'Biology and control of vector-borne infections in Europe' — is a European Commission FP7 project (http://www.edenext.eu).
([84]) Climate-TRAP: 'Training, Adaptation, Preparedness of the Health Care System to Climate Change' (http://www.climatetrap.eu).
([85]) CIRCE — 'Climate Change and Impact Research: the Mediterranean Environment' — is a European Commission FP6 project (http://www.iddri.org/Iddri/Circe-Overview.pdf).
([86]) PESETA II — 'Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis' — is a European Commission FP7 project (http://peseta.jrc.ec.europa.eu).
([87]) IMPACT2C — 'Quantifying projected impacts under 2°C warming' — is a European Commission FP7 project (http://impact2c.hzg.de).
([88]) RAMSES — 'Reconciling, adaptation, mitigation and sustainable development for cities' — is a European Commission FP7 project (http://www.ramses-cities.eu/about/project-setup).
([89]) VBORNET: 'European Network for Arthropod Vector Surveillance for Human Public Health' (http://www.vbornet.eu).

5.2.2 Extreme weather events and health

Relevance

Extreme climate and weather events, such as heat waves (see Section 3.2.3), wind storms (see Section 3.2.6), hail (see Section 3.2.7), river floods (see Section 4.3.3), droughts (see Section 4.3.4), storm surges (see Section 4.2.2) and forest fires (see Section 4.4.6), have adverse social and health effects in Europe and in the Arctic, as well as significant impacts in multiple economic sectors (Kirch et al., 2005; Confalonieri et al., 2007; EEA, 2011a; IPCC, 2012, 2014b). However, human vulnerability to extreme weather events is determined by a complex set of factors.

Evidence suggests that, globally, climate change has led to changes in climate extremes, including heat waves, record high temperatures and, in many regions, heavy precipitation in the past half century (IPCC, 2013). If vulnerable populations are exposed to such climate extremes, or a series thereof, this can lead to substantial health impacts (IPCC, 2012). There are regional differences in the observed changes; for example, while there is high confidence in the fact that heat waves have become more severe in southern Europe and the Mediterranean, there is less confidence in the significance of the observed trend in central and northern Europe.

Past trends

According to the EM-DAT international disaster database ([90]) (see Section 5.1), heat waves were the deadliest extreme weather event in the period 1991–2015 in Europe, particularly in southern and western Europe. Cold events and storms were the deadliest weather extremes in eastern Europe. Floods and wet mass movements, including landslides, were linked to the highest death rates in southern and eastern Europe, wildfires were linked to the highest death rates in southern Europe and the deadliest storms were reported in northern and western Europe (Table 5.2). However, the comparability of the data over time is very limited (see 'Data needs and uncertainty' in Section 5.2.1). Furthermore, the interpretation of the time series can be dominated by a single extreme event, such as the 2003 summer heat wave (June–September 2003), with over 70 000 excess deaths in southern and western Europe. In addition, in the case of flood-related fatalities, where the total number of fatalities is much lower, the overall number of deaths depends strongly on single events. Extreme events threaten human health, but may also be considered an argument for a transition to more sustainable and healthy societies with 'climate-resilient' health systems.

The damages from extreme climate events have increased in Europe since 1991 (see Section 5.1.2).

Table 5.2 Number of people killed per million due to extreme weather events, by European sub-regions for the period 1991–2015

	Flood and wet mass movement ([a])	Cold event	Heat wave	Storm	Wildfire
Eastern Europe	8.57	28.27	11.39	1.73	0.54
Northern Europe	0.99	1.67	11.17	2.48	0.01
Southern Europe	6.75	0.92	177.98	1.19	0.97
Western Europe	2.09	0.89	191.58	2.79	0.04
Total	4.64	5.31	128.98	1.99	0.46

Note: ([a]) Includes landslides.

The rate given in each cell is the cumulative numbers of deaths per 1 000 000 people over the whole time period (1991–2015). The country groupings, as reported to EM-DAT/CRED, are as follows: eastern Europe is Bulgaria, the Czech Republic, Hungary, Poland, Romania and Slovakia; northern Europe is Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden and the United Kingdom; southern Europe, including western Asia, is Albania, Bosnia and Herzegovina, Croatia, Cyprus, Greece, Italy, the former Yugoslav Republic of Macedonia, Montenegro, Portugal, Serbia, Slovenia, Spain and Turkey; and western Europe is Austria, Belgium, France, Germany, Luxembourg, the Netherlands and Switzerland. Population rates calculated using population data from 2013.

Source: EM-DAT ([91]), Eurostat ([92]) and WHO ([93]).

([90]) http://www.emdat.be.
([91]) http://www.emdat.be/database.
([92]) http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-data.
([93]) http://www.euro.who.int/en/data-and-evidence.

However, such figures need to be interpreted with caution. Trend patterns in disaster burden, in terms of number of people affected and economic loss, are difficult to explain, as several interlinked factors play a role. These include changes in wealth, changes in population numbers, changes in intensity or frequency of extreme weather events, and changes in vulnerability. Therefore, the direct attribution of changes in disaster burden to one specific factor, such as climate change, should be avoided (Visser et al., 2012).

Projections

Extreme weather is projected to increase in frequency and severity in many areas of the world, including Europe, and includes heat and heat waves, fires, droughts, heavy precipitation and floods (IPCC, 2012, 2014b). Long-term climate extremes such as droughts are generally expected to increase, while the direction of change is uncertain for some short-term meteorological extremes, such as storms (see Section 3.2.6). Model projections show increases in hydrological extremes (i.e. floods) are likely. Such an increase is more certain for coastal floods owing to the projected sea level rise (see Section 4.2.2) than for river floods (see Section 4.3.3).

Estimates of the projected health impacts of coastal and river floods, temperature and infectious diseases are reflected in the next sections. They have been produced by EU research projects and through research by EU and UN agencies (Feyen and Watkiss, 2011; Kovats et al., 2011; Watkiss and Hunt, 2012; Watts et al., 2015).

5.2.3 *Floods and health*

Key messages

- River and coastal flooding have affected many millions of people in Europe since 2000. Flooding affects human health through drowning, heart attacks, injuries, infections, exposure to chemical hazards and mental health consequences. Disruption of services, including health services, safe water, sanitation and transportation ways, plays a major role in vulnerability.
- Observed increases in heavy precipitation and extreme coastal water levels have increased the risk of river and coastal flooding in many European regions.
- In the absence of additional adaptation, the projected increases in extreme precipitation events and in sea level would substantially increase the health risks associated with river and coastal flooding in Europe.

Relevance

Climate change can increase the severity and frequency of extreme weather events, such as heavy precipitation, and floods, storms and storm surges. Floods caused by these events can affect people immediately (e.g. through drowning and injuries) and after the event (e.g. through displacement, the destruction of homes, water shortages, disruption of essential services and financial loss). The stress that flood victims are exposed to can also affect their mental health, and effects can persist a long time after the event. Two-thirds of flood-related deaths worldwide are from drowning and one-third are from physical trauma, heart attacks, electrocution, carbon monoxide poisoning, fire and infectious diseases. Health system infrastructure (e.g. hospitals) is vulnerable to extreme weather events, in particular to flooding. Disruption of services, including health services, safe water, sanitation and transportation ways, plays a major role in vulnerability (Radovic et al., 2012; Stanke et al., 2012; Brown and Murray, 2013; WHO and PHE, 2013). Information about economic damages from floods is presented in Sections 5.1 and 6.3.

Past trends

Most regions in Europe have exhibited an increasing trend in heavy precipitation over recent decades, in particular in winter (see Section 3.2.5). The number of large inland floods in Europe has been increasing since the 1980s; however, there is not yet conclusive evidence that climate change has already contributed to this trend (Zolina et al., 2010; Hov et al., 2013; Kundzewicz et al., 2013) (see Section 4.3.3).

Estimates for the WHO European Region based on a combination of data from EM-DAT and the DFO indicate that coastal and inland floods killed more than 2 000 people and affected 8.7 million in the period 2000–2014. Map 5.1 shows the number of deaths related to flooding in each EEA member and cooperating country for the same period, normalised by their population. The largest numbers are found in south-eastern Europe, eastern Europe and central Europe. Note that, because of the relatively short time period of 15 years, the value of the indicator can be significantly affected by a single catastrophic event. For example, at least 50 people were killed in massive floods in the Balkan countries in May 2014 (Holt, 2014).

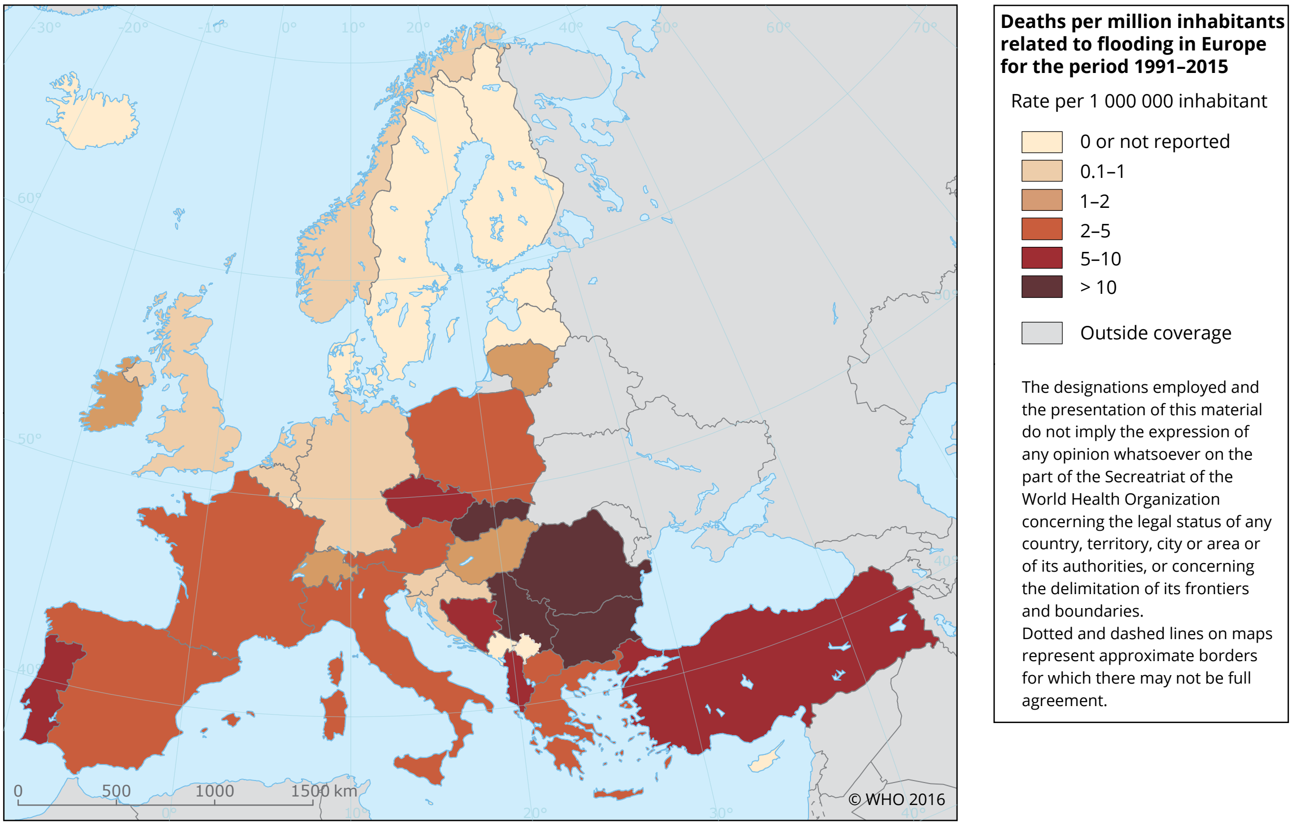
The EM-DATA database also includes data on people injured or (otherwise) affected by floods. This information is not presented here owing to concerns regarding the consistency with which these data are assessed and reported across countries and even for different flood events in the same country.

Projections

Heavy precipitation events are likely to become more frequent in many regions in Europe, and sea level rise is projected to accelerate compared with the 20th century under all emissions scenarios. The PESETA II project and the ClimateCost project have estimated the economic and health effects of river and coastal flooding under various climate change scenarios, including sea level rise.

For a medium emissions scenario (SRES A1B) and in the absence of adaptation, river flooding is estimated to affect about 300 000 people per year in the EU by the 2050s and 390 000 people by the 2080s; the latter figure corresponds to more than a doubling with respect to the baseline period (1961–1990). The British Isles, western Europe and northern Italy show a robust

Map 5.1 Deaths related to flooding in Europe for the period 1991–2015



Note: This map shows the number of deaths per million inhabitants related to flooding in Europe (cumulative over the period 1991–2015).

Source: EM-DAT, adapted from WHO and PHE, 2013. © 2016 WHO.

increase in future flood hazards; these regions also show the greatest increase in the population affected by river floods (Rojas et al., 2012, 2013; Ciscar et al., 2014).

If no additional adaptation measures were taken, the number of people affected by coastal flooding in the EU at the end of the 21st century would range from 775 000 to 5.5 million people annually, depending on the emissions scenario. The number of deaths in the EU due to coastal flooding in the 2080s would increase by 3 000, 620 and 150 per year under a high emissions scenario (assuming 88 cm sea level rise), the SRES A1B 'business as usual' scenario and the E1 mitigation scenario, respectively. Two-thirds of these deaths would occur in western Europe. Coastal adaptation measures (dikes and beach nourishment) could significantly reduce risks to less than 10 deaths per year in 2080 (Ciscar et al., 2011; Kovats et al., 2011). Somewhat different estimates were provided in another study (Wolf et al., 2015).

Flooding is also associated with mental health impacts. Coastal flooding in the EU could potentially cause five million additional cases of mild depression annually by the end of the 21st century under a high sea level rise scenario in the absence of adaptation (Bosello et al., 2011; Watkiss and Hunt, 2012).

5.2.4 Extreme temperatures and health

Key messages

- Heat waves and extreme cold spells are associated with decreases in general population well-being and with increases in mortality and morbidity, especially in vulnerable population groups. Temperature thresholds for health impacts differ according to the region and season.
- The number of heat extremes has substantially increased across Europe in recent decades. Heat waves have caused tens of thousands of premature deaths in Europe since 2000.
- It is virtually certain that the length, frequency and intensity of heat waves will increase in the future. This increase will lead to a substantial increase in mortality over the next decades, especially in vulnerable population groups, unless adaptation measures are taken.
- Cold-related mortality is projected to decrease owing to better social, economic and housing conditions in many countries in Europe. There is inconclusive evidence about whether or not the projected warming will lead to a further substantial decrease in cold-related mortality.

Relevance

Temperature affects human well-being and mortality. Both cold and heat have public health impacts in Europe.

Heat or hot weather that lasts for several days, often referred to as 'a heat wave', can have a significant impact on society, including a rise in mortality and morbidity (WMO and WHO, 2015). Heat waves have caused far more fatalities in Europe in recent decades than any other extreme weather event. The effects of exposure can be directly related to heat (heat stroke, heat fatigue and dehydration, or heat stress) or can be the result of a worsening of respiratory and cardiovascular diseases, electrolyte disorders and kidney problems (Aström et al., 2013; Analitis et al., 2014; Breitner et al., 2014). Heat-related problems are greatest in cities; among many interrelated factors, the urban heat island effect plays an important role. During hot weather, synergistic effects between high temperature and air pollution (particulate matter with a diameter ≤10 micrometres (PM_{10}) and ozone) were observed (Katsouyanni and Analitis, 2009; Burkart et al., 2013; De Sario et al., 2013). Long warm and dry periods, in combination with other factors, can also lead to forest fires, which have been shown to have severe health impacts (Analitis et al., 2012). Future climate change is very likely to increase the frequency, intensity and duration of heat waves.

Extreme cold can also significantly affect human health. The physiological and pathological effects of short-term exposure to cold are well known (Holmér et al., 2012). People with cardiovascular and respiratory diseases and the elderly are potentially more susceptible to the effects of cold spells (Ryti et al., 2015). Excess winter mortality in Mediterranean countries is higher than in northern European countries, and deaths often occur several days or weeks after the coldest day of a cold period (Healy, 2003; Analitis et al., 2008).

As well as extreme temperature events, 'non-extreme' temperatures outside a local comfort temperature range are also linked to increased mortality and other adverse health outcomes. The effects of heat occur mostly on the same day and in the following three days, whereas cold effects were greatest two to three weeks after the event (WHO, 2011; Ye et al., 2011). A multi-country global observational study found that moderate temperatures, rather than extreme temperatures, represented most of the total health burden (Gasparrini et al., 2015). The development of adaptation strategies according to local conditions should treat heat and cold extremes separately (Dear and Wang, 2015).

The capacity to adapt to the effects of heat and cold in Europe is high compared with other world regions, but there are important differences in the impacts of heat and cold and in the capacity to respond between and within the European sub-regions. Adaptations to buildings or work practices are likely to be needed to maintain labour productivity during hot weather (IPCC, 2014b).

Past trends

In large parts of Europe, summertime temperature records, which are associated with prolonged heat waves, have increased substantially in recent decades (see Section 3.2.3). The summer of 2003 broke temperature records in large parts of western Europe; temperature records were again broken in different parts of Europe during the summers of 2006, 2007, 2010, 2013, 2014 and 2015 (Barriopedro et al., 2011; Coumou et al., 2013). The record warm summer of 2003 was an outstanding example of increased mortality during periods of extreme temperatures, with an estimated premature mortality of 70 000 people in Europe (Robine et al., 2008). The heat waves of the summer of 2015 caused more than 3 000 deaths in France alone (CRED, 2016).

The largest effect of heat has been observed among the elderly, but in some cities younger adults have also been affected (D'Ippoliti et al., 2010; Baccini et al., 2011). Elderly people are more vulnerable to the effects of heat waves, owing, in part, to poorer physical health and the effects of cognitive impairment on the perception of heat-related health risk; this is the population considered most at risk of heat-related mortality (Josseran et al., 2009). In addition to the elderly, those with chronic diseases and persons of lower socio-economic status also have a heightened risk of heat-related mortality (Wolf et al., 2015). Furthermore, health risks during heat extremes are greater in people who are physically very active. This has importance for outdoor recreational activities, and it is especially relevant for the impacts of climate change on occupational health (e.g. for manual labourers) (Lucas et al., 2014).

The above-mentioned multi-country global observational study found that (moderate) cold was responsible for a higher proportion of deaths than (moderate) heat. The study collected data for daily mortality, temperature and other confounding variables from Italy (11 cities, 1987–2010), Spain (51 cities, 1990–2010), Sweden (one county, 1990–2002), the United Kingdom (10 regions, 1993–2006) and other areas outside Europe (Gasparrini et al., 2015). The results should be interpreted with caution when applied to other regions that were not included in the database.

Figure 5.6 shows the overall cumulative exposure–response curves for four European cities with the corresponding minimum mortality temperature and the cut-offs used to define extreme temperatures. Risk increases slowly and linearly for cold temperatures below the minimum mortality temperature, although some locations (e.g. London and Madrid) showed a higher increase for extreme cold than others. Risk generally escalated quickly and non-linearly at high temperatures. Deaths attributable to extreme heat are roughly as frequent as those attributable to moderate heat, while those attributable to extreme cold are negligible compared with those caused by moderate cold (Gasparrini et al., 2015). Other studies have estimated that 1.6–2.0 % of total mortality in the warm season is attributable to heat; about 40 % of these deaths occur on isolated hot days in periods that would not be classified as heat waves (Baccini et al., 2011; Basagaña et al., 2011).

Comparison of these estimates should be made with caution, as not only the methods used to estimate the excess deaths, but also the exposures were different. The impact of high temperatures later in the summer is sometimes diminished after an early heat wave. In Europe, heat waves occurring in June result in relatively high mortality compared with those occurring later in the summer (WMO and WHO, 2015).

Synergistic effects between high temperature and air pollution (PM_{10} and ozone) have been observed to have led to an increase in hospital admissions as a result of cardiovascular and respiratory diseases. Furthermore, long warm and dry periods, in combination with other factors, can lead to forest fires, which can also have severe health impacts (Analitis et al., 2012, 2014; Aström et al., 2013).

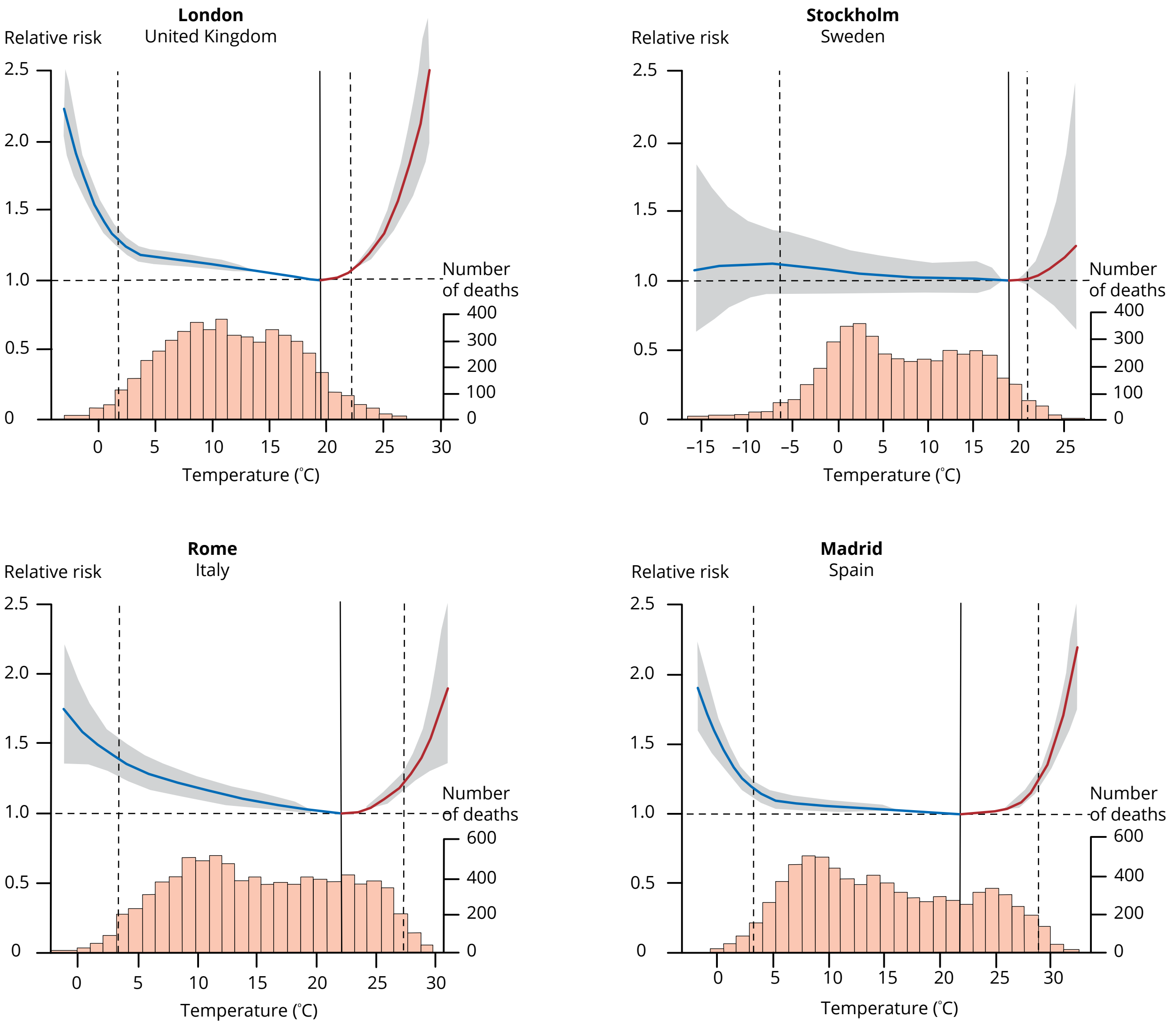
Projections

It is virtually certain that heat extremes will continue to become more frequent over most land areas in the future (see Section 3.2.3). The number of monthly heat records globally is projected to be more than 12 times as high under a medium global warming scenario by the 2040s as in a climate with no long-term warming (Coumou et al., 2013). The projected return period of extreme heat events, such as those experienced in 2003 in western Europe, will significantly shorten. This increase in heat extremes will lead to a marked increase in heat-attributable deaths under future warming, unless adaptation measures are taken. Highly urbanised areas are projected to be at an increased risk of heat stress compared with surrounding areas. Projections of future heat effects on human health need to consider that the European population is projected to age (see Section 6.1), because elderly populations are especially vulnerable (Lung et al., 2013; Watts et al., 2015).

Several studies have estimated future heat-related mortality in Europe using similar methods and have arrived at largely comparable results, namely PESETA, ClimateCost and PESETA II (Ciscar et al., 2011; Kovats et al., 2011; Watkiss and Hunt, 2012; Paci, 2014).

The PESETA study estimates that, without adaptation and physiological acclimatisation, heat-related mortality in Europe would increase by between 60 000 and

Figure 5.6 **Overall cumulative exposure–response associations in four European cities**



Note: This figure shows exposure–response associations as best linear unbiased predictions (with the 95 % empirical confidence interval shaded grey) in representative cities of four countries, with related distributions of temperature and number of deaths. Solid vertical lines show the minimum mortality temperatures and dashed vertical lines show the 2.5th and 97.5th percentiles.

Source: Adapted from Gasparrini et al., 2015. © Gasparrini et al. Open Access article distributed under the terms of CC BY.

165 000 deaths per year by the 2080s compared with the present baseline, with the highest impacts in southern Europe. The results vary across climate models and emissions scenarios, with high emissions scenarios leading to much higher heat-related mortality than low emissions scenarios. Heat-related mortality would be significantly lower under full acclimatisation if, for example, currently cool regions were able to achieve the temperature–mortality relationship of currently warm regions (Ciscar et al., 2011; Huang et al., 2011). The results from the PESETA II study confirm, to a large extent, the results of earlier assessments (in particular, those from the PESETA and ClimateCost projects), although with slightly higher impacts (both in physical and economic terms) (Ciscar et al., 2014). Comparable estimates were made by the WHO for the WHO European Region (Hales et al., 2014; Honda et al., 2014).

Another study estimates that climate change will lead to an increase in hospital admissions owing to heat-related respiratory diseases from 11 000 admissions (0.18 %) in the period 1981–2010 to 26 000 (0.4 %) in 2021–2050. The total number of hospital admissions and the increase as a result of climate change are largest in southern Europe, with the proportion of heat-related admissions for respiratory conditions expected to approximately triple in this region over this time period (Aström et al., 2013).

The PESETA study estimated that cold-related mortality would decrease by between 60 000 and 250 000 deaths per year by the 2080s, which is about the same magnitude as the projected increase in heat-related mortality (Ciscar et al., 2011). The PESETA II study no longer considers a potential reduction in cold-related mortality in its climate impact estimates (Paci, 2014). The choice not to include cold spells reflects recent evidence that does not suggest a significant shift in the balance of deaths between winters and summers because of lower cold-related mortality (Aström et al., 2013; Ebi and Mills, 2013; Kinney et al., 2015). However, the risk from (moderate) cold is expected to continue to account for most of the temperature-related risk throughout this century (Vardoulakis et al., 2014; Arbuthnott et al., 2016).

5.2.5 *Vector-borne diseases*

Key messages

- The transmission cycles of vector-borne diseases are sensitive to climatic factors, but disease risks are also affected by factors such as land use, vector control, human behaviour, population movements and public health capacities.
- Climate change is regarded as the principal factor behind the observed move of the tick species *Ixodes ricinus* — the vector of Lyme borreliosis and tick-borne encephalitis in Europe — to higher latitudes and altitudes. Climate change is projected to lead to further northwards and upwards shifts in the distribution of *Ixodes ricinus.*
- It is generally suspected that climate change has played (and will continue to play) a role in the expansion of other disease vectors, notably the Asian tiger mosquito (*Aedes albopictus*), which can disseminate several diseases including dengue, chikungunya and Zika, and *Phlebotomus* species of sandflies, which transmit leishmaniasis.
- The unprecedented upsurge in the number of human West Nile fever infections in the summer of 2010 in south-eastern Europe was preceded by extreme hot spells in this region. High temperature anomalies in July were identified as contributing factors to the recurrent outbreaks in the subsequent years.

Relevance

Climate change can lead to significant shifts in the geographic and seasonal distribution ranges of vector-borne diseases in Europe (Semenza and Menne, 2009), but there remain significant knowledge gaps related to attributing historical shifts in infectious disease transmission to climate change, as well as to projecting future transmission patterns (Altizer et al., 2013; Rodó et al., 2013; Ostfeld and Brunner, 2015; Parham et al., 2015).

Climate can affect vector-borne diseases by affecting the life cycles of disease vectors and the replication rates of viruses and parasites inside vectors and human hosts. Temperature increases may shorten the life cycles of vectors and the incubation periods of vector-borne pathogens, thereby potentially leading to larger vector populations and higher transmission risks, but beyond certain thresholds pathogen growth in vectors might be interrupted. Over the longer term, seasonal changes could affect both vectors and host animals, as well as human behaviours and land-use patterns, thereby further influencing the geographical distribution, seasonal activity and overall prevalence of vector-borne diseases in Europe (Lindgren et al., 2012). Furthermore, climatic suitability is essential for the arrival, establishment and spread of 'exotic' diseases that are not currently established in continental Europe (Randolph and Rogers, 2010). However, in addition to climate change, the risk of communicable diseases is also affected by a wide range of ecological, economic and social factors, such as land-use patterns and agricultural practices; biological diversity; the capacity of public health systems; travel, trade and migration; and human behaviours affecting individual risk factors (Jones et al., 2008; Suk and Semenza, 2011; McMichael, 2013). Thus, vulnerabilities to health systems and populations must also be accounted for alongside climatic changes when assessing future infectious disease risks (Suk et al., 2014).

Past trends: tick-borne diseases

Tick-borne encephalitis (TBE) and Lyme borreliosis (Lyme disease) are the two most important tick-borne diseases in Europe, both of which are transmitted primarily by *Ixodes ricinus*. Lyme disease is the most common vector-borne disease in the EU, with a reported incidence of approximately 65 000 cases per year. However, there is no standardised case definition or diagnosis for Lyme disease in Europe, so this number represents only a best estimate. The number of reported cases of TBE in the EU was 2 560 during 2012. The mean annual reporting of TBE cases has increased by approximately 400 % in European endemic areas over the past 30 years, although this is almost certainly the result of more robust detection methods and diagnosis (Medlock et al., 2013; ECDC, 2014).

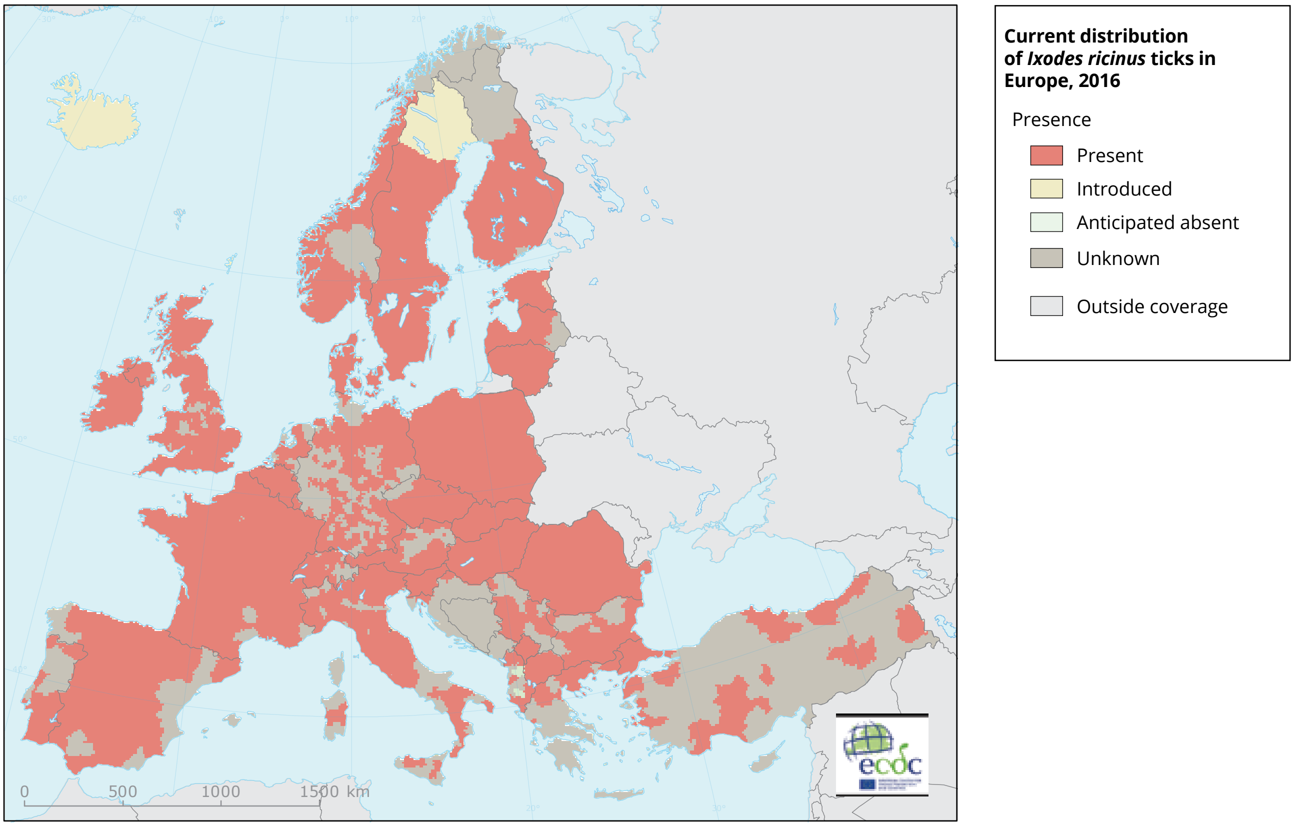
A key determinant of the number of reported cases is the abundance of ticks, a factor which is sensitive to climatic variables, notably temperature and humidity. Currently, *Ixodes ricinus* is present across much of continental Europe (Map 5.2). There have already been reports on the northerly migration of the tick species in Sweden (Jaenson et al., 2012), and to higher altitudes in the Czech Republic and Austria (Daniel et al., 2003; Heinz et al., 2015). Range shifts have also been observed in Germany and Norway (Semenza and Menne, 2009).

A high incidence of tick-borne disease is correlated with mild winters and warm, humid summers in Hungary, Slovakia and Sweden, although this could be the result of climate effects on human behaviour (Ostfeld and Brunner, 2015). A high risk of Lyme disease has been associated with mild winters, high summer temperatures, low seasonal variation of temperatures and high scores on vegetation indices (Estrada-Pena et al., 2011). There are considerable differences between the distribution of ticks and the observed incidence of TBE (Süss et al., 2006). It is not currently possible to assess the relative importance of climatic changes and of other factors influencing disease incidence, including vaccination coverage, tourism patterns, public awareness, distribution of rodent host populations and socio-economic conditions (Randolph, 2008). There is limited evidence that other tick-borne diseases may be sensitive to climate change. Some models have suggested that the Mediterranean basin has become suitable for an expansion of Crimean–Congo haemorrhagic fever (Maltezou and Papa, 2010), but demographic factors, farming practices and land-use change may be more important drivers (Estrada-Peña, Jameson, et al., 2012). The distribution of *Rickettsia* has also expanded in recent years, but the reasons for this are not yet well understood (Gouriet et al., 2006), and few if any recent studies have interrogated the links between rickettsia diseases and climate change.

Past trends: mosquito-borne diseases

Mosquito habitats are influenced by temperature, humidity and precipitation levels. The Asian tiger mosquito (*Aedes albopictus*) is an important vector in Europe for transmitting viral diseases, including Zika, chikungunya and dengue. The first record of its

Map 5.2 Current distribution of *Ixodes ricinus* ticks in Europe



Note: The map shows the current distribution of the tick species *Ixodes ricinus* in Europe at the 'regional' administrative level (NUTS3). The map is based on published historical data and confirmed data provided by experts from the countries as part of the VectorNet project ([94]). However, there is underreporting because the data are not reportable by law.

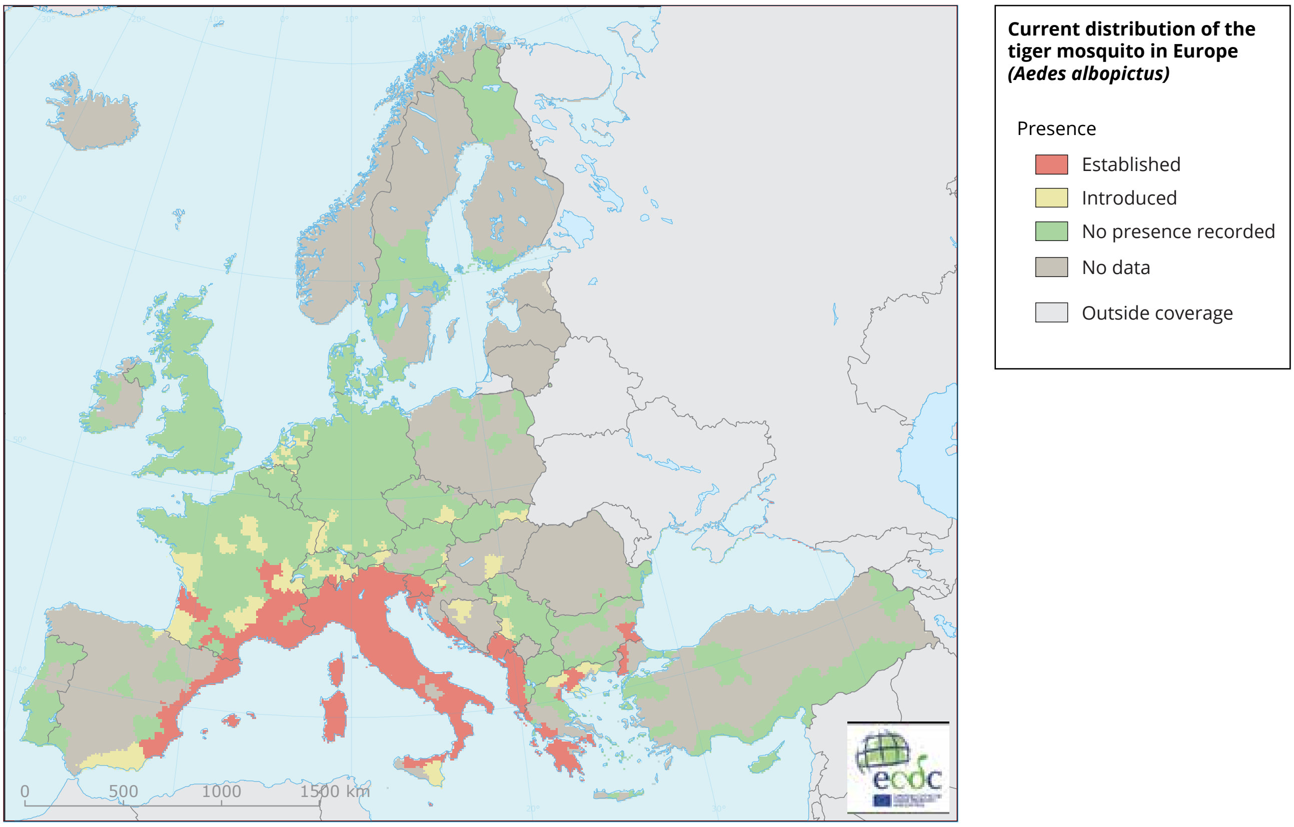
Source: Copyright © 2016 European Centre for Disease Prevention and Control (ECDC) and the European Food Safety Authority (EFSA). Reproduced with permission.

([94]) http://ecdc.europa.eu/en/activities/diseaseprogrammes/emerging_and_vector_borne_diseases/Pages/VBORNET.aspx.

establishment was in Italy in 1990, and *Aedes albopictus* is now present in several EU Member States and in some countries neighbouring the EU (Map 5.3). It has substantially extended its range in recent years, aided by trade and travel. It is generally suspected that climate change has also played a role in this expansion, but the extent to which this is the case is unclear (Caminade et al., 2012). The introduction and geographical expansion of the distribution of *Aedes albopictus* within Europe has coincided with favourable climatic suitability for the mosquito in the Balkans, Italy, France and Benelux and in western Germany, on the eastern coast of Spain and on the eastern coast of the Adriatic Sea (Caminade et al., 2012). Other parts of Europe are also climatically suitable for *Aedes albopictus*, even if they have not recorded the presence of the vector (Map 5.4) (Rogers et al., 2014; Proestos et al., 2015).

Mosquito-borne diseases have not been a substantial concern within Europe until recently. However, locally transmitted (i.e. autochthonous) outbreaks of chikungunya, dengue and even malaria have occurred in recent years (ECDC, 2014). Several disease outbreaks transmitted by *Aedes. albopictus* have been reported in Europe: chikungunya in Italy and in France in 2010, 2014 and 2015, as well as local transmissions of dengue in France and Croatia in 2010 (Rezza et al., 2007; La Ruche et al., 2010; Gjenero-Margan et al., 2011; Grandadam et al., 2011; Delisle et al., 2015). Heavy rainfall events may have increased the risk of the autochthonous transmission of chikungunya in France in 2014 by leading to a rapid rise in vector abundance (Roiz et al., 2011; ECDC, 2015). No autochthonous transmission of dengue has been reported in Europe since 2010.

Map 5.3 **Current distribution of *Aedes albopictus* in Europe**

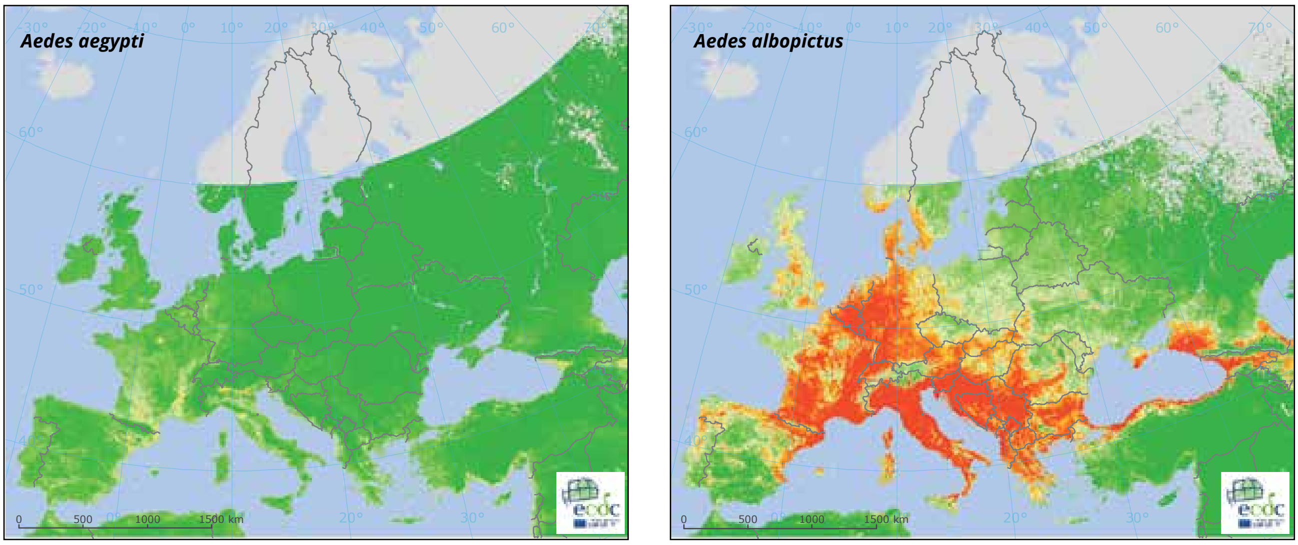


Note: The map shows the current distribution of the invasive mosquito species *Aedes albopictus* in Europe at the 'regional' administrative level (NUTS3). The map is based only on confirmed data (published and unpublished) provided by experts from the countries as part of the VectorNet project ([95]). However, there is underreporting because the data are not reportable by law. Red shows that established populations (evidence of reproduction and overwintering) of the species have been observed in at least one municipality within the administrative unit. Yellow shows that the species has been introduced (but without confirmed establishment) in the administrative unit within the last five years of the distribution status date. Green shows that field surveys or studies on mosquitoes were conducted with no introduction (during the last five years) and no established population of the species having been reported. Dark grey shows that no data for the last five years are available to local experts.

Source: Copyright © 2015 European Centre for Disease Prevention and Control. Reproduced with permission.

([95]) http://ecdc.europa.eu/en/activities/diseaseprogrammes/emerging_and_vector_borne_diseases/Pages/VBORNET.aspx.

Map 5.4 Climatic suitability for the mosquitos *Aedes aegypti* and *Aedes albopictus* in Europe



Climatic suitability for *Aedes aegypti* and *Aedes albopictus* (Asian tiger mosquito) in Europe

Suitability (%)

0–9 | 10–19 | 20–29 | 30–39 | 40–49 | 50–59 | 60–69 | 70–79 | 80–89 | 90–100 | No prediction

Note: The map shows climatic suitability for the mosquitos *Aedes aegypti* (left) and *Aedes albopictus* (right) in Europe. Shades of green indicate conditions that are not suitable for the vector (darker being the most unsuitable), whereas yellow to red colours indicate conditions that are increasingly suitable for the vector. Grey indicates that no prediction is possible.

Source: ECDC, 2012. Copyright © 2012 European Centre for Disease Prevention and Control. Reproduced with permission.

The risk of travellers importing Zika, dengue or chikungunya coincides with the seasons and locations of active *Aedes albopictus* in Europe (Semenza et al., 2014). With continued expansion of *Aedes albopictus* in continental Europe, the risk of further introduction and transmission of Zika, chikungunya and dengue will continue to exist. The risk of chikungunya introductions into Europe via returning travellers has probably increased following the large-scale outbreak of chikungunya that began in the Caribbean in late 2013 and has subsequently continued in many American countries (Van Bortel et al., 2014).

Aedes albopictus is not the primary vector for dengue and, although **s**ome parts of Europe are currently climatically suitable to its primary vector (*Aedes aegypti*), the risk of significant dengue transmission in continental Europe is currently very low, providing that the vector remains unestablished and control measures are in place (ECDC, 2012). *Aedes aegypti* has, however, been responsible for dengue outbreaks in European territories, such as the 2013 outbreak in Madeira, Portugal (ECDC, 2013).

Malaria was largely eradicated in Europe in the second half of the 20th century. However, the malaria vectors (*Anopheles* mosquitos) are still present in much of the European Union, and a few sporadic cases of local transmission occur each year (Florescu et al., 2011). The risk of malaria re-establishment in a particular region depends on climatic and ecological factors, as well as human vulnerabilities to infection. During 2009–2012, Greece experienced autochthonous malaria transmission; temperature and other environmental variables were identified as determinants of environmental suitability (Sudre et al., 2013). However, socio-economic development is a key mitigating factor of malaria risk (Gething et al., 2010), which therefore remains very low throughout Europe.

West Nile virus (WNV) infections in humans can be quite severe, particularly among the elderly, but many other cases can go unnoticed (more than 60 % are asymptomatic) and occur through mosquito (*Culex* species) bites. Cases can also be acquired through blood transfusion or organ, tissue and cell transplantations and, although rare, such cases have been reported

(Petersen et al., 2013). Since 2010, there have been annual outbreaks in south-eastern and eastern Europe, suggesting an endemic transmission cycle and thus a resurgent public health problem (Map 5.5) (Paz and Semenza, 2013; Semenza et al., 2016). Positive temperature anomalies from the monthly averages were the most important determinants of the 2010 WNV outbreak (Paz et al., 2013). Over the subsequent years, other environmental drivers (besides temperature) were also identified as important, such as the state of vegetation, water bodies (modified normalised difference water index) and bird migratory routes (Tran et al., 2014; Marcantonio et al., 2015).

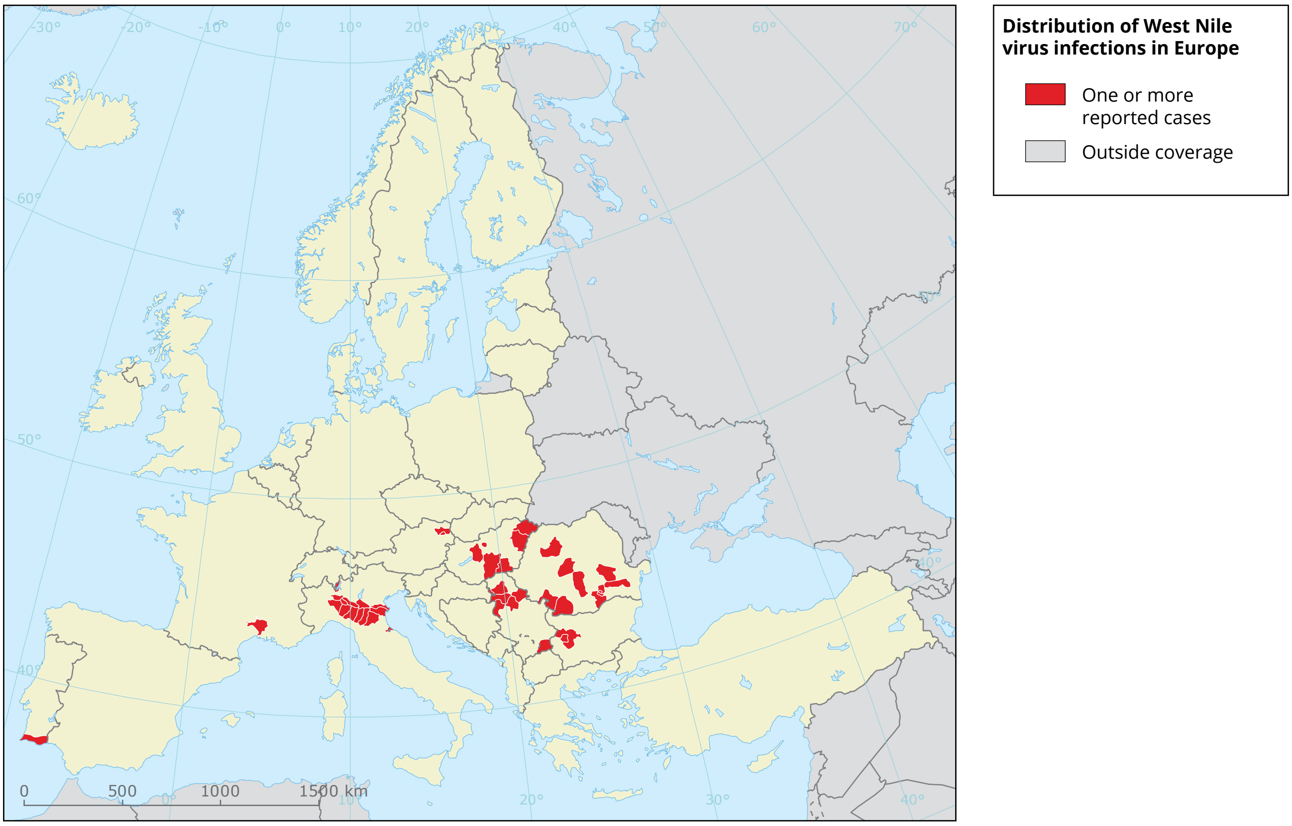
Past trends: sandfly-borne diseases

Leishmaniasis is the most common disease transmitted by phlebotomine sandflies in Europe. The transmission of the two parasites responsible for this disease that are endemic in the EU (*Leishmania infantum*, causing visceral leishmaniasis, and *Leishmania tropica*, causing cutaneous leishmaniasis) is heavily influenced by temperature. *Leishmania tropica* occurs sporadically in Greece and neighbouring countries, while *Leishmania infantum* is endemic in the Mediterranean region of the EU. Sandfly vectors currently have wider distribution ranges than the parasites. The evidence for an impact of climate change on the distribution of the sandfly in Europe is scarce (Ready, 2010). Climate change was suggested as one possible reason for the observed northwards expansion of sandfly vectors in Italy (Maroli et al., 2008). The contemporary risk for central Europe has been estimated to be low owing to temperature constraints on pathogen growth (Fischer et al., 2010).

Projections: tick-borne diseases

Cold temperatures appear to determine the altitudinal and latitudinal limits of *Ixodes ricinus* (Ostfeld and Brunner, 2015). Thus, an expansion of the distribution range of ticks to higher altitudes and latitudes is projected, as milder winter temperatures, longer vegetation seasons and earlier onsets of summer appear and warmer temperatures occur, under the condition that their natural hosts (deer) would also shift their distribution (Jaenson and Lindgren, 2011). One

Map 5.5 Current distribution of West Nile virus infections in Europe



Note: The map shows districts with probable and confirmed cases of West Nile virus infections, as of 20 November 2014.

Source: Adapted from Semenza et al., 2016.

climate projection model anticipates a 3.8 % overall habitat expansion for *Ixodes ricinus* in Europe by 2040–2060, with expansion into higher altitudes and latitudes (notably Scandinavia and the Baltic countries) and a contraction in some areas including the Alps, the Pyrenees, the interior of Italy and north-western Poland (Boeckmann and Joyner, 2014). This aligns with other models of climate change that anticipate *Ixodes ricinus* range expansions under climate change scenarios (Estrada-Peña, Ayllón, et al., 2012; Porretta et al., 2013), but it has been acknowledged that many uncertainties exist in these models and that extrapolating the projected habitat range of ticks to generate projections of the incidence of tick-borne disease leads to additional uncertainties.

Nonetheless, the incidence of TBE may shift to higher altitudes and latitudes along with the distribution of *Ixodes ricinus*, potentially increasing the risk in some parts of northern and central Europe, unless targeted vaccination programmes and TBE surveillance are introduced. Similarly, TBE risk is generally expected to decrease in southern Europe. Warmer winters may facilitate the expansion of Lyme disease to higher latitudes and altitudes, particularly in northern Europe, but it would decrease in the parts of Europe that are projected to experience increased droughts (Semenza and Menne, 2009).

Projections: mosquito-borne diseases

Various studies have found that warm seasonal and annual temperature and sufficient rainfall provide favourable climatic conditions for *Aedes albopictus* in Europe (Roiz et al., 2011). The climatic suitability for *Aedes albopictus* is projected to increase where climate models project warmer and wetter climates, such as south-eastern United Kingdom (Medlock and Leach, 2015), the Balkans and central Europe, while suitability generally decreases where climate becomes drier, such as in some regions of Spain and Portugal (Caminade et al., 2012). This corresponds with a modelling study that demonstrated a general decline in habitat suitability in southern Europe and the Mediterranean area, and an increase in habitat suitability in northern and eastern European countries (Proestos et al., 2015).

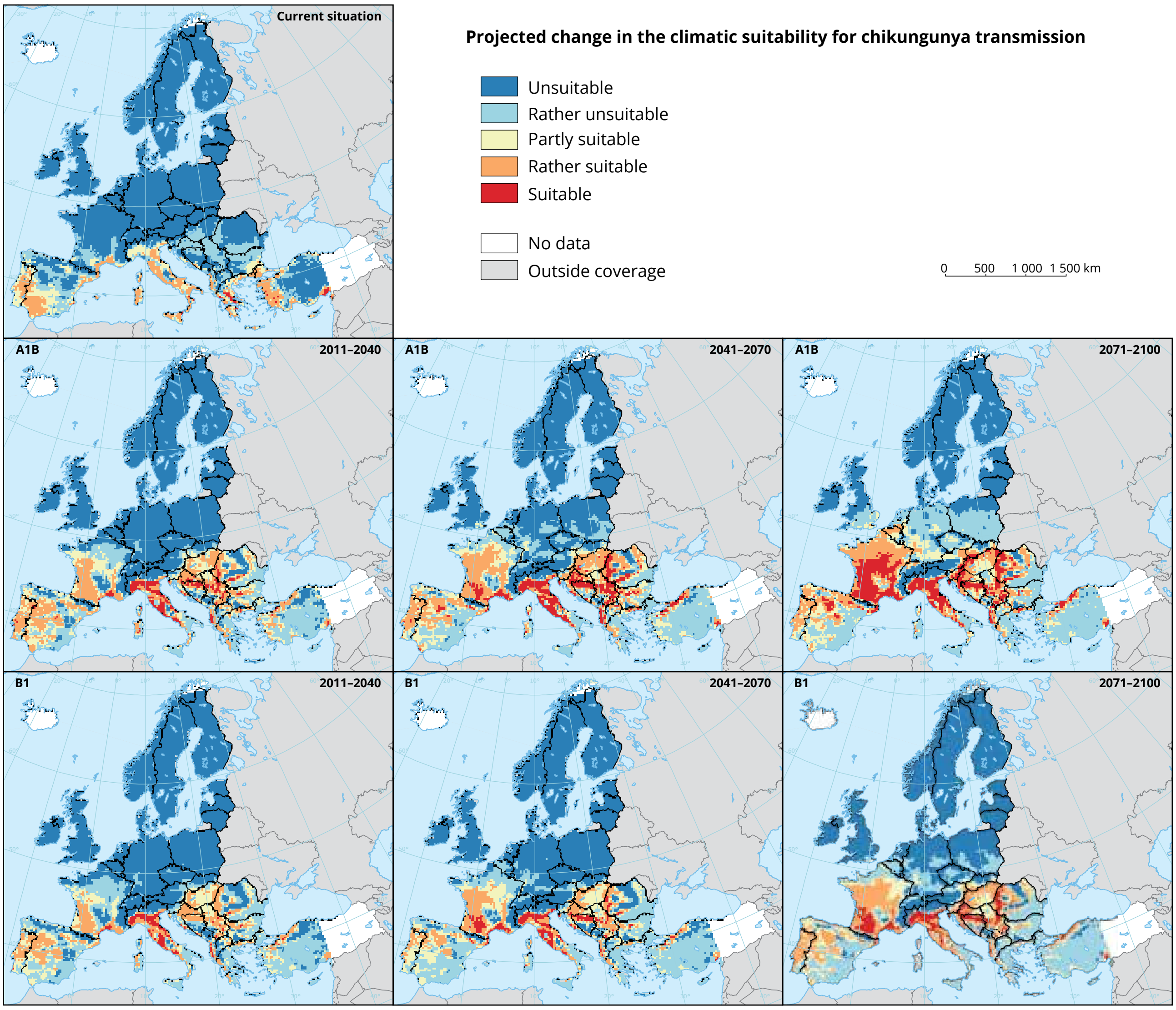
The risk of chikungunya may increase in Europe, particularly in those regions where the seasonal activity of *Aedes albopictus* aligns with the seasonality of endemic chikungunya infections abroad, thereby potentially increasing the risk of importation via travellers (Charrel et al., 2008). Models of chikungunya transmission in Europe under climate change scenarios have identified France, northern Italy and the Pannonian Basin (east-central Europe) as the areas at highest risk, with increases in the level of risk in much of western Europe, including the Benelux countries and Germany. In contrast, Mediterranean regions demonstrated a decreased risk, although the models suggested that they will mostly remain climatically suitable for chikungunya transmission (Map 5.6) (Fischer et al., 2013).

A climate-related increase in the density or active season of *Aedes albopictus* could lead to a small increase in the risk of dengue in Europe. The risk could also increase if the temperature increase facilitated the re-establishment of *Aedes aegypti*, the primary dengue vector. Further modelling studies are required to assess whether climate change would increase or decrease the climatic suitability for *Aedes aegypti* in continental Europe.

Some malaria models suggest that there will be increased suitability for malaria transmission in continental Europe under future climate change, but projected malaria impacts are highly sensitive to model design (Caminade et al., 2014). Nevertheless, socio-economic development, land-use and public health control measures would most likely be sufficient to mitigate the risk of malaria at the fringes of its distribution, despite the likelihood of sporadic introductions of the parasite through global travel (Semenza et al., 2014).

Climate change has previously not been expected to have a significant impact on WNV transmission in Europe (Gale et al., 2009; Gould and Higgs, 2009). However, climate change could influence the transmission of the virus by affecting the geographical distribution of vectors and pathogens, by changing the migratory patterns of bird populations and through changes in the life cycle of bird-associated pathogens. Temperature increases could also play a role. The WNV risk in Europe has been projected into 2025 and 2050, with July temperature projections under a medium emissions scenario (SRES A1B), keeping other variables constant (e.g. state of vegetation, water bodies and bird migratory routes) (Semenza et al., 2016). The results reveal a progressive expansion of areas with an elevated probability for WNV infections, particularly at the edges of the transmission areas (Map 5.7). Projections for 2025 show an increased probability of WNV infection in eastern Croatia, north-eastern Greece and north-western Turkey; high-risk areas will have expanded even more by 2050.

Map 5.6 Projected change in the climatic suitability for chikungunya transmission



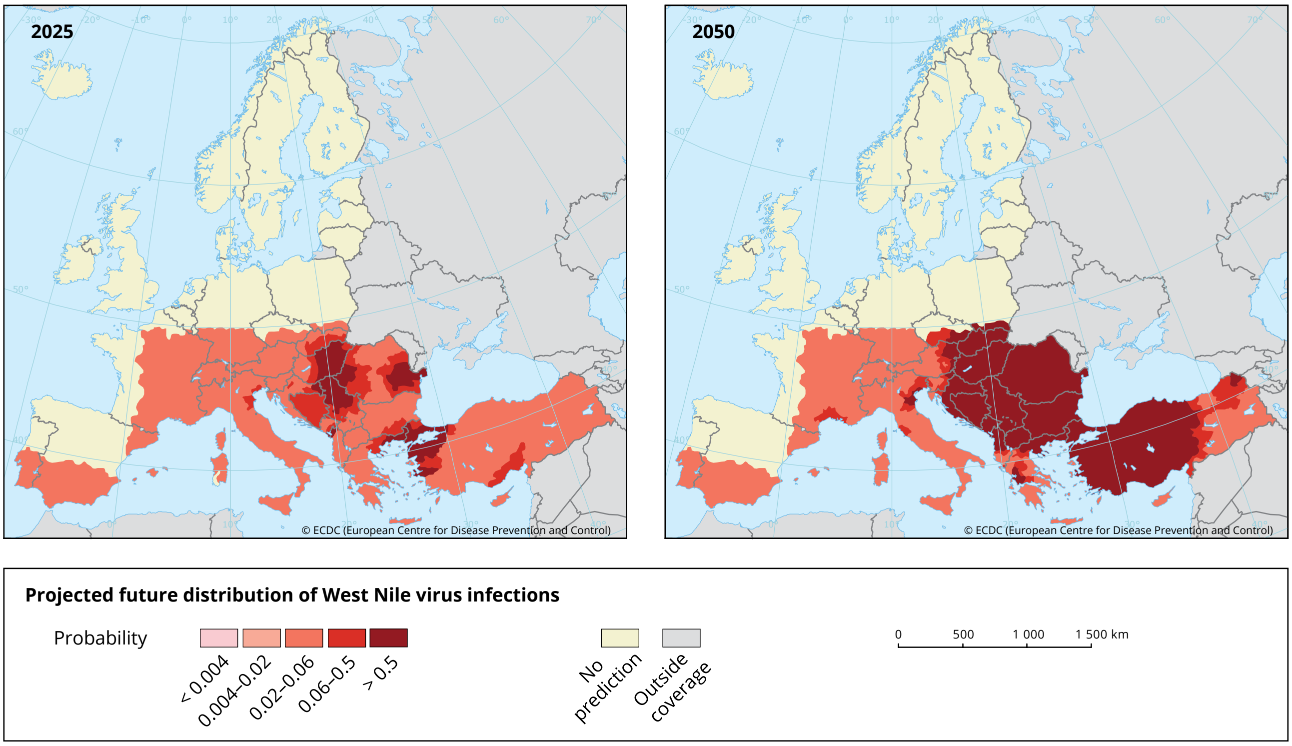
Note: The map shows the risk for chikungunya transmission in Europe. It was generated by combining temperature requirements of the chikungunya virus with the climatic suitability of the vector *Aedes albopictus*. Projections for different time frames are based on projections by the regional climate model COSMO-CLM for two emissions scenarios (A1B, a medium emissions scenario, and B1, a low emissions scenario). The 'current situation' refers to the 1960–1990 baseline climate.

Source: Adapted from Fischer et al., 2013. © 2013 Fischer et al.; licensee BioMed Central Ltd. Open access article distributed under the terms of the Creative Commons Attribution License.

Projections: sandfly-borne diseases

Future climate change could have an impact on the distribution of leishmaniasis by affecting the abundance of vector species and parasite development. Recent modelling indicates that the central European climate will become increasingly suitable for *Phlebotomus* species of sandflies (Fischer et al., 2011). One modelling study concluded that, by the end of the 2060s, France, Germany, western Poland and southern United Kingdom could be colonised by sandfly species, principally *Phlebotomus ariasi* and *Phlebotomus pernicious*, while the entire Mediterranean Basin, Balkan Peninsula and Pannonian Basin would all be potentially climatically suitable habitats for many *Phlebotomus* species (Trájer et al., 2013). Such expansions of sandfly species would increase the risk of leishmaniasis, but may be somewhat constrained by the limited migration ability of sandflies. The risk of disease transmission may also decrease in some areas in southern Europe where climate conditions become too hot and dry for vector survival.

Map 5.7 Projected future distribution of West Nile virus infections



Note: The map shows the predicted probability of districts with West Nile virus infections based on July temperatures for A1B scenario projections for 2025 (left) and 2050 (right).

Source: Adapted from Semenza et al., 2016.

5.2.6 Water- and food-borne diseases

Key messages

- It is not possible to assess whether past climate change has already affected water- and food-borne diseases in Europe, but the sensitivity of pathogens to climate factors suggest that climate change could be having effects on these diseases.
- The number of vibriosis infections, which can be life-threatening, has increased substantially in Baltic Sea states since 1980. This increase has been linked to observed increases in sea surface temperature, which has improved environmental conditions for *Vibrio* species blooms in marine waters. The unprecedented number of vibriosis infections in 2014 has been attributed to the unprecedented 2014 heat wave in the Baltic region.
- Increased temperatures could increase the risk of salmonellosis.
- The risk of campylobacteriosis and cryptosporidiosis could increase in those regions where precipitation or extreme flooding is projected to increase.
- Climate change can have an impact on food safety hazards throughout the food chain.

Relevance

A rise in air and water temperature, extreme precipitation events, seasonal changes, storms, droughts and flooding, associated with climate change, can have implications for food- and water-borne diseases in Europe (Semenza, Herbst, et al., 2012; Semenza, Houser, et al., 2012) (Table 5.3). These climatic events can alter growth rates of pathogens, contaminate drinking, recreational and irrigation water, and disrupt water treatment and sanitation systems. Conversely, potential impacts will be modulated by the quality of food safety measures, the capacity and quality of water treatment systems, human behaviour and a range of other conditions.

High air temperatures can adversely affect food quality during transport, storage and handling. Elevated marine water temperatures accelerate the growth rate of certain pathogens, such as *Vibrio* species that can cause food-borne outbreaks (seafood). On rare occasions, they may lead to severe necrotic ulcers, septicaemia and death in susceptible individuals exposed during bathing in contaminated marine environments. Floods and increased water flows can lead to the contamination of drinking, recreational or irrigation water and thus can increase the risk of water-borne diseases, such as cryptosporidiosis.

Attributing past trends in these diseases, or individual outbreaks, to climate change is very challenging, owing to data gaps for selected pathogens and climatic determinants. For example, legionnaires' disease is associated with temperature and vapour pressure but not with climate change per se (Conza et al., 2013).

The current knowledge on the relationship between climatic factors and the risk associated with several climate-sensitive food- and water-borne diseases (caused by bacteria, viruses and parasites) in Europe is presented in Table 5.3.

Vibrio species (non-cholera)

Brackish water and elevated ambient temperature are ideal environmental growth conditions for certain *Vibrio* species. These conditions can be found during the summer months in estuaries and enclosed water bodies with moderate salinity, such as the Baltic Sea. In contrast, open ocean environments do not offer appropriate growth conditions for these bacteria owing to the high salt content, lower temperature and limited nutrient content. Of the most relevance to human health are the *Vibrio* species that can cause vibriosis infections, including *Vibrio parahaemolyticus*, *Vibrio vulnificus* and the non-toxigenic *Vibrio cholerae*.

Elevated levels of non-cholera *Vibrio* species infections have been observed during extended hot summer seasons with water temperatures above 20 °C in the Baltic Sea and the North Sea (Hemmer et al., 2007; Baker-Austin et al., 2012; Sterk et al., 2015). The availability of data is best for the Baltic Sea region, where a recent analysis found strong links between the temporal and spatial peaks in sea surface temperatures and the number and distribution of *Vibrio* infections. Figure 5.7 shows the observed and projected levels of *Vibrio* infections in the Baltic Sea region from 1982 to 2010, which was a period of unprecedented sea surface temperature warming (see also Section 3.1)

Table 5.3 Demonstrable links between climatic variables and selected pathogens

	Campylobacter	Salmonella	Listeria	Vibrio	Cryptosporidium	Norovirus
Temperature	⬄	⬄	?	⬄	⬄	⬄
Extreme temperature	⬄	?	?	⬄	⬄	?
Temperature threshold	⬄	⬄	?	⬄	⬄	?
Precipitation	⬄	⬄	?	⬄	⬄	?
Precipitation pattern ([a])	⬄	?	?	?	⬄	⬄
Extreme precipitation	⬄	?	?	⬄	⬄	⬄
Humidity	⬄	⬄	⬄	?	?	?
UV light	⬄	⬄	⬄	⬄	⬄	?
Seasonality	⬄	⬄	?	⬄	⬄	⬄
Salinity	O	O	O	⬄	O	O
Floods	⬄	⬄	?	⬄	⬄	⬄
Drought	⬄	?	?	O	⬄	?
Storms	?	?	?	⬄	?	?
Irrigation ([b])	?	⬄	?	O	⬄	?
Recreational activities	⬄	⬄	?	⬄	⬄	⬄
Shellfish production	⬄	⬄	⬄	⬄	?	⬄
Consumption habits	⬄	⬄	⬄	⬄	⬄	⬄

Note: ([a]) For example, seasonality of rain events.

([b]) Water.

⬄ = impact; O = no impact; ? = impact unknown.

Source: Semenza et al., 2012.

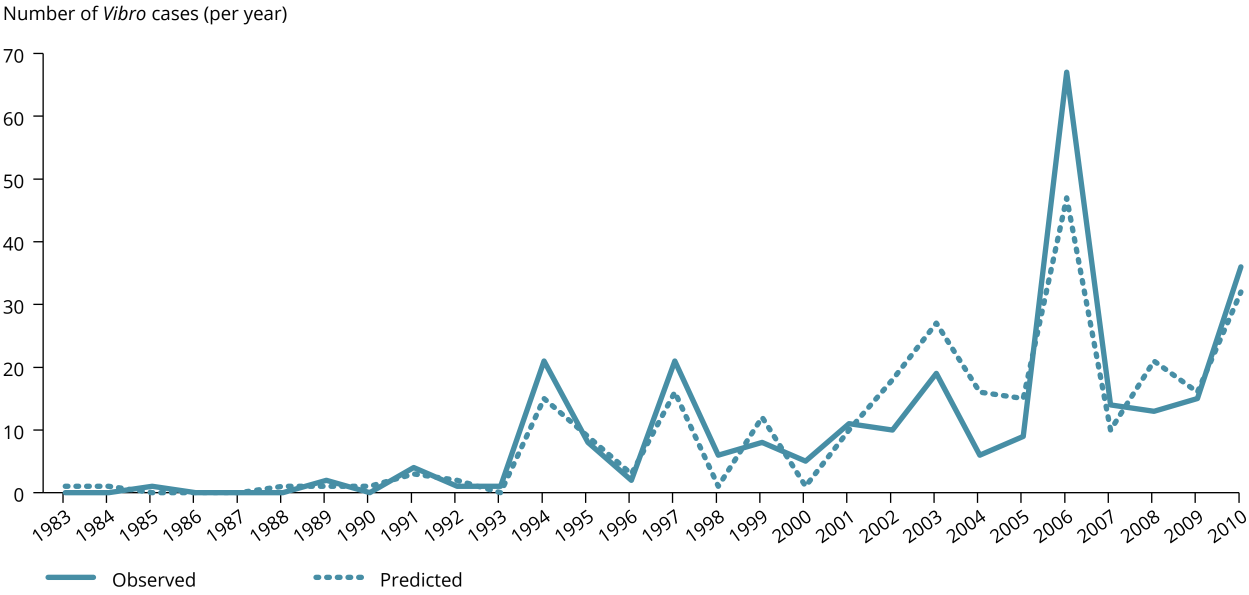
(Baker-Austin et al., 2012). Increased numbers of infections can be expected based on the effects of increased temperatures under climate change scenarios. Map 5.8 presents *Vibrio* risk maps for 2006 (left) and 2050 under elevated sea surface temperature (right). The projected increase in risk is substantial, but the absolute increase is projected to be modest owing to low current incidence rates. More recent studies in this region suggest that this warming trend has continued, with the July 2014 heat wave experienced in Sweden and Finland leading to an unprecedented number of *Vibrio* wound infections reported in the region, many at extremely high latitudes (e.g. > 65 N) (Baker-Austin et al., 2016). Environmentally acquired *Vibrio* infections in humans associated with particularly high sea surface temperatures have also been reported along the North Sea coast of Europe in recent years (Vezzulli et al., 2016).

Bacterial *Vibrio* blooms in coastal water can be monitored on the E3 Geoportal developed by the ECDC (ECDC, 2016). The tool uses daily updated remotely sensed data to examine environmentally suitable conditions for *Vibrio* species in coastal waters internationally.

Cryptosporidium

Cryptosporidiosis is an acute diarrhoeal disease caused by intracellular protozoan parasites, *Cryptosporidium* species. Transmission is through the faecal–oral route via contaminated water, soil or food products, and the most commonly identified vehicles are contaminated drinking water and contaminated recreational water. For example, several days of heavy rain in June 2013 resulted in river flooding in eastern Germany, and activities in the dried out floodplain led to infection among children (Gertler et al., 2015). Heavy rainfall has also been associated with the contamination of water supplies and outbreaks of cryptosporidiosis (Aksoy et al., 2007; Hoek et al., 2008), as the concentration

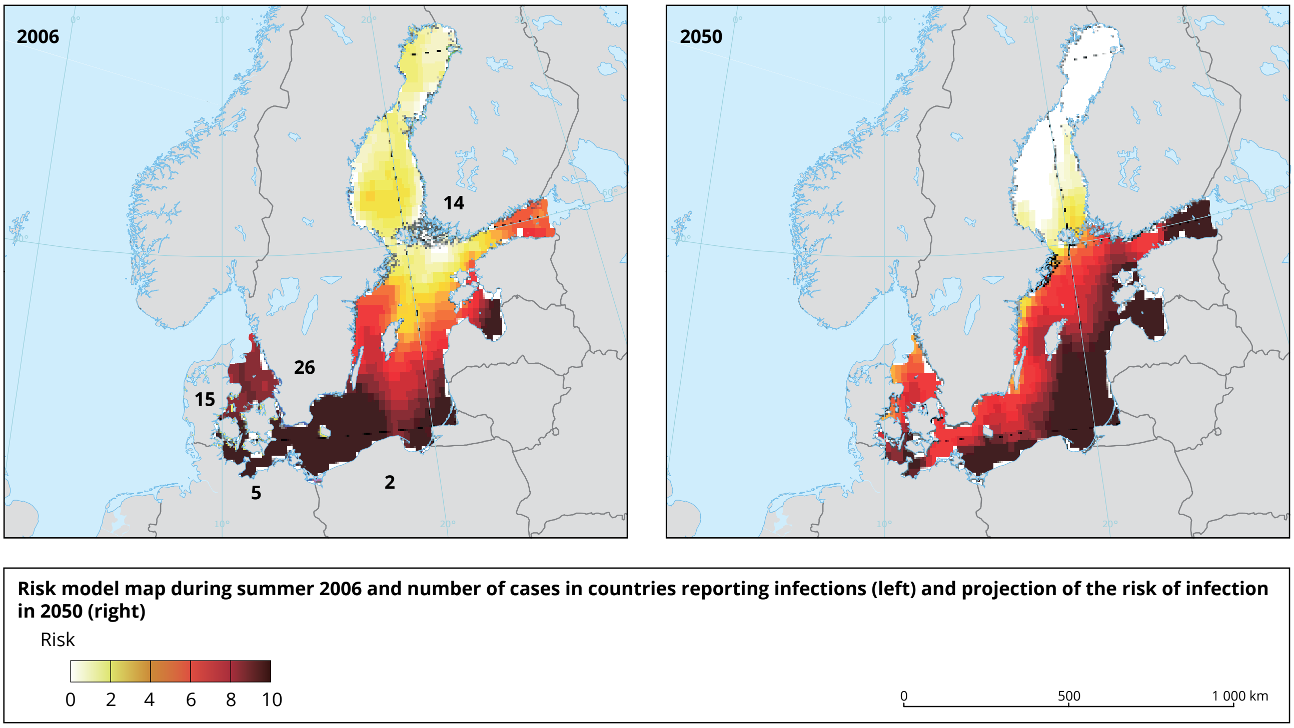
Figure 5.7 Time series of Baltic Sea *Vibrio* cases



Note: The solid line in this figure shows the observed cases and dotted line shows the GLM model predictions based on the influence of maximum sea surface temperature and time.

Source: Adapted from Baker-Austin et al., 2012.

Map 5.8 Current and projected risk of vibriosis infections in the Baltic Sea region



Note: Left: A risk model map during summer 2006 showing the number of cases in countries reporting infections. Right: A projection of the risk of infection in 2050.

Source: Adapted from Baker-Austin et al., 2012. © 2012 Macmillan Publishers Ltd. Reproduced with permission.

of *Cryptosporidium* oocysts in river water increases significantly during rainfall events. Dry weather conditions preceding a heavy rain event have also been associated with drinking water outbreaks (Nichols et al., 2009). Thus, heavy precipitation can result in the persistence of oocysts in the water distribution system and the infiltration of drinking water reservoirs from springs and lakes. Inadequate barriers to remove or inactivate *Cryptosporidium* in the public water supply have in the past resulted in a large outbreak of *Cryptosporidium* in Sweden (Widerstrom et al., 2014).

Campylobacter

In Europe, campylobacteriosis is the most common bacterial cause of diarrhoeal disease. The association of campylobacteriosis with a number of weather-related factors, such as temperature, rainfall, humidity and sunshine is inconsistent and lacks a clear explanatory mechanism, as *Campylobacter* does not replicate outside its animal host. There is a clear seasonality to the data in a number of European countries, with more cases during the summer months, and an association with the ambient temperature that preceded the diagnosis of the cases by 10 to 14 weeks (Nylen et al., 2002). Temperature has also been found to be linked to cases in a number of studies from England and Wales (Louis et al., 2005; Tam et al., 2006; Nichols et al., 2012) but not in other countries (Kovats et al., 2005). Rain in early spring can trigger campylobacteriosis outbreaks (Louis et al., 2005). With the projected increase in heavy rainfall events in northern Europe, the risk of surface and groundwater contamination is expected to rise. Climate change might increase the use of rainwater for irrigation or drinking water during times of drought in certain locations.

Norovirus

Norovirus is the most common cause of viral diarrhoea in humans with a pronounced winter seasonality. Food-borne norovirus outbreaks have been linked to climate and weather events; for example, heavy rainfall and floods may lead to wastewater overflow which can contaminate shellfish farming sites. Flood water has been associated with a norovirus outbreak in Austria (Schmid et al., 2005). In Europe, norovirus season strength was positively associated with average rainfall in the wettest month (Ahmed et al., 2013). Water-borne transmission of the virus is probably influenced by rainfall, causing norovirus seasonality (Marshall and Bruggink, 2011). The magnitude of rainfall has also been related to viral contamination of the marine environment and with peaks in diarrhoea incidence (Miossec et al., 2000). The predicted increase of heavy rainfall events under climate change scenarios could lead to an increase in norovirus infections because floods are known to be linked to norovirus outbreaks.

Salmonella

Salmonellosis is the second most commonly reported gastrointestinal infection and an important cause of food-borne outbreaks in Europe. However, overall reported cases of salmonellosis have declined steadily for several years in Europe, in part because of control measures implemented in poultry production. An increase in weekly temperature has been associated with an increase in salmonellosis in different settings (Naumova et al., 2006; Zhang et al., 2007; Nichols et al., 2009). Seasonal temperatures have been linked to salmonellosis cases, but public health interventions can attenuate the effect of warmer temperature. Extreme precipitation events that result in faecal contamination events have also been associated with salmonellosis (Craig et al., 2003; Martinez-Urtaza et al., 2004). Floods caused by heavy rainfall events may disrupt water treatment and sewage systems and contribute to increased exposure to *Salmonella* species and other pathogens.

Available climate change projections indicate that the average annual number of temperature-related cases of salmonellosis in Europe may increase by almost 20 000 by the 2020s, in addition to increases expected from population changes. Under a high emissions scenario, climate change could result in up to 50 % more temperature-related cases by the end of the 21st century than would be expected on the basis of population change alone. However, these estimates are associated with high uncertainty (Watkiss and Hunt, 2012). Moreover, health promotion and food safety policies can mitigate adverse impacts on public health.

5.3 Agriculture

Key messages

- An increase in the duration of the thermal growing season has led to the northwards expansion of areas that are suitable for several crops.
- Changes in crop phenology have been observed, such as the advancement of flowering and harvest dates in cereals. These changes are expected to continue in many regions, leading to reductions in grain yield.
- Recent heat waves, droughts and floods have greatly reduced the yield of some crops. The projected increase in the occurrence of such events would be particularly detrimental for crop production in central and southern Europe, where such events will occur more frequently and add to current stresses. Throughout Europe, the increased frequency of extreme events is expected to increase the risk of crop losses and impose risks on livestock production.
- Irrigation demand is projected to increase, in particular in southern Europe where there is already considerable competition between different water users.
- Climate change is projected to improve the suitability of northern Europe for growing crops and to reduce crop productivity in large parts of southern Europe. Projections based on different climate models agree on the direction of the change, but with some variation in its magnitude. Furthermore, effects will differ between crop types and livestock categories, depending on short- and long-term adaptation efforts.

5.3.1 Overview

Relevance

The cultivation of crops, their productivity and their quality are directly dependent on different climatic factors. Livestock are another very important part of European agricultural systems, and livestock are affected by climate change directly through changes in temperature and humidity affecting animal performance and indirectly through effects on feed production and availability, as well as through livestock disease prevalence (Olesen and Bindi, 2002; Gauly et al., 2013). Climate change is already having an impact on agriculture (Peltonen-Sainio et al., 2010; Olesen et al., 2011) and it has been found to be one of the factors contributing to stagnation in wheat yields in parts of Europe, despite continued progress in crop breeding (Brisson et al., 2010). Climate change is expected to continue to affect agriculture in the future (Olesen et al., 2011), and the effects will vary greatly in space across Europe (Trnka, Olesen, et al., 2011), but may also change over time (Trnka, Eitzinger, et al., 2011). It is generally accepted that the productivity of crops will increase in northern Europe owing to a lengthened growing season and an extension of the frost-free period. In southern Europe, climate change is likely to negatively affect the productivity of crops and their suitability in certain regions, primarily as a result of extreme heat events and an overall expected reduction in precipitation and water availability (Iglesias et al., 2010). Year-to-year variability in yields is generally expected to increase throughout Europe, owing to extreme climatic events and other factors, including pests and diseases (Ferrise et al., 2011; Kristensen et al., 2011; Trnka et al., 2014).

There is large variation across the European continent in climatic conditions, soils, land use, infrastructure, and political and economic conditions, which greatly influences the responsiveness to climatic change (Olesen et al., 2011; Trnka, Olesen, et al., 2011). Intensive farming systems in western and central Europe generally have a low sensitivity to climate change, because a given change in temperature or rainfall has a modest impact and because farmers have resources to adapt to these changes by changing their management approach (Reidsma et al., 2010). However, there may be considerable differences in adaptive capacity between cropping systems and farms depending on their specialisation and other farm characteristics (Reidsma and Ewert, 2008).

Policy context

With the expanding global population and increasing wealth, there is growing concern for food security, both globally and in a European context (Vermeulen et al., 2012). This concern is enhanced by the many conflicting demands on scarce land and water resources, which are also needed for many other human uses, including biofuels, biodiversity and recreational activities (Soussana et al., 2012). Climate change is increasingly seen as a threat to global food security, because projections of climate change impacts show that rising temperatures have negative effects on crop yield and water availability (Challinor et al., 2014). Agriculture in the EU is, to a great extent, affected by the EU CAP (EU Regulations 1305–1308/2013), which is being shaped by concerns for food security and influenced by the need to reduce the environmental and greenhouse gas burdens from agricultural production systems. However, these influencing factors on farming systems have different time dimensions, where changes in the agricultural policy mostly operate on a short time scale and the need for adaptation in many cases has a longer time horizon. Within the CAP, the need to consider the use of various instruments is considered under the rural development pillar for supporting adaptation, in particular where climate change results in the need for changes in farming systems in land use. The adaptations are highly regionally specific depending on the local context in terms of climate, soils and farming systems, as illustrated in Box 5.1.

Selection of indicators

The following indicators were chosen to evaluate selected impacts of climate change on agriculture, with the following sections dealing with each of these in turn:

- *growing season for agricultural crops* — this indicator determines the suitability for growing agricultural crops, as determined by temperature;
- *agrophenology* — this indicator traces changes in the timing of the annual cycle of agricultural crops;
- *water-limited crop yield* — this indicator considers potential changes in crop productivity caused by changes in temperature, rainfall and atmospheric CO_2 concentration;
- *crop water demand* — this indicator estimates the water needs for maintaining maximum crop yields, thereby assessing the adaptation needs of agricultural water supply.

The concluding section describes impacts on livestock, but not as an indicator, as the indirect effects on livestock through feed production are partly covered by the indicators covering water-limited crop productivity and water requirements for irrigation. In addition, the impacts of climate change on livestock production are exemplified in three case study regions in Europe in Box 5.1.

The indicators were chosen based on various criteria, including the availability of relevant data across Europe and the ability to identify the main drivers of agricultural change to inform the design of adaptation policy. The indicators presented here focus on the biophysical effects of changes in temperature and precipitation. Agricultural production and land use are also, to a great extent, driven by changes in technology and socio-economic conditions, which are not considered here, although the biophysical effects will also be relevant to changing technology and socio-economic conditions. As well as changes in climatic conditions, crop yield and quality are also affected directly by changes in atmospheric CO_2 concentration through impacts on photosynthesis and water use (Box 5.2). Essentially, effects on crop yield in the future will be shaped by the interaction between changes in climate, atmospheric CO_2 and technology.

Data quality and data needs

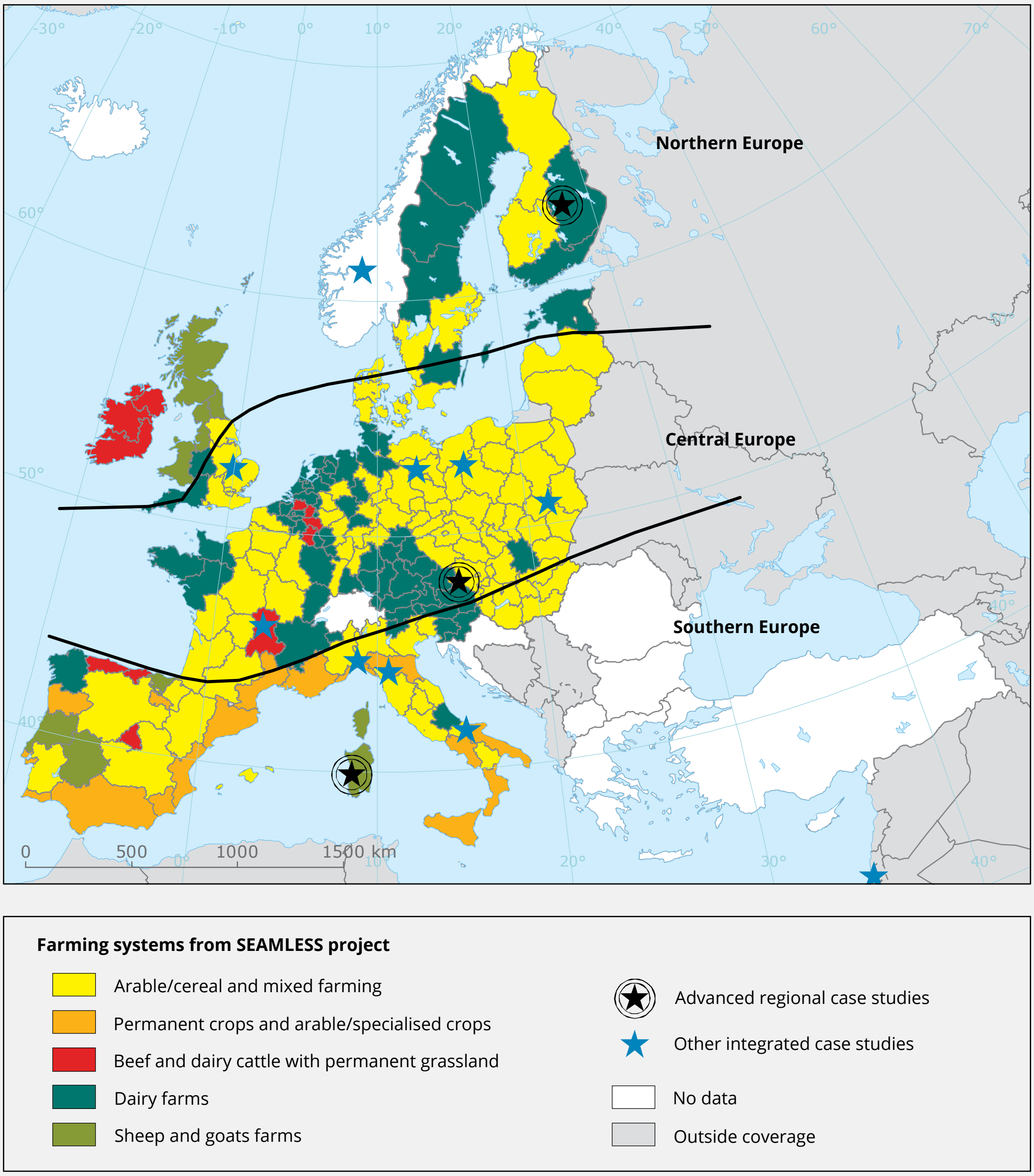
The effects of climate change on the growing season and crop phenology can be monitored directly, partly through remote sensing of the growing season and partly through monitoring of specific phenological events such as flowering. There is no common monitoring network for crop phenology in Europe, and therefore data on crop phenology have to be based on various national recordings, often from agronomic experiments (Olesen et al., 2012). Crop yield and crop requirements for irrigation are affected not only by climate change, but also by management and a range of socio-economic factors (see Chapter 6). The effects of climate change on these factors therefore have to be estimated indirectly using agrometeorological indicators and through statistical analyses of the interaction between climatic variables and factors such as crop yield (Caubel et al., 2015).

The projections of climate change impacts and adaptation in agriculture rely heavily on modelling, and it needs to be recognised that there is often a chain of uncertainty involved in the projections, which range from emissions scenarios, through climate modelling and downscaling, to assessments of impacts using an impact model (Ewert et al., 2015). The relevant modelling approaches in Europe have been discussed in a recent report of the Food and Agriculture Organization (FAO) (Rötter and Höhn, 2015). The extent of all these uncertainties is rarely quantified, even though some studies have assessed uncertainties related to individual components. The crop modelling community has only recently started addressing uncertainties related to modelling impacts of climate change on crop yield and the effect of possible adaptation options (Rötter et al., 2011; Asseng et al., 2013), and so far only a few studies have involved livestock systems. Recently, the effects of extreme climate events have also been included in impact assessments (Trnka et al., 2014; Lesk et al., 2016), but other effects such as those related to biotic hazards (e.g. pests and diseases) still need to be explored (Garrett et al., 2013; Launay et al., 2014).

Box 5.1 Regional case studies from the MACSUR project

The European MACSUR project ([96]) has explored the impacts of and adaptations to climate change in three European case study regions in Europe, representing different climatic conditions and farming systems (Map 5.9). The case studies are from the North Savo region in Finland, the Mostviertel region in Austria and the Oristanese region in Sardinia (Italy). These regions represent a north to south climate gradient in Europe, but they do not cover the climatic conditions along the Atlantic.

Map 5.9 Farming systems in Europe and location of MACSUR regional pilot studies



Source: MACSUR project, based on the SEAMLESS project ([97]).

([96]) Modelling European Agriculture with Climate Change for Food Security (http://macsur.eu).
([97]) System for Environmental and Agricultural Modelling: Linking European Science and Society (http://www.seamless-ip.org).

Box 5.1 Regional case studies from the MACSUR project (cont.)

North Savo region (Finland)

This region covers an area of 2 million ha, of which only 7.3 % is in agricultural use, most of which is for dairy production, with 56 % of the agricultural area being grass. The milk production per cow is relatively high, but the livestock density is low. The cereals grown are primarily spring barley and oats, covering 30 % of the agricultural area.

Climate change causes higher temperatures and rates of precipitation, especially in the winter. Both droughts and wet conditions in the summer have been observed as becoming more frequent. The combined effect of more frequent wet conditions, heavier axle loads with increasing farm size, and higher costs of not harvesting grass silage at the right times has led to gradually increasing soil compaction problems, resulting in declining soil fertility. Higher temperatures, which are more marked in winter than in summer, lead to increasing winter damage to grasslands. Melting snow and loss of snow cover, followed by low temperatures of – 20 to – 30 °C, cause ice encasement and frost damage. Plant pests and diseases are also becoming more abundant.

The projected increase in temperatures and in the frequency of many adverse weather conditions require long-term investments in drainage, soil structure and other equipment. Some farmers have made such investments already, but many farmers find them risky because of the increased volatility of input and output prices. Despite the increased frequency of adverse weather conditions, the gradually increasing crop yield potential of grass may result in higher actual yields on farms. This would lead to efficiency gains and cost savings. New cultivars of grass and cereals provide opportunities to increase or retain crop yield levels. However, the projected increase in potential production in the region is not likely to be realised, as production costs in the region are still relatively high, despite rapid structural changes.

Mostviertel region (Austria)

The Austrian Mostviertel region is a hilly to mountainous agriculturally diverse and fertile region situated in the Alpine foothills between the Danube and the Alps. Large pear and apple trees scattered over the landscape give the region its name ('Most' being German for 'cider'). Cropland is prevalent in the north — the main crops being maize and winter wheat — while in the south permanent grassland dominates the agricultural landscape. Along this gradient are arable and mixed livestock farms specialised in bull and pig fattening in the north and in dairy and suckler cow farms in the south.

The temperature change has been more pronounced in the Alps than in the northern hemisphere on average, and Alpine temperature is expected to increase by + 1.5 °C by the middle of the 21st century. Precipitation has shown no clear trend, and future changes in precipitation, although uncertain, are of particular importance because of the susceptibility of agricultural land in this region to soil erosion by water (Mitter et al., 2014). An integrated modelling framework was applied on a climate scenario of + 1.5 °C warming and at least a 20 % increase in annual precipitation. Major adaptation options include changes in crop species and crop management (e.g. fertilisation intensity, irrigation, mowing frequency on meadows), land-use change (e.g. conversion of permanent grassland to either cropland or forests) and changes in livestock management (e.g. livestock numbers and feeding diets).

Until 2040, increasing temperatures accompanied by sufficient precipitation for rainfed agriculture are likely to increase crop productivity on average, despite increasing soil erosion risks from extreme precipitation events and unknown changes in pests and diseases. The results of the integrated modelling framework show increasing average farm gross margins between + 1 % and + 5 %, subject to autonomous adaptation by farmers. Farmers in the region acknowledge the demand for adaptation to climate change but also express their need for guidance on new crops, varieties and cropping techniques to manage the emerging risks. Fertilisation levels are likely to increase, but irrigation will play a role only for high-value crops. Grasslands will particularly benefit from climatic changes and are less susceptible to soil erosion by water. More favourable conditions may even enhance the conversion of permanent grasslands to cropland in the long run if this is not constrained by adverse soil conditions and steepness. However, results indicate a considerable spatial heterogeneity among farms, even within a small landscape, mainly driven by different soil conditions.

Oristanese region (Sardinia, Italy)

This region covers 60 000 ha and is characterised by a variety of Mediterranean rainfed and irrigated farming systems. More than half of the agricultural area is equipped for irrigation, but only 30 % is actually irrigated. Of these, some 3 000 ha are cultivated with paddy rice and another 6 000 ha with silage maize–Italian ryegrass double crop or lucerne for dairy cattle feeding. Horticultural crops (mainly artichokes and melon, as well as citrus fruit and vineyards) are also present. Some 50 % of the rainfed area is managed as temporary grasslands in rotation with hay crops (30 %), which represent some 70 % of the diet of dairy sheep (the main livestock business of Sardinia) and beef cattle grazing systems. Durum wheat, barley, oats and triticale are also grown in this area.

Box 5.1 Regional case studies from the MACSUR project (cont.)

The effects of climate change in the near future (2020–2030) are likely to be a rise in daily maximum temperatures in summer of up to + 1.7 °C, a 33 % reduction of April–June rainfall and an increased frequency of storms in autumn. The expected reduced spring rainfall will have a significant impact on rainfed pasture and the production of hay and hence on dairy sheep farming (up to a 13 % reduction in net income). The intensive dairy cattle system will be affected mostly by more frequent summer heat waves, resulting in up to a 6 % net income reduction because of reduced milk yield and quality, reduced fertility and increased dairy mortality in the tourist season, when fresh milk demand is highest. A reduction in the income from livestock farming has been projected even if currently available adaptation options are implemented. Positive impacts of climate change are expected for rice (up to a 9 % increase in income) and winter cereals (a 2 % increase in income), but estimates may be biased by the high sensitivity of the applied crop models to increased CO_2 concentration. The overall net income reduction in the case study area is expected to be 2.6 %.

The adoption of maize hybrid or rice varieties with later phenology may compensate for the yield reduction due to reduced crop cycles under higher temperatures. However, given the significant impact of climate change on livestock farming that is expected, adaptation options should be developed far beyond adjusting current farm management. This could involve consideration of new farming systems or new interactions between farming systems, e.g. to better ensure feed supply for livestock under climate change. However, such changes would need to be incentivised through changes in agricultural and rural policies.

Box 5.2 Effects of enhanced atmospheric CO_2

Plants are affected not only by changes in temperature and precipitation, but also by changes in atmospheric CO_2 concentration, which affects crop yield and quality both directly and indirectly. Plant photosynthesis is stimulated by enhanced CO_2 in plants that have the C3 photosynthesis pathway, namely most of the crops grown in Europe, except tropical grasses such as maize and *Miscanthus*, which have the C4 pathway.

The extent to which photosynthesis is stimulated and yield is increased by elevated CO_2 concentrations depends on the crop species and growing conditions (Ainsworth and Long, 2005; Wang et al., 2011). Recent experimental results also indicate considerable differences between crop cultivars, showing that there may be scope for exploiting genetic variation to enhance yield under higher atmospheric CO_2 (Ingvordsen et al., 2015). The stimulation of growth under high CO_2 has been shown to be particularly large in legumes, as the greater availability of carbohydrates in plants stimulates biological nitrogen fixation, although this may interact with changes in climatic conditions (Vadez et al., 2011).

Higher CO_2 concentrations will reduce the stomatal conductance of all plant species, leading to reduced transpiration and higher water use efficiency (Kruijt et al., 2008). This is of particular importance under dry conditions, where the lower transpiration rates will delay the onset of agricultural drought and thus reduce the impact of higher transpiration rates under warmer conditions.

The overall effect of higher atmospheric CO_2 in C3 cereal crops such as wheat is to balance the yield reduction from higher temperatures. As a result, there may be little net yield change for wheat under modest warming levels when the beneficial effects of elevated CO_2 are also considered (Makowski et al., 2015). The higher assimilation at elevated CO_2 leads to a shift in the plant carbon-to-nitrogen ratio, which affects the quality of plant biomass and crop yield. The effects differ between plant species and some of these effects may reduce the susceptibility of plants to insect pests, reducing the need for pest control, but also reducing the quality of feed and food, e.g. through lower protein content in grain (Högy et al., 2012).

5.3.2 *Growing season for agricultural crops*

Key messages

- The thermal growing season for agricultural crops in Europe has lengthened by more than 10 days since 1992. The delay in the end of the growing season has been more pronounced than the advance of the start of the season. The length of the growing season has increased more in northern and eastern Europe than in western and southern Europe.
- The growing season is projected to increase further throughout most of Europe owing to the earlier onset of growth in spring and later senescence in autumn.
- The projected lengthening of the thermal growing season would allow a northwards expansion of warm-season crops to areas that were not previously suitable. In parts of southern Europe (e.g. Spain), warmer conditions will allow crop cultivation to be shifted to the winter.

Relevance

The thermal growing season is a basic agroecological indicator that shows where and when crops can potentially be grown, assuming sufficient water, radiation and suitable soils. The duration of the growing season is, for a large part of Europe, defined by the duration of the period during which the temperature is above a certain threshold. The duration of the frost-free season is considered the most favourable period for growth in many plant species (e.g. for flowering). However, active growth of plants requires higher temperatures and, for most of the temperate crops grown in Europe, a threshold temperature of 5 °C can be used (Trnka, Olesen, et al., 2011).

Past trends

Increasing air temperatures are significantly affecting the duration of the growing season over large areas of Europe. Many studies report a lengthening of the period between the occurrence of the last spring frost and the first autumn frost. This has occurred in recent decades in several areas in Europe and more generally in the northern hemisphere (Trnka, Brázdil, et al., 2011). Studies of changes in the growing season based on remote sensing show a diverse spatial pattern in Europe (Schwartz et al., 2006). Across all of Europe, the delay in the end of the season of 8.2 days in the period 1992–2008 was more significant than the advanced start of the season by 3.2 days (Jeong et al., 2011).

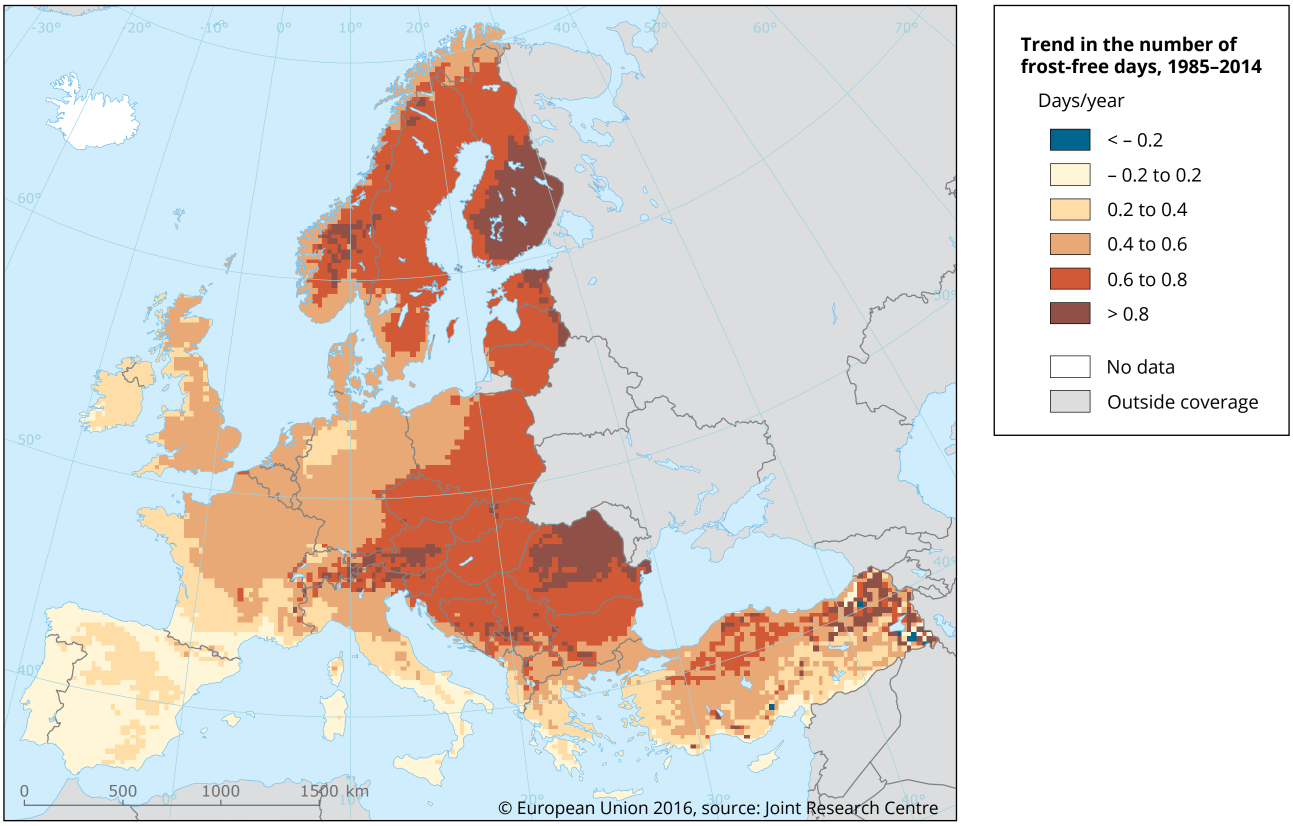
An analysis of the frost-free period in Europe between 1985 and 2014 shows a general and clear increasing trend (Map 5.10). The trend is not uniformly spread over Europe. The highest rates of change (an extension of the frost-free period by more than 0.8 days per year) were recorded in eastern and northern Europe; little or no change was observed along the Mediterranean coast, where frost is a rare phenomenon.

Projections

A warming of the climate is expected to result in an earlier start of the growing season in spring and a longer duration in autumn. The date of the last frost in spring is projected to advance by about 5–10 days by 2030 and by 10–15 days by 2050 throughout most of Europe (Trnka, Olesen, et al., 2011). A longer growing season will, in many cases, allow for the introduction of new crop species that were previously unfavourable owing to low temperatures or short growing seasons, but it may also increase the spread of weeds, insect pests and diseases (Roos et al., 2010). The suitability for growing certain crops will also depend on the total amount of heat received during the growing season, expressed as a temperature sum. Projections show that the greatest absolute increases in temperature sum will be in southern Europe, whereas relative changes are much larger in northern than in southern Europe (Trnka, Olesen, et al., 2011).

The extension of the growing season is expected to be particularly beneficial in northern Europe, where new crops could be cultivated and where water availability generally does not restrict growth (Elsgaard et al., 2012). In parts of the Mediterranean area, the cultivation of some crops may shift from the summer season to the winter season, which could offset some of the negative impacts of heat waves and droughts during summer. Other areas of Europe, such as western France and parts of south-eastern Europe, will experience yield reductions from hot, dry summers without the possibility of shifting the crop production into the winter seasons (Mínguez et al., 2007; Olesen et al., 2011).

Map 5.10 Trend in the number of frost-free days, 1985–2014



Source: MARS/STAT database ([98]).

([98]) Monitoring Agriculture with Remote Sensing — Stat Action database.

5.3.3 *Agrophenology*

Key messages

- The flowering of several perennial and annual crops has advanced by about two days per decade during the last 50 years.
- Changes in crop phenology are affecting crop production and the relative performance of different crop species and varieties. The shortening of the grain-filling phase of cereals and oilseed crops can be particularly detrimental to yield.
- Shortening of the growth phases of many crops is expected to continue, but this may be altered by selecting other crop cultivars and changing planting dates, which in some cases can lead to longer growth periods.

Relevance

Changes in crop phenology provide important evidence of responses to recent regional climate change (Menzel et al., 2003). Although phenological changes are often influenced by management practices, in particular the sowing date and choice of cultivar, recent warming in Europe has clearly caused the advancement of a significant part of the agricultural calendar. Specific stages of growth (e.g. flowering, grain filling) are particularly sensitive to weather conditions are critical to the final yield. The timing of the crop cycle (agrophenology) determines the productive success of the crop. In general, a longer crop cycle is strongly correlated with higher yields, as a longer cycle permits better use of the available thermal energy, solar radiation and water resources.

Past trends

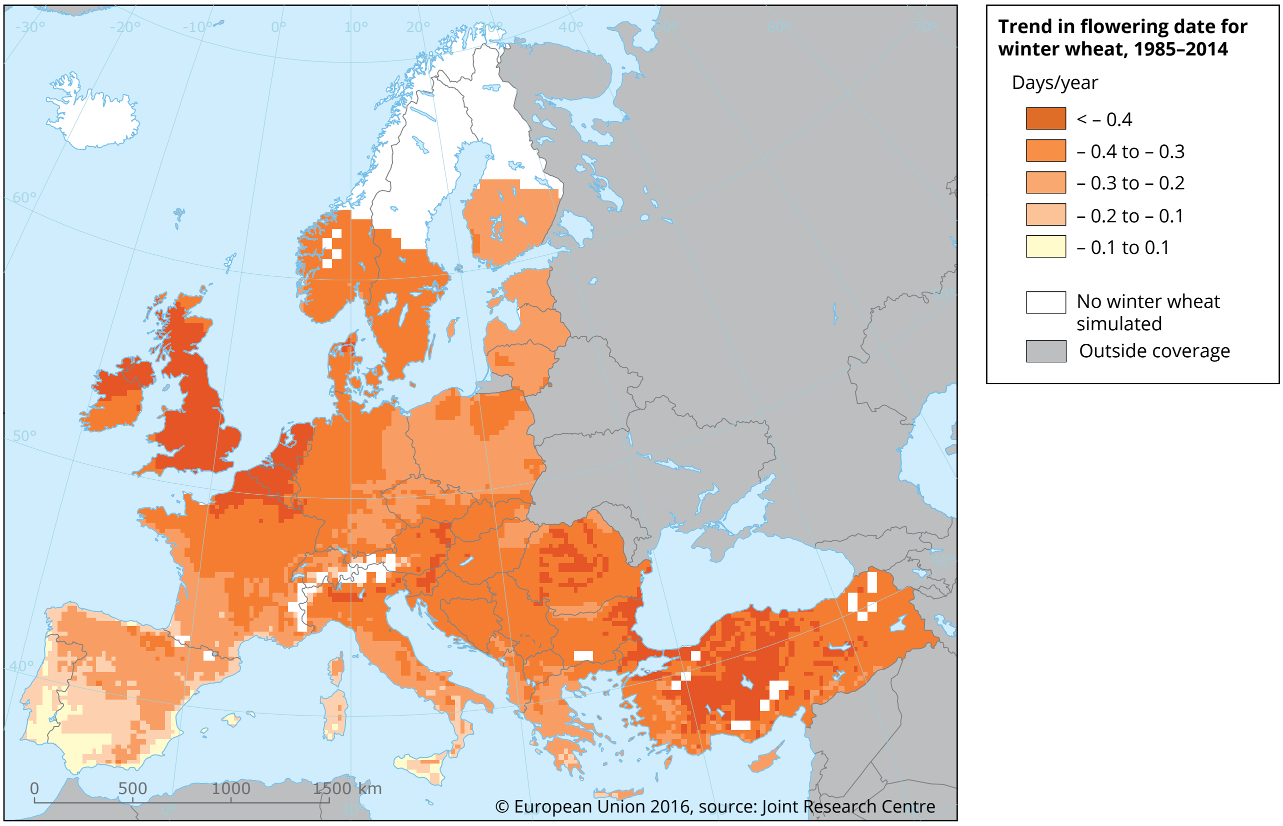
Changes in the phenological phases of several perennial crops in Europe, such as advances in the start of the growing season of fruit trees (2.3 days/decade), cherry tree blossom (2.0 days/decade) and apple tree blossom (2.2 days/decade), in line with increases of up to 1.4 °C in mean annual air temperature, were observed in Germany during 1961–2000 (Chmielewski et al., 2004). Sowing or planting dates of several agricultural crops have advanced; for example, for oats in Germany (1959–2009), sowing has advanced by 0.2 days/decade, flowering by 1.9 days/decade, maturity by 3.3 days/decade and harvest by 2.1 days/decade (Siebert and Ewert, 2012). This indicates that factors other than temperature may be affecting sowing and harvesting dates, e.g. soil workability and grain moisture for harvesting.

An analysis of the modelled flowering date for winter wheat in Europe between 1985 and 2014 shows a general and clear increasing trend, which is most pronounced in north-western Europe (Map 5.11). In large parts of Europe, the modelled flowering date has advanced by two to four days/decade. This modelled advance in flowering date probably exceeds what is observed in reality, as a longer growth duration will alter plants' responses to day length and farmers' choices of cultivars, reducing the overall response.

Projections

With the projected warming of the climate in Europe, further reductions in the number of days required for flowering and to reach maturity in cereals may be expected throughout Europe (Olesen et al., 2012). Since many plants (including cereals) in Europe require long days to flower, the effect of warming on the date of flowering is smaller than would otherwise be expected. The flowering date for winter wheat was projected to show the greatest advance in western parts of Europe, with an advance of up to two weeks by 2050. The projected advance in the date of reaching maturity is greater than the advance in flowering date, leading to a shortening of the grain-filling period, which will negatively affect yields. One of the main adaptation options to cope with the shortening of crop growth phases is choosing crop cultivars that have higher thermal requirements, as this will reduce the negative yield effects of a shorter growth duration. In practice, this needs to be balanced against the need to avoid periods of high temperature stresses and drought. Breeding for crop cultivars with optimal timing of crop phenological phases is therefore a critical adaptation option (Semenov et al., 2014).

Map 5.11 Trend in flowering date for winter wheat, 1985–2014



Source: MARS/STAT database.

5.3.4 Water-limited crop yield

Key messages

- Yields of several rainfed crops are levelling off (e.g. wheat in some European countries) or decreasing (e.g. grapes in Spain), whereas yields of other crops (e.g. maize in northern Europe) are increasing. These changes are attributed partly to observed climate change, in particular warming.
- Extreme climatic events, including droughts and heat waves, have negatively affected crop productivity in Europe during the first decade of the 21st century.
- Future climate change could lead to both decreases and increases in average yield, depending on the crop type and the climatic and management conditions in the region. There is a general pattern of projected increases in productivity in northern Europe and reductions in southern Europe, but with differences between crop types.
- Projected increases in extreme climatic events are expected to increase crop yield variability and to lead to yield reductions in the future throughout Europe.

Relevance

The production of biomass in crops is the result of the capture and conversion of solar energy through the process of photosynthesis. However, this process may be restricted by low (or high) temperatures or by water limitations (Trnka, Olesen, et al., 2011). Crop yields are affected by the combined effects of changes in temperature, rainfall and atmospheric CO_2 concentration (Box 5.2). In practice, the response depends on soil type, which can differ greatly in capacity for storing soil moisture, and on the possibilities for supplementary irrigation. Crop yield also depends on the timing of the crop growth and yield formation. Yields in cereal and oilseed crops respond particularly to the duration of the grain-filling period (Kristensen et al., 2011). The impacts of unfavourable meteorological conditions and extreme events vary considerably, depending on the timing of occurrence and the development stage of the crops (Moriondo et al., 2011; Trnka et al., 2014; Eyshi Rezaei et al., 2015). Changes in the occurrence of extreme events such as heat waves, droughts, heavy precipitation and floods will greatly affect crop yield leading to increased variability and economic consequences (Ciscar et al., 2011).

Past trends

A global analysis of yields of cereal crops (wheat, maize and barley) has shown that increasing mean temperatures in recent decades have had a negative effect on yield (Lobell and Field, 2007). Similar effects have been observed for various countries in Europe (Peltonen-Sainio et al., 2011). Increasing temperatures have been identified as one of the main causes of the lack of yield increase in winter wheat in France, despite improvements in crop breeding (Brisson et al., 2010). Grain yields in southern Europe seem to have been levelling off. There is also a tendency for an increasing variability of grain yields in France and Italy, linked to the occurrence of heat waves and droughts (Olesen et al., 2011). Similar effects of heat haves and droughts have been observed globally, whereas floods and intense rainfall have not been seen to affect overall crop production (Lesk et al., 2016). In Italy and southern-central Europe, the potential crop yields of potato, wheat, maize and barley significantly decreased over the time period 1976–2005 owing to temperature and radiation change effects (Supit et al., 2010). In north-east Spain, grape yield has been declining because of increasing water deficits since the 1960s (Camps and Ramos, 2012). Droughts and heat waves affected the crop production in large areas of southern and central Europe in 2003 and 2007 (Peltonen-Sainio et al., 2010). An increase in climate-induced variability in maize yield has been observed over recent decades in France (Hawkins et al., 2013).

Climate change has also shown positive effects on yields. Potato and sugar beet have responded positively to increasing temperatures through an increase in yields, most likely due to the longer growing seasons (Peltonen-Sainio et al., 2010, 2011). In Scotland, increasing temperatures are estimated to have increased the potential potato yield by up to 39 % over the period 1960–2006 (Gregory and Marshall, 2012). In parts of the United Kingdom and parts of northern-central Europe, the yield potential of wheat, sugar beet and maize has increased since 1976 (Supit et al., 2010). Grain yields in maize have been steadily increasing in northern Europe, most likely linked to the warmer climate (Olesen et al., 2011).

Projections

The impact of future changes in climate on crop yield depends on the characteristics of the climatic change within a region, as well as on a combination of other environmental, economic, technological and management factors (Reidsma et al., 2010). A broad analysis of climate change scenarios for agricultural productivity in Europe has provided a clear picture of deterioration of agroclimatic conditions through increased drought stress and a shortening of the active growing season across large parts of southern and central Europe (Trnka, Olesen, et al., 2011). Other studies suggest an increasing number of unfavourable years for agricultural production in many European climatic zones, limiting winter crop expansion and increasing the risk of cereal yield loss (Peltonen-Sainio et al., 2011; Rötter et al., 2011; Trnka et al., 2014).

Dynamic crop models may be used to evaluate the effect of climate change on crop production, provided that the model is tested for the accuracy of its response to various climate change factors (Ewert et al., 2015). Map 5.12 shows projected changes in water-limited winter wheat yields in Europe for the 2030s (compared with the 2000s) for climate projections from two different climate models (HadGEM2-ES ([99]) and MIROC-ESM-CHEM ([100])) using the WOFOST ([101]) crop model. The top row of the map shows the results when the CO_2 concentration is assumed to be that of the 2000s, whereas the bottom row shows the results when the effect of CO_2 fertilisation (see Box 5.2) on crop growth was simulated. When no CO_2 fertilisation effect is taken into account, simulations using both climate models show a decrease in wheat yields over most of Europe, with the exception of some northern areas. When the CO_2 fertilisation effect is taken into account, model simulations generally show a yield increase in most areas, with the notable exception of central Europe for one climate model (HadGEM2). The simulated moderate yield reduction over central Europe for this model indicates that increased CO_2 does not compensate for unfavourable climatic conditions, such as prolonged and more intense droughts. These simulations did not include adaptations to climate change, such as changes in crop species and crop management, owing to the inherent complexity of agricultural systems. Therefore, the projected yields in 2030 may be slightly underestimated. A study on the potential effectiveness by 2040 of adaptation by farmers in southern and central Europe suggests that the adaptation potential to future warming is large for maize but limited for wheat and barley (Moore and Lobell, 2014).

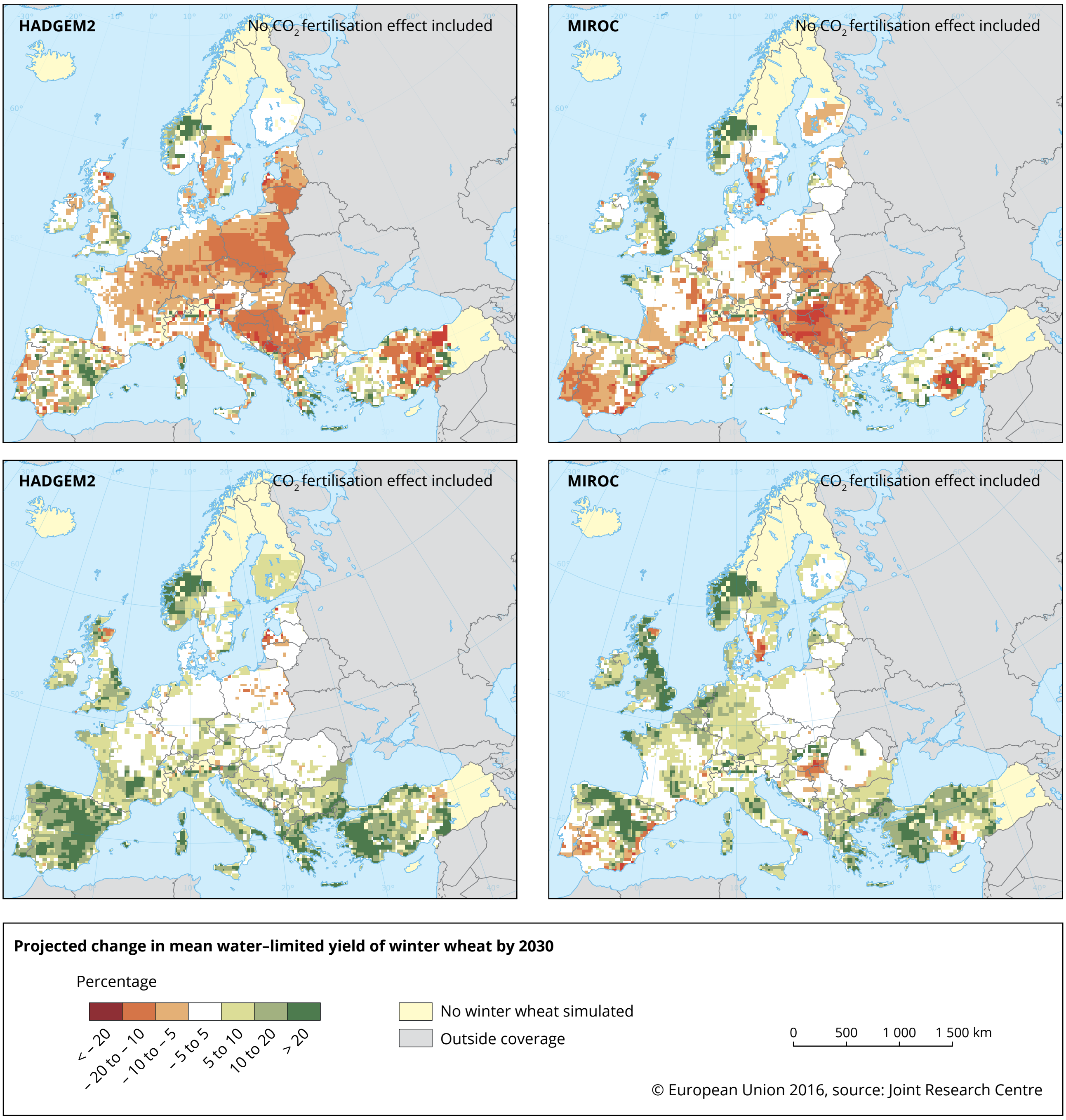
Future crop yield developments are subject to considerable uncertainty, in particular with regard to climate projections and the magnitude of CO_2 fertilisation effects in practice. For example, Map 5.12 does not consider all of the main sources of uncertainty, as only two climate models and one crop model have been used to produce the simulations. A wider variation would have been found if more climate model projections and more crop models had been used. A large proportion of the uncertainty in climate change impact projections for crop yields are the result of variations among different crop models rather than the variations among the downscaled climate projections (Asseng et al., 2013). Uncertainties in simulated impacts increase with higher CO_2 concentrations and associated warming.

Map 5.13 provides an aggregated picture of the expected changes in crop yields across Europe by considering three crops, an ensemble of 12 GCMs and the current irrigated area. These estimates include the effects of changes in temperature, precipitation and CO_2 concentration on crop yield. The regional pattern of projected impacts is clear, generally showing improved conditions in northern Europe and worse conditions in southern Europe.

Despite the above-mentioned uncertainties, there is a clear indication of deteriorating agroclimatic conditions in terms of increased drought stress and a shortening of the active growing season in central and southern Europe (Trnka, Olesen, et al., 2011). There is a risk of an increasing number of extremely unfavourable years, which might lead to higher interannual variability in crop yield and constitute a challenge for proper crop management. Some of the climate-related risk factors, such as high temperature stress, flooding and adverse sowing and harvesting conditions, are included only to a limited extent in current crop models, such as those used for the projections in Map 5.12. Map 5.14 shows that the frequency of adverse agroclimatic conditions for wheat is projected to increase substantially across Europe under climate change, with the largest risks generally experienced in southern parts of Europe. These increases in extreme events may severely restrict the efficiency of adaptations to climate change, including the shifting of wheat production to other regions as the risk of adverse events beyond the key wheat-growing areas increases even more (Trnka et al., 2014, 2015).

([99]) HadGEM-ES: Earth System version of HadGEM2.
([100]) MIROC-ESM-CHEM: atmospheric chemistry coupled version of MIROC-ESM ('Model for Interdisciplinary Research on Climate — Earth System Model').
([101]) WOFOST: 'WOrld FOod STudies'.

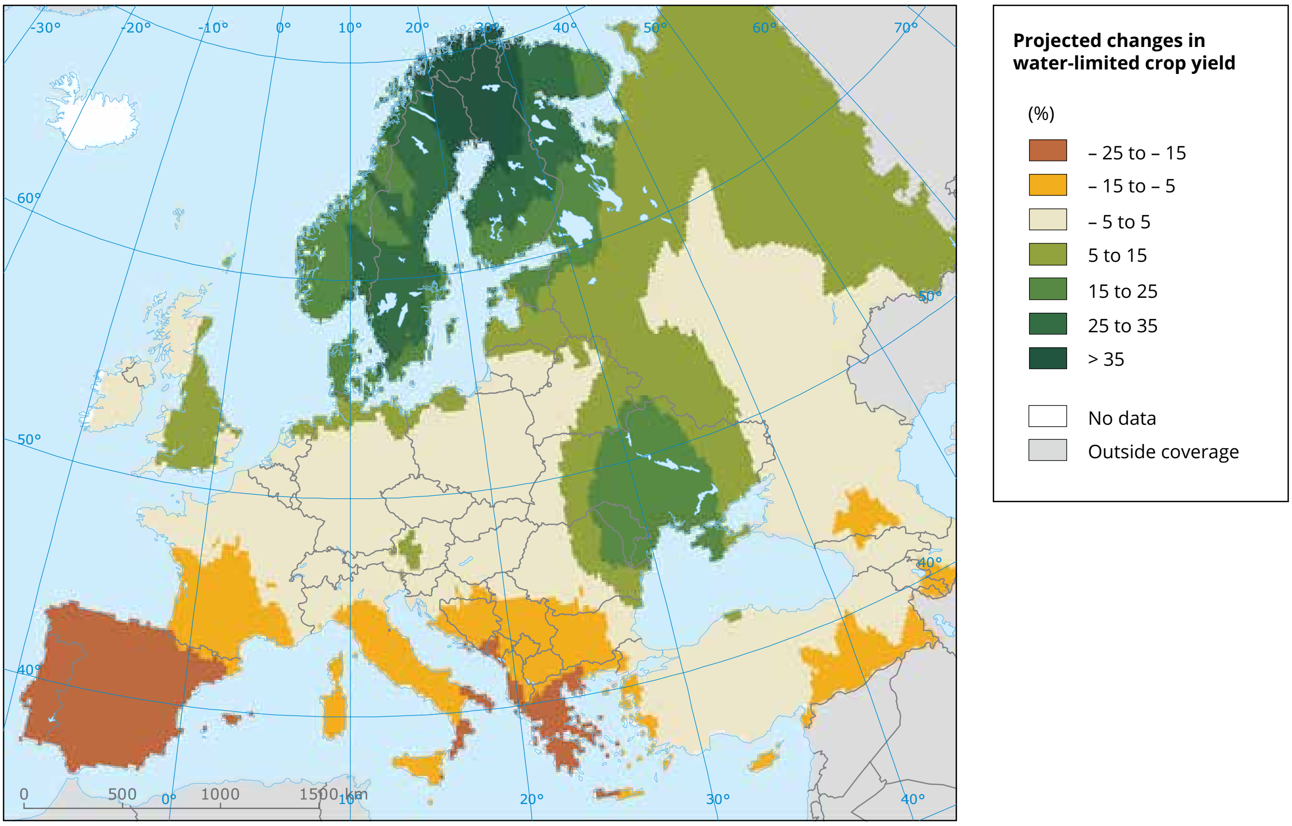
Map 5.12 Projected changes in water-limited yield of winter wheat, 2000–2030



Note: The map shows projections of the change in water-limited yield of winter wheat in the 2030s compared with the reference period centred on 2000 for two different global climate models. The upper maps represent yields without CO_2 fertilisation and the lower maps represent yields with the CO_2 fertilisation effect. The simulations were performed using the WOFOST model for the RCM8.5 emissions scenario.

Source: JRC.

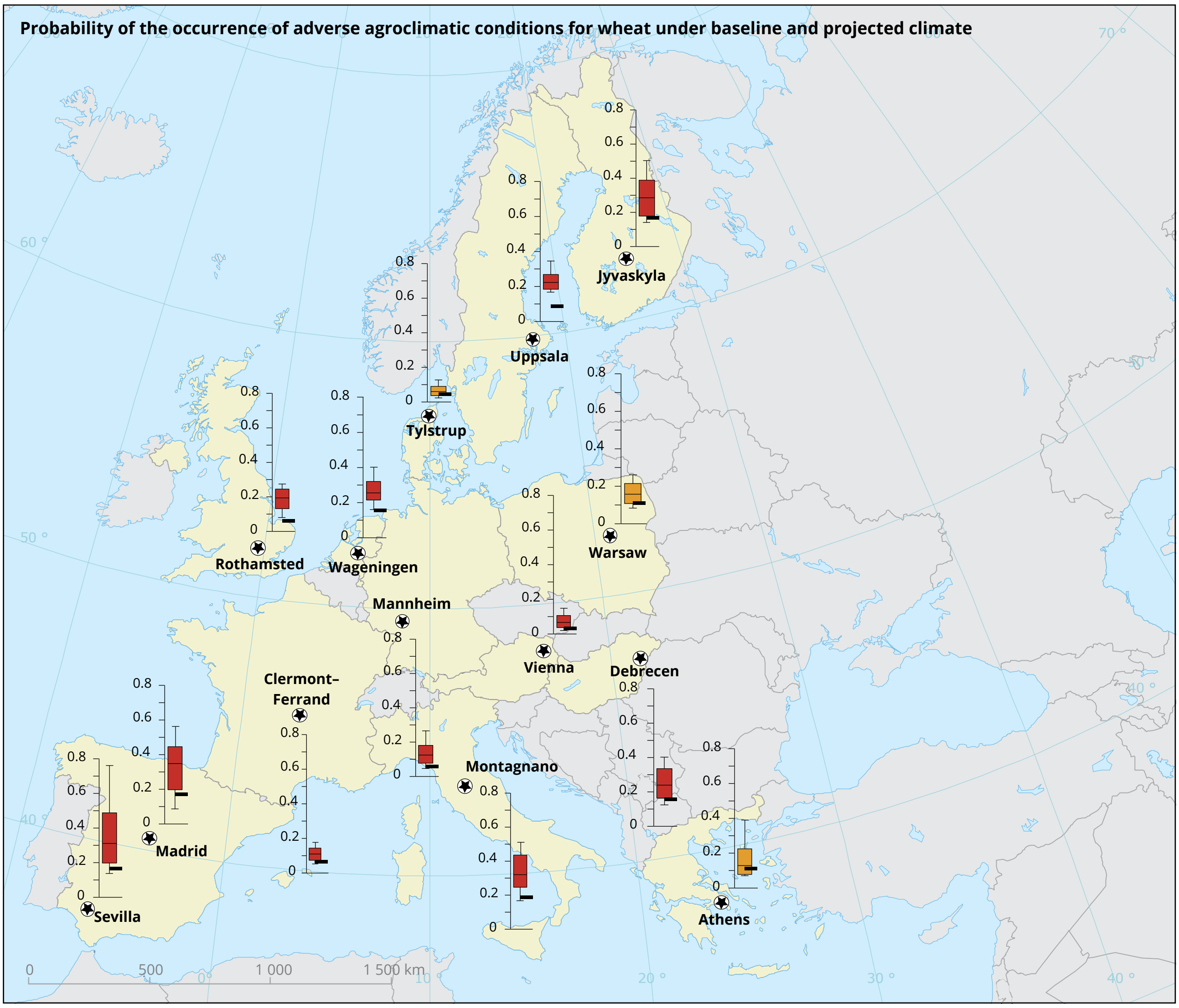
Map 5.13 Projected changes in water-limited crop yield



Note: The map shows the mean relative changes in water-limited crop yield simulated by the ClimateCrop model for the 2050s compared with the period 1961–1990 for 12 different climate model projections under the A1B emissions scenario. The simulation assumes that the irrigated area remains constant, and the results combine the response of the key crops wheat, maize and soybean, weighted by their current distribution.

Source: Adapted from Iglesias et al., 2012 and Ciscar et al., 2011.

Map 5.14 Probability of the occurrence of adverse agroclimatic conditions for wheat under baseline and projected climate



Note: Black rectangles indicate the 1981–2010 baseline climate and box plots indicate the 2060 (RCP8.5) climate scenarios. The calculations consider a medium-ripening wheat cultivar. The red boxes mark the sites where the results for at least 14 out of the 16 CMIP5 models showed an increased probability of adverse events compared with the baseline. The orange boxes mark the sites where more than half of the CMIP5 models showed an increased probability of adverse events.

Source: Adapted from Trnka et al., 2014.

5.3.5 Crop water demand

Key messages

- Climate change led to an increase in the crop water demand and thus the crop water deficit from 1995 to 2015 in large parts of southern and eastern Europe; a decrease has been estimated for parts of north-western Europe.
- The projected increases in temperature will lead to increased evapotranspiration rates, thereby increasing crop water demand across Europe. This increase may partly be alleviated through reduced transpiration at higher atmospheric CO_2 levels.
- The impact of increasing water requirements is expected to be most acute in southern and central Europe, where the crop water deficit and irrigation requirements are projected to increase. This may lead to an expansion of irrigation systems, even in regions currently without irrigation systems. However, this expansion may be constrained by projected reductions in water availability and increased demand from other sectors and for other uses.

Relevance

Water is essential for plant growth and there is a relationship between plant biomass production and transpiration, with water-use efficiency (biomass production per unit of water transpired) being affected by crop species and management. The increasing atmospheric CO_2 concentration will lead to higher water-use efficiency through reductions in plant transpiration and increased photosynthesis (Box 5.1). However, higher temperatures and lower relative humidity will lead to higher evaporative demands, which will reduce water-use efficiency. The resulting effect of climate change on water-use efficiency will therefore be the result of a combination of changes in climate and atmospheric CO_2 concentration, as well as changes in crop choice and management. The water demand by crops must be met through rainfall during the growing period, soil water storage or irrigation. In drought-prone areas, increasing demands for water by industrial and urban users intensify the competition for irrigation water (Iglesias et al., 2007), and managing this requires an integrated approach (Falloon and Betts, 2010).

Past trends

Irrigation in Europe is currently concentrated along the Mediterranean, where in some countries more than 80 % of the total freshwater abstraction is used for agricultural purposes (EEA, 2009). However, consistent observations of water demand and consumption for agriculture do not currently exist for Europe, partly because of unrecorded water abstractions and national differences in accounting and reporting. Modelling approaches can be used to compute net irrigation requirements. Two studies estimated the net irrigation requirements in Europe for 1995–2002 and for the year 2000 with a total of three different model systems (Wriedt et al., 2009; aus der Beek et al., 2010). The results show an irrigation requirement of up to 21–40 km^3 for Spain, which had the highest net irrigation requirement in the EU-27.

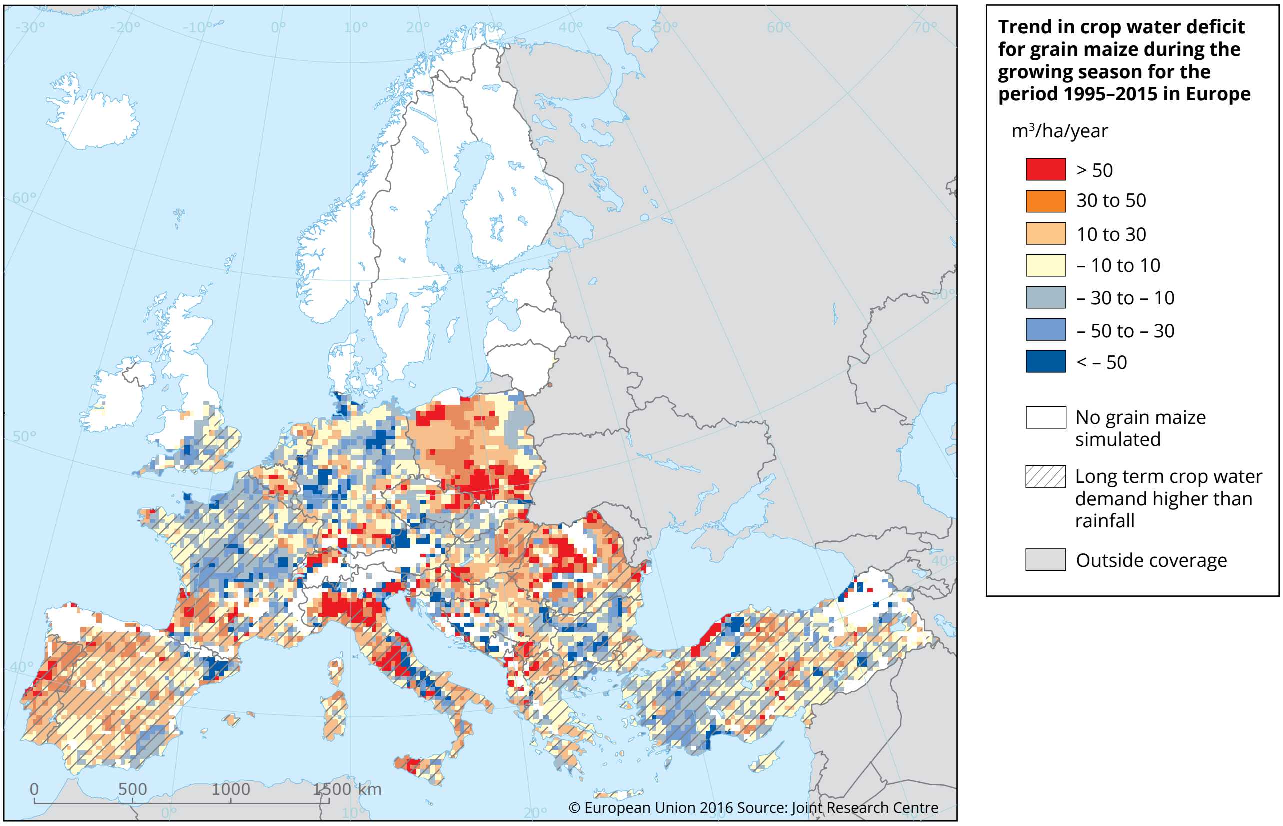
Crop water demand, defined as the water consumed during the growing season, depends on the crop type and the timing of the growing season. Water demand can be modelled using meteorological data and information on crop management, and the difference between crop water demand and rainfall constitutes the crop water deficit. Map 5.15 shows the change in the crop water deficit for grain maize, which is a crop that is often grown under irrigated conditions because it is mostly grown during the summer season. The hatched areas in Map 5.15 show the areas where crop water demand exceeds average rainfall and thus may have an irrigation demand. The trends for 1995–2015 show an increase in the crop water deficit for maize in large parts of southern and eastern Europe; a decrease has been estimated for parts of north-western Europe

Some of the effects of estimated changes in the crop water deficit may also be related to the duration of the crop growing period, which is shortened under higher temperatures, thus leading to less water being consumed.

Projections

A multi-model study using seven global hydrological models driven by five global climate models under four RCP scenarios estimated changes in irrigation water demand (IWD) across regions during the 21st century. Under the low and low-to-medium emissions scenarios (RCP2.6 and RCP4.5, respectively), the simulated changes in IWD across Europe were small. For RCP6.0, the multi-model average suggests a substantial

Map 5.15 Trend in crop water deficit for grain maize during the growing season, 1995–2015



Note: The linear trend in the crop water deficit is expressed in cubic metres per hectare per year (m³/ha/year). The map provides an estimate of the decrease (blue) or increase (red) of the crop water deficit calculated using the WOFOST model and the JRC's MARS gridded meteorological data. An increase in the deficit will, in water-limited regions, translate into a corresponding increase in irrigation demand. Areas where the seasonal crop water demand regularly exceeds the water availability are marked by hatching.

Source: MARS/STAT database.

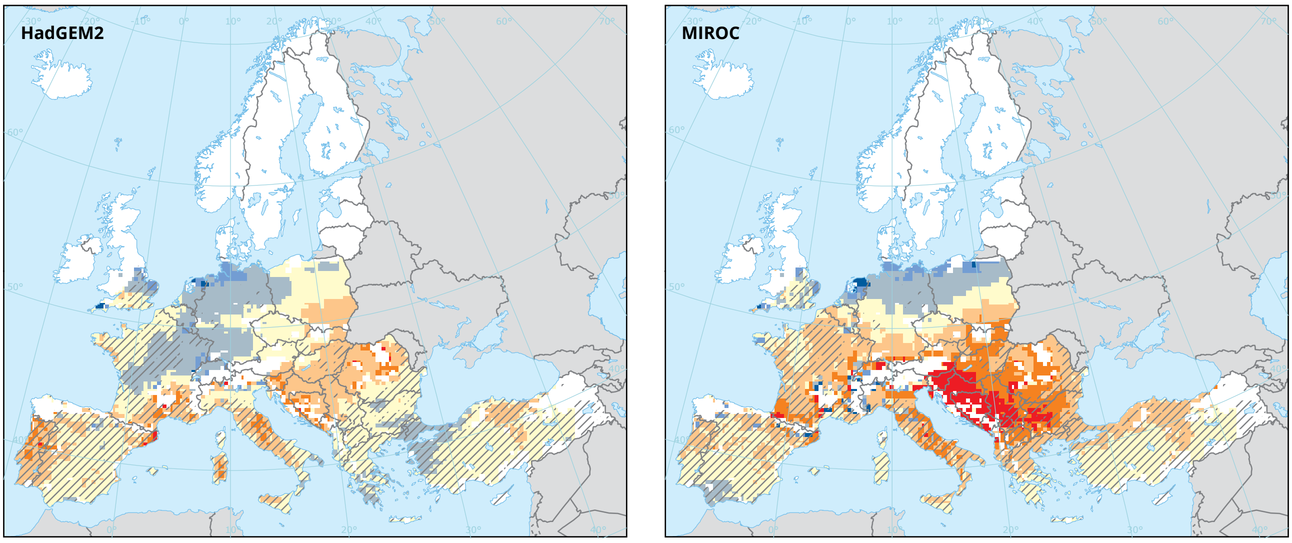
increase in IWD in most of Europe. For RCP8.5, the projected increase in IWD exceeds 25 % in most of the irrigated regions in Europe (Wada et al., 2013). Most hydrological models in this multi-model study did not consider the physiological effect of increased CO_2, which can increase the water-use efficiency of crop plants. The only available study using a hydrological and a crop model that considers the physiological effect of increased CO_2 still estimates that there is a high likelihood that IWD in southern Europe will increase by more than 20 % until 2080 (Konzmann et al., 2013). Regional case studies suggest much higher increases in IWD in some regions (Savé et al., 2012).

Climate change will also affect water availability. The Mediterranean area is projected to experience a decline in water availability, and future irrigation will be constrained by reduced run-off and groundwater resources, by demand from other sectors and by economic costs (Olesen et al., 2011). Assuming that urban water demands would be prioritised over agricultural purposes, the proportional reduction of water availability for irrigation in many European basins is larger than the reduction in annual run-off (Iglesias et al., 2013).

The projected changes in the crop water deficit for grain maize are shown in Map 5.16 for two different climate models. The simulations are based on the WOFOST crop model, which considers the effect of increases in the CO_2 concentrations on the water use efficiency of maize. The simulations for both climate model projections for the 2030s show an increasing crop water deficit for large areas of Europe, in particular over central Europe. This will increase the water requirement for irrigation, including in areas not currently applying irrigation.

Adaptation measures and the integrated management of water, often at catchment scale, are needed to address future competing demands for water between agriculture, energy, conservation and human settlements. New irrigation infrastructure will be required in some regions (van der Velde et al., 2010).

Map 5.16 Projected change in the crop water deficit for grain maize during the growing season, 2015–2045



Projected change of the crop water deficit for grain maize during the growing season, 2015–2045

m³/ha/year

> 50
30 to 50
10 to 30
– 10 to 10
– 30 to – 10
– 50 to – 30
< – 50

No grain maize simulated
Long term crop water demand higher than rainfall (1995–2015)
Outside coverage

0 500 1 000 1 500 km

Note: The map shows projections of changes in the crop water deficit for grain maize in the growing season in the 2030s compared with the reference period centred on 2000 for two different global climate models. The simulations were performed using the WOFOST model for the RCM8.5 emissions scenario. Red indicates an increase in the crop water deficit and blue indicates a reduction of the deficit. Areas where the seasonal crop water requirement regularly exceeds the water availability are marked by hatching.

Source: JRC.

5.3.6 *Livestock systems*

Key messages

- In some areas of southern Europe, higher temperatures and the increasing drought risk are expected to reduce livestock production through negative impacts on both grassland productivity — which may be partly alleviated by increased CO_2 levels — and animal health.
- A reliance on feed concentrates from beyond Europe is a source of vulnerability under climate change, especially for pig and poultry production and intensive dairy farming systems.
- The increased growing season for crops and grasslands may boost livestock system production in northern Europe, but across Europe changes in the distribution of pathogens and pathogen vectors present challenges.
- The projected increase in rainfall in northern Europe may pose challenges for grazing livestock and grass harvesting owing to the accessibility of land and declining soil fertility through soil compaction.
- Sustainably maximising production resilience and efficiency will require both incremental and step changes in production; the former are often incentivised by market forces and the latter require long-term strategic policy action to support and encourage the exploration of transitions to novel farming systems.

Relevance

Livestock production systems are of major economic, environmental and cultural importance to the EU, producing outputs worth EUR 168 billion in 2014 and accounting for 28 % of land use (Leip et al., 2015), including sites of high biodiversity and cultural value. As they are reliant on crop and grass yields and quality, livestock production systems are highly exposed to the impacts of climate change at local (grazing and home-grown forage) and global (feed concentrate imports) levels. Livestock production systems in Europe are affected by climate change directly (through the effects of changing environmental conditions on animal health and welfare) and indirectly (through impacts on pathogens and feed (quantity, type and quality) and through the socio-economic changes entangled with climate change). In this context, international political settlements and policy choices (relating to both agricultural and non-agricultural issues) will have an important influence on, and interact with, production responses to the evolving impacts of climate change, adding uncertainty to projections of the future.

Trends in European livestock systems

Livestock production systems are many and varied. In the EU in 2014, there were 355 million livestock, consisting of pigs (42 %), cattle (25 %), sheep (28 %) and goats (4 %). Goats, being concentrated geographically in the upland regions of southern and eastern Europe, are of high economic and social importance regionally. The number of livestock in the EU decreased by 8 % between 2004 and 2014 (FAO, 2016, subset Production-Live animals). The number of livestock farms in the EU-27 decreased by 32 % (from 9 million to 6.1 million) between 2005 and 2013, with the largest decrease in eastern European countries, and with production becoming more specialised at the individual farm and regional levels (Eurostat, 2016, subset ef_olslsuft).

Intensification has continued alongside land abandonment in areas of marginal production, with both processes having potentially negative effects on biodiversity, ecosystem services, landscapes and rural communities. The EU experienced a 6 % decrease in permanent meadows and pastures (from 70 to 66 Mio ha) between 2005 and 2013, which exceeds the overall decrease in agricultural land of 4 % (from 194 to 187 Mio ha) (FAO, 2016, subset Inputs–Land) ([102]). Production intensification, particularly in monogastric (pig and poultry) systems, has also led to an increasing reliance on high-protein feed concentrates, with feed imports to the EU increasing more than five-fold since the 1960s. This trend has increased the systemic vulnerability to changes in world prices and production

([102]) In contrast to FAO, Eurostat reports a 5 % *increase* in permanent meadows and pastures (from 56 to 59 Mio ha) in the EU-27 between 2005 and 2013 (Eurostat, 2016, subset ef_pograss). However, the Eurostat dataset includes very strong (up to 12-fold) increases in permanent meadows and pastures in a few EU Member States during this period, which raises questions regarding their validity.

conditions (including expected climatic change) and also involves increased global transfer of nutrients, which can have potentially damaging consequences for feed-producing countries (soil impoverishment and erosion) and feed-importing countries (pollution and eutrophication of natural water courses) (Leip et al., 2015). At the same time as (and interacting with) these changes in production, consumers are increasingly putting pressure on producers to produce more in a sustainable manner (Broom et al., 2013).

Alongside the economic changes described above, climate change is already having an impact on livestock production systems. In northern countries, the length of the growing season is increasing, leading to changes in grazing and cutting regimes in grassland-based systems (Höglind et al., 2013). These changes can bring about management challenges, such as those described in the North Savo region of Finland, where one of the challenges is increasing wet conditions that, coupled with use of heavier machinery, lead to increasing soil compaction and declining soil fertility (Box 5.1). Climate change is also beginning to have an impact on animal health. The number of days in which the temperature–humidity index exceeds the critical maximum threshold is increasing in many parts of Europe (Gauly et al., 2013; Dunn et al., 2014). Exposure to a high temperature–humidity index can effect milk production and quality, mortality, reproductive health and disease susceptibility, especially in intensive dairy cattle (Vitali et al., 2009). Some livestock pathogens and pathogen vectors appear to be expanding their ranges and abundance as a result of climate change, such as the spread of bluetongue in northern Europe. For other pathogens, climate change is only one of a range of variables affecting their occurrence, and may not always have a negative effect (Perry et al., 2013).

All these changes take place in the context of a changing policy landscape. Support for agriculture under the EU CAP is being de-coupled from production. Furthermore, under the second pillar of the EU CAP, there is support for improving the way that livestock systems conserve and enhance the provision of societal goods, such as biodiversity and ecosystem services, which are often undervalued by the market.

Projections

So far, the modelling of future changes in livestock production under climate change at the European scale includes only indirect impacts on livestock systems, via changes in crop production and prices. Most of these studies have shown that climate change impacts are less important than socio-economic factors in affecting livestock production in Europe (Audsley et al., 2006; Leclère et al., 2013). As increased CO_2 and warmer conditions lead to increases in the productivity of crops in Europe, livestock systems are expected to rely more on high-protein feeds and less on grasslands. Such trends are also driven by climate change, namely reductions in global crop yields and the subsequent price increases (Frank et al., 2014). Increases in crop demand may be driven more by biofuel production and animal feed than by human consumption.

The modelling predictions described above do not take account of changes in grassland productivity resulting from climate-change related conditions, although it has been suggested that this might only be a marginal factor (Leclère et al., 2013). A model-based study estimated a 3 % increase in annual grassland production between 1961 and 2010, but the model used does not yet consider changes in forage quality resulting from climate change (Chang et al., 2015). Livestock systems are potentially affected by a much wider range of variables, beyond those affecting feed sources. These include (1) the species and genetic characteristics of the livestock being farmed, (2) the health and welfare status of animals, (3) management at individual and herd levels (including health interventions and diet choices) and (4) longer term strategic decisions about the type of farming system and its adaptation to local conditions. Such choices are mediated by socio-economic factors working at multiple and interacting scales, and from within and beyond Europe. There have been early attempts to model the impacts of heat stress on dairy cattle in a regional study of Austrian livestock production under climate change, but models cannot yet capture the variety of climate change impacts involved (Schönhart and Nadeem, 2015). As a result, there is much uncertainty about the response of livestock production to climate change.

Table 5.4 demonstrates that climate change presents very different challenges depending on whether it is assumed that there is a continuation in the production trends considered above (where producers 'push' for the intensification of livestock systems under continued globalisation, and with a switch in land use towards croplands and the abandonment of marginal grazing) or if a 'pull' model is considered, with growing consumer demands and policy support for production based on a wider definition of sustainability (including biodiversity and ecosystem services) (Bindi and Olesen, 2011; Broom et al., 2013).

Different societal choices (social, political and economic) are likely to create systems that may face very different challenges under climate change. While the 'push' model of livestock production systems may continue to drive intensification in some sectors and regions, others might be 'pulled' in other directions by

Table 5.4 Illustration of challenges and adaptation solutions to climate change impacts on European livestock systems

Climate effect	Intensified livestock systems (high inputs and outputs, reduced or zero grazing)		Wide-value systems (grazing, low inputs, systemic diversity)	
	Features and challenges	**Adaptations**	**Features and challenges**	**Adaptations**
Increased temperatures and temperature extremes (especially in southern Europe)	Housed animals are protected from extremes, but higher productivity animals are more susceptible to heat stress; extra heat is also produced from animals being in close proximity	Improve ventilation and housing conditions; genetic approaches for breeds that have better resilience against heat stress	Grazing animals are exposed to temperature extremes, but lower productivity animals are more resilient to heat stress; droughts will have effects on pasture productivity	Provision of shaded areas in pasture; trees for shade can also improve the resilience of swards to extremes; genetic approaches for breeds that have better resilience against heat stress
Spread and increased incidence of pathogens and pathogen vectors	Housed animals avoid many pathogens, but large numbers of animals kept in close proximity to each other increases potential hazards	Use of antibiotics (but limited by increasing resistance); new medical interventions, including use of feeds and supplements; monitoring of health status; genetic approaches for resilient breeds	Grazing animals expected to be more susceptible to liver-fluke and other pathogens under climate change (increased risk), but smaller herd sizes and more diversity reduce hazards	Use of antibiotics (limited by resistance); new medical interventions; monitoring of health status; genetic approaches for resilient breeds; land management to reduce pathogen impact
Increased crop and grass productivity; changes in nutritional quality	It is possible to identify and import feeds for the most efficient dietary mix and control diets on an individual basis, but changes in nutritional quality need to be explored	Improve efficiency of nutrient uptake from feed and make predictions of impacts of changes on nutritional quality; identification of best crops and management approaches in different conditions	Increased pasture and meadow productivity can improve livestock productivity and improve the productivity of home-grown feed crops, but quality may vary	Improve efficiency of nutrient uptake from feed and make predictions of impacts of changes on nutritional quality; identification of new grazing management approaches and supplementary feeds
Increased pressure on water supplies	Intensive systems use large amounts of water, increasing use of feed concentrates increases water demand	More efficient collection, storage and transport of water; regulation to minimise water demand; improve water governance	Provision of water in the field may be difficult and inefficient; drought may reduce grassland productivity	Provision of shade can reduce water demand; more efficient storage and transport of water; improve water governance
Increased variability in crop and grass yields	Reliance on imported feeds brings vulnerability to price increases; de-coupling from local feed production reduces impacts of local climate; increased rainfall increases soil compaction from harvesting grasslands	Use of home-grown protein crops; increase diversity in feed crops grown; control traffic operations to restrict soil compaction	Variability in local conditions can negatively affect grass growth and fodder crops for home-grown feeds, but systems are robust to changes in global feed prices; increased rainfall may reduce land availability for grazing	Improve systems (use of legumes in mixed swards, agroforestry) and management to increase sward resilience to extreme conditions; restrict grazing during very wet periods

Source: ETC-CCA.

value-driven consumers and long-term policy choices. In Europe, the future development of livestock systems is therefore likely to vary by region; for example, in the north-west of Europe dairy farms are already highly intensified, while in eastern and central Europe dairy farming systems remain small scale and traditional, so that different factors need to be focused on (increased efficiency and increased productivity, respectively) for sustainable intensification to be achieved in these differing areas (Taube et al., 2014).

It is not certain that the delivery of wider (non-commoditised) and longer term goals (such as adaptation to the impacts of climate change) will be met by 'natural' market processes. These goals require intervention that stimulates and supports shifts to more sustainable production structures. Such innovative leaps may require the acceptance of short-term reductions in profitability in order to secure long-term security of production and ecosystem services. Innovations may include the development of legume-based grassland livestock systems, which can reduce the reliance on artificial fertiliser inputs, reduce animal susceptibility to some pathogens and increase productivity (Lüscher et al., 2014), or the exploration of silvopastoral systems, which have been shown to increase productivity and environmental sustainability, increase livestock welfare and resilience to temperature extremes, reduce pests, and increase pest predators in tropical zones (Broom et al., 2013). The aim of these explorations should be to find ways to use livestock systems positively to improve and enhance a range of ecosystem services. Achieving this can have potentially positive 'overflow' effects on crop productivity at the landscape level, while also efficiently (and profitably) supplying nutritious food and safeguarding rural communities.

5.4 Energy

Key messages

- Climate change has affected the demand for heating and will affect future energy demand more generally. The total energy demand in Europe is not expected to change substantially, but significant seasonal shifts and effects on the energy mix are expected, with large regional differences.
- The number of population-weighted heating degree days has decreased in recent decades, whereas the number of cooling degree days has increased. As a result, the energy demand for heating has decreased, particularly in northern and north-western Europe, whereas the energy demand for cooling has increased, in particular in southern and central Europe. The absolute change is larger for heating degree days, but the relative change is larger for cooling degree days.
- Further increases in temperature and the occurrence of droughts may limit the availability of cooling water for thermal power generation in summer when the abundance of cooling water is at its lowest.
- Increasing temperatures, changing precipitation patterns and possible increases in storm severity and frequency can have an impact on both renewable and conventional electricity generators. Most of the projected impacts of climate change will be negative, but some positive impacts may occur, in particular for renewable energy production in northern Europe.
- Energy transport infrastructures across Europe are exposed to substantial risks from increasing frequency and magnitude of extreme events induced by climate change. Infrastructures in mountain regions will be threatened by geological instability owing to increased precipitation. Countries in north-western Europe appear to be ahead in preparedness regarding coastal energy infrastructure.

5.4.1 Overview

Relevance

Energy plays a fundamental role in supporting all aspects of modern life. This sector is responsible directly or indirectly for the majority of anthropogenic greenhouse gas emissions (Edenhofer et al., 2014). At the same time, both energy supply and energy demand are sensitive to changes in climate, in particular in temperature. The increasing frequency of extreme weather events, including heat waves, droughts and potentially storms, poses additional challenges for energy systems (Rademaekers et al., 2011). In particular, the efficiency and outputs of thermal power plants can be adversely affected by a rise in temperature or a decrease in the availability of cooling water (low flows as a result of droughts). Storms, extreme wind gusts and ice storms could also pose a challenge for energy infrastructure, such as transmission and distribution networks, as well as renewable generators. Increased flooding could affect power stations and substations. Changed precipitation patterns or variability could create greater uncertainty when investing in hydropower facilities and could alter output, but could also result in local benefits from increased hydropower output in some regions. Hydropower production could also be affected by increased silting of sediment into reservoirs caused by increased erosion and sediment displacement as a consequence of climate change. Other renewable energy supplies could also be affected by climate change, in particular through impacts on the production of bioenergy, but also on wind turbines and solar cells.

Climate change is reducing the demand for space heating and increasing the demand for space cooling, both globally and in Europe. However, socio-economic and technical factors also play an important role in the future energy demand for heating and cooling. Projected increases in income levels in the EU are considered the main driver for increases in the cooling demand up to 2050, while energy efficiency upgrades and demand-side management are curbing future energy demand. This latter factor is particularly relevant to the fact that the energy sector is a major source of greenhouse gas emissions and, therefore, is a major target of mitigation policies. Modelling the possible future impacts of climate change on energy demand requires alternative scenarios to be modelled, which typically differ in the strength of the mitigation policies to be adopted, which in turn may support energy efficiency and thus contribute to reducing energy demand, or may modify the energy mix and therefore the exposure of the energy system to stresses induced by climate change such as water scarcity (Dowling, 2013; Mima and Criqui, 2015).

Indicator selection

This section uses one indicator, which combines information on heating degree days (HDDs) and cooling degree days (CDDs), as a proxy for climate change impacts on energy demand. The sections that follow present information on changes in energy demand, electricity production and energy infrastructure, which do not qualify to be presented as indicators owing to limited data availability.

Data quality and data needs

The climatological input datasets for computing HDDs and CDDs for Europe combine temperature data with daily resolution from three different station datasets — the JRC's MARS meteorological database (EC, 2015), the NOAA National Climatic Data Center (NCDC)'s Global Historical Climatology Network dataset (GHCN; Menne et al., 2012) and the European Climate and Assessment Dataset of the Royal Meteorological Institute of the Netherlands (KNMI-ECA&D; Klein Tank and Wijngaard, 2002) — and from one gridded dataset (E-OBS versions 10 and 11; Haylock et al., 2008). These datasets are considered rather robust. However, different definitions exist for computing HDDs and CDDs, which can lead to different magnitudes of calculated trends (see Section 5.4.2).

Information on past and projected impacts of climate change on electricity demand and electricity generation is very fragmented. The effect of long-term climate change can be difficult to determine owing to concurrent changes in technical, social, behavioural and economic aspects, while the effects of extreme events are usually easier to detect.

5.4.2 Heating and cooling degree days

Key messages

- The number of population-weighted heating degree days (HDD) decreased by 8.2 % between the periods 1951–1980 and 1981–2014; the decrease during the period 1981–2014 was on average 9.9 HDDs per year (0.45 % per year). The largest absolute decrease occurred in northern and north-western Europe.
- The number of population-weighted cooling degree days (CDD) increased by 49.1 % between the periods 1951–1980 and 1981–2014; the increase during the period 1981–2014 was on average 1.2 HDDs per year (1.9 % per year). The largest absolute increase occurred in southern Europe.
- The projected decrease in HDDs as a result of future climate change during the 21st century is somewhat larger than the projected increase in CDDs in absolute terms. However, in economic terms, these two effects are almost equal in Europe, because cooling is generally more expensive than heating.
- The projected increases in the cooling demand in southern and central Europe may further exacerbate peaks in electricity demand in the summer unless appropriate adaptation measures are taken.

Relevance

Space heating and cooling is responsible for a large fraction of European energy use. HDDs and CDDs are proxies for the energy demand needed to heat or cool, respectively, a home or a business. Both variables are derived from measurements of outside air temperature. The heating and cooling requirements for a given structure at a specific location are considered, to some degree, proportional to the number of HDDs and CDDs at that location. However, they also depend on a large number of other factors, in particular building design, energy prices, income levels and behavioural aspects.

HDDs and CDDs are defined relative to a base temperature — the outside temperature — below which a building is assumed to need heating or cooling. They can be computed in different ways, depending, among other things, on the specific target application and the availability of sub-daily temperature data. The previous version of this EEA report (EEA, 2012) applied the methodology of Eurostat, which uses daily mean temperature only and has a jump discontinuity when daily mean temperature falls below the base temperature (Eurostat, 2014). This report uses an approach developed by the UK Met Office, which uses daily mean, minimum and maximum temperatures and does not exhibit a discontinuity. Note that this approach, being based on both minimum (T_n) and maximum (T_x) temperatures and not solely on the mean temperature (T_m), increases the accuracy of HDDs and CDDs for the purpose of gauging the impacts of climate change on energy demand, because the cooling of the environment depends more on T_x than on T_m, while T_n is more relevant for heating. The baseline temperatures for HDDs and CDDs are 15.5 °C and 22 °C, respectively (Spinoni et al., 2015). As a result of the methodological changes, the magnitudes of the trends between the previous report and this report cannot be directly compared.

The aggregation of regional changes in HDDs and CDDs to larger areas can be done using area weighting or population weighting (with a fixed population). Population weighting is preferable for estimating trends in energy demand over large regions with an uneven population distribution (e.g. Scandinavia or Europe) (EPA, 2014).

Past trends

The number of population-weighted HDDs decreased by 8.2 % between the periods 1951–1980 and 1981–2014. The decrease during the period 1981–2014 was on average 9.9 HDDs per year, although with substantial interannual variation (Figure 5.8, left); this linear trend corresponds to an annual decrease of 0.45% (relative to the 1951–1980 average). The largest absolute decrease occurred in northern and north-western Europe, where the heating demand is highest (Map 5.17, left panel).

The number of population-weighted CDDs increased by 49.1 % between the periods 1951–1980 and 1981–2014. The increase during the period 1981–2014 was on average 1.2 CDDs per year, although with substantial interannual variation (Figure 5.8, right); this linear trend corresponds to an annual increase of 1.9 % (relative to the 1951–1980 average). The largest absolute increase occurred in southern Europe (latitudes below 45 °N), where the energy demand for cooling in summer is highest (Map 5.17, right panel).

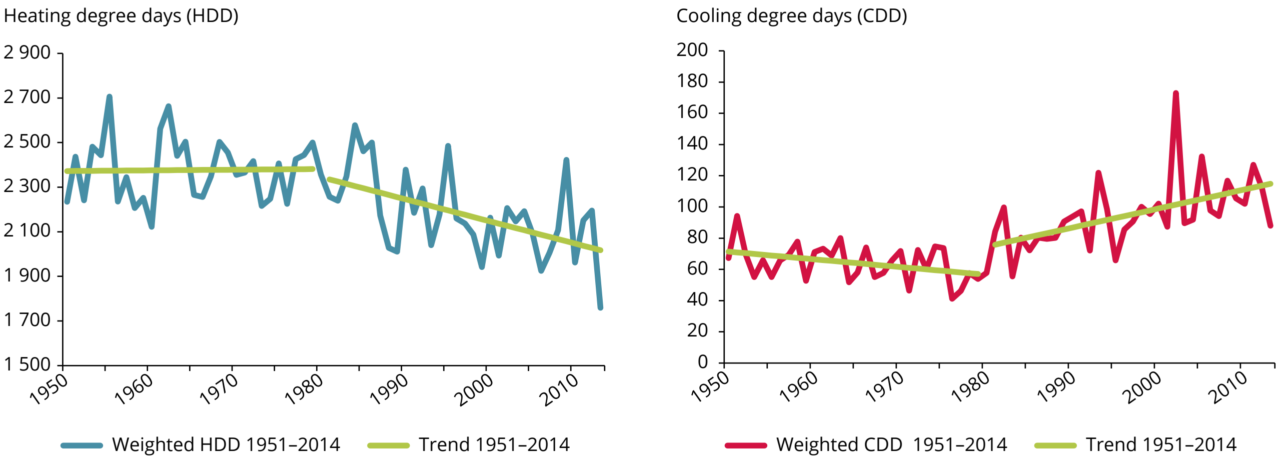
The relative increase in CDDs is much higher than the relative decrease in HDDs, because of lower absolute values. In principle, HDD and CDD values can be added together to give a new indicator, energy degree days, which has shown a decrease since the 1950s. However, one must consider that HDDs and CDDs are climatological parameters and that the energy demand linked to their values is not the same, as heating and cooling systems are often based on different technologies.

Figure 5.8 highlights some important features of the evolution of the pattern of HDDs and CDDs in Europe since the 1950s. In the first three decades, HDDs were roughly constant and CDDs declined slightly. Since the beginning of the 1980s, Europe has started experiencing a markedly declining overall trend in HDDs, and a markedly increasing trend in CDDs, pointing to a general increase in cooling needs and a general decrease in heating needs. Map 5.17 shows that the decrease in HDDs has been particularly strong in the Alpine areas and the Baltic and Scandinavian countries, whereas the increase in CDDs is particularly strong in southern Europe, around the Mediterranean and in the Balkan countries. Some overlapping of medium to strong HDD and CDD effects is noticeable in Bulgaria, southern France, Italy, Portugal, Romania and Spain.

Projections

Temperatures in Europe are projected to continue to increase. Hence, the trend of a decreasing number of HDDs and an increasing number of CDDs is very likely to continue, and most likely to accelerate (Benestad, 2008). Model simulations performed in the ClimateCost project (based on HDD and CDD data) have estimated the decrease in residential heating energy demand in the EU as a result of climate change alone (above the SRES A1B baseline without climate change) to be 28 million tonnes of oil equivalent (Mtoe)/year by 2050 and 65 Mtoe/year by 2100; the corresponding projected increase in cooling energy demand is 16 Mtoe/year by 2050 and 53 Mtoe/year by 2100. While the projected physical energy reductions for heating are higher than the increase in cooling demand, in economic terms the projected reduction in total heating demand is about the same as the increase in cooling demand, as cooling is more expensive than heating. In cold countries, such as Norway, the net effect of projected temperature increases reduces total energy demand, whereas in warm countries, such as Spain, it increases energy demand. All projected changes are considerably lower under a mitigation scenario with lower emissions (Mima and Criqui, 2015).

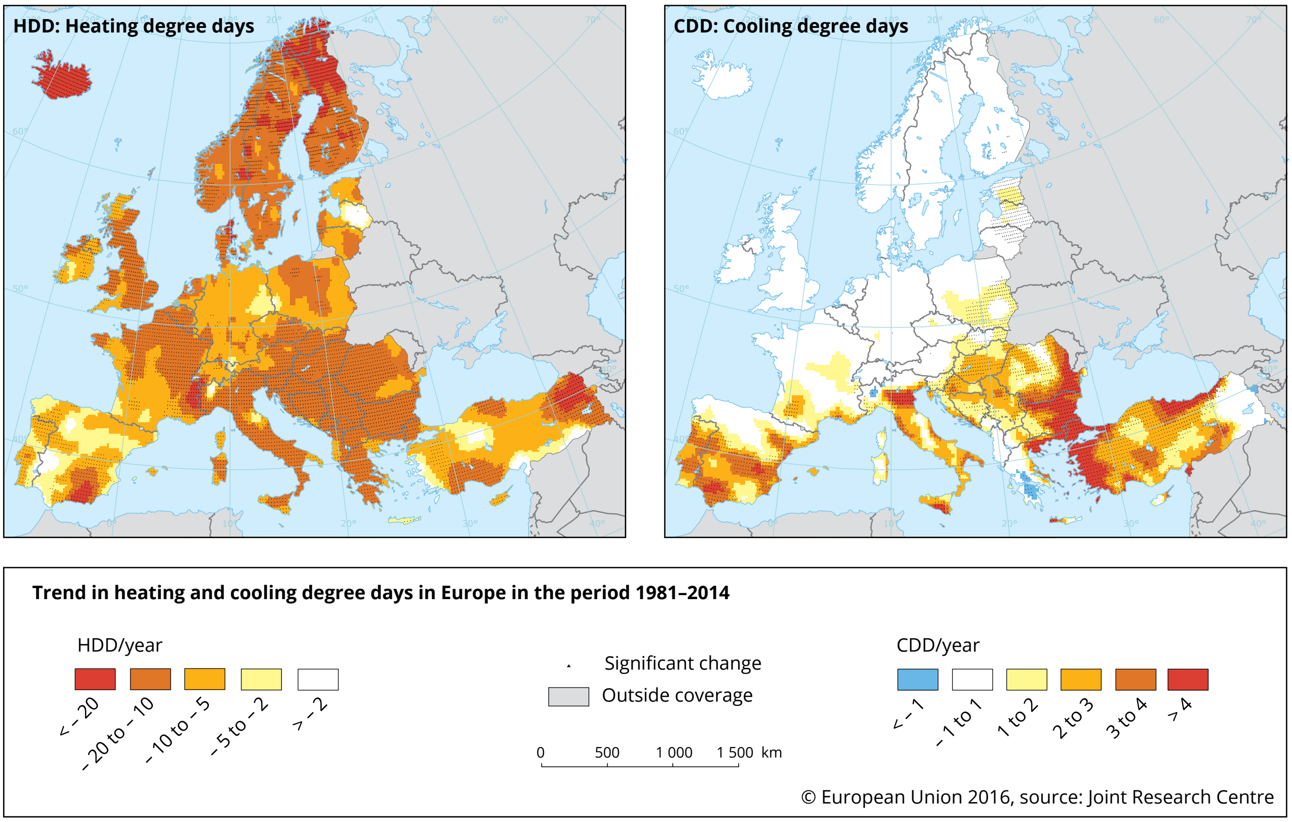
Figure 5.8 Time series of population-weighted heating and cooling degree days averaged over Europe



Note: This figure shows time series of heating degree days (left) and cooling degree days (right) averaged over Europe (EU-28 without Cyprus but including Liechtenstein, Norway and Switzerland) over the period 1951–2014, including linear trends for 1951–1980 and 1981–2014. Population weighting was applied during spatial aggregation.

Source: JRC, KNMI-ECA&D (E-OBS version 11) and Eurostat GEOSTAT 2011 dataset.

Map 5.17 Trends in heating and cooling degree days, 1981–2014



Note: The maps shows the observed linear trends in heating degree days (left) and cooling degree days (right) over the period 1981–2014 for all EEA member and cooperating countries. Stippling depicts regions where the trend is statistically significant at the 5 % level.

Source: JRC and KNMI-ECA&D (E-OBS version 11).

5.4.3 Energy demand

The literature on the effects of climate change on energy demand and production is not very extensive, particularly for sectors other than residential and for fuels other than electricity. However, key impacts across Europe can be identified. While most studies have a specific sectoral or regional focus and look at either the demand or the supply side, the ClimateCost and PESETA II projects attempt to provide comprehensive assessments for the entire European energy system, considering the impacts on demand and supply jointly. Both studies rely on the same energy model, Prospective Outlook on Long-term Energy Systems (POLES) (Mima and Criqui, 2015). The main results from POLES regarding energy demand are summarised in Section 5.4.2 under 'Projections', and in the final two rows of Table 5.5.

The main focus of most studies on energy demand is on electricity, and in particular on residential electricity use. Approximately one-third of Europe's domestic space heating requirement is provided by electricity, but with substantial variation across countries (Mideksa and Kallbekken, 2010). Cooling is almost exclusively provided by electricity. Therefore, changes in heating demand, and even more so in cooling demand, will directly influence electricity demand. It is worth noting that an increased electricity demand peak in the summer would coincide with increased difficulty in obtaining sufficient cooling water for thermal power generation during very hot conditions (Förster and Lilliestam, 2009).

Table 5.5 summarises the studies that have looked at projected trends for different European countries. The heterogeneity in results is generally the result of the selection of different climate change scenarios, the different time span considered and whether or not economic and societal change is considered in addition to climate change.

Table 5.5 Overview of studies on climate change impacts on future energy demand

Study	Region	Date of projection	Which demand?	Change in demand	Peak demand
Pilli-Sihvola et al., 2010	Finland, France, Germany, the Netherlands and Spain	2015–2050	Electricity (total across sectors)	Decreases in northern countries, increase in Spain; overall neutral	+ 2 % to + 4 %, Spain (projected summer electricity demand in 2050 compared with 2007)
Mirasgedis et al., 2007	Greece	2070–2100	Electricity (total across sectors)	+ 3 % to + 6 %	+ 13 %, June
Eskeland and Mideksa, 2010	Europe	2100	Residential electricity consumption	Small, but disguises large regional variations (from – 21 % in Lithuania to + 19 % in Turkey in 2100, compared with the 1995–2005 average)	+ 19 %, Turkey (compared with the 1995–2005 average)
Mima et al., 2012	Europe	2010–2100	Heating demand (oil, gas, biomass and electricity); cooling demand (electricity); residential and tertiary sector	+ 12 % by 2050, rising to + 24 % by 2100 (EU-28, Croatia not included), as a result of electricity for cooling demand above future baseline (A1B scenario), reduced to + 8 % across period for E1 mitigation scenario	Strong regional variations, with larger increases in cooling demand in southern Europe and heating demand in west Europe (neither of which is quantified as a percentage in the study)

Table 5.5 Overview of studies on climate change impacts on future energy demand (cont.)

Study	Region	Date of projection	Which demand?	Change in demand	Peak demand
De Cian et al., 2012	OECD	2085	Natural gas, oil products, electricity	Decrease in overall energy consumption across the EU (e.g. – 14 Mtoe of electricity in Norway and – 180 Mtoe of all fuels in the United Kingdom)	+ 8.7 Mtoe (equivalent to + 13 %) in Switzerland
Ciscar et al., 2014	Europe	2071–2100	Heating demand (various fuels); cooling demand (electricity); residential and tertiary sector	– 13 % (3.5 °C scenario) and – 7 % (2 °C scenario) compared with 1961–1990	+ 8 % southern Europe in the 3.5 °C scenario
Raible and CH2014-Impacts Initiative, 2014, Chapter 10	Switzerland	2035, 2060, 2085	Heating and cooling demand	Overall decrease: – 3 % to –18 % by 2060, – 4 % to – 29 % by 2085	+ 248.5 % in 2050 for cooling (no information for 2085); more than compensated for, however, by decrease in heating demand
Mima and Criqui, (2015)	Europe	2020–2100	Heating demand (oil, gas, biomass and electricity); cooling demand (electricity); residential and tertiary sector	– 15 % to – 35 % decrease in EU heating demand in SRES A1B by 2010; + 3 % annual increase in EU cooling demand	Four-fold increase in cooling demand in tertiary sector by 2100

Note: All of the studies take into account macro drivers and separate the effects of these drivers from those stemming directly from climate change, either by controlling for macro drivers such as GDP, population, income and GDP per capita in the econometric models estimated, or by keeping track of their roles in the SRES scenarios and isolating their effects from the purely climatic ones (with the possible exception of the last study, where this is not explicitly mentioned).

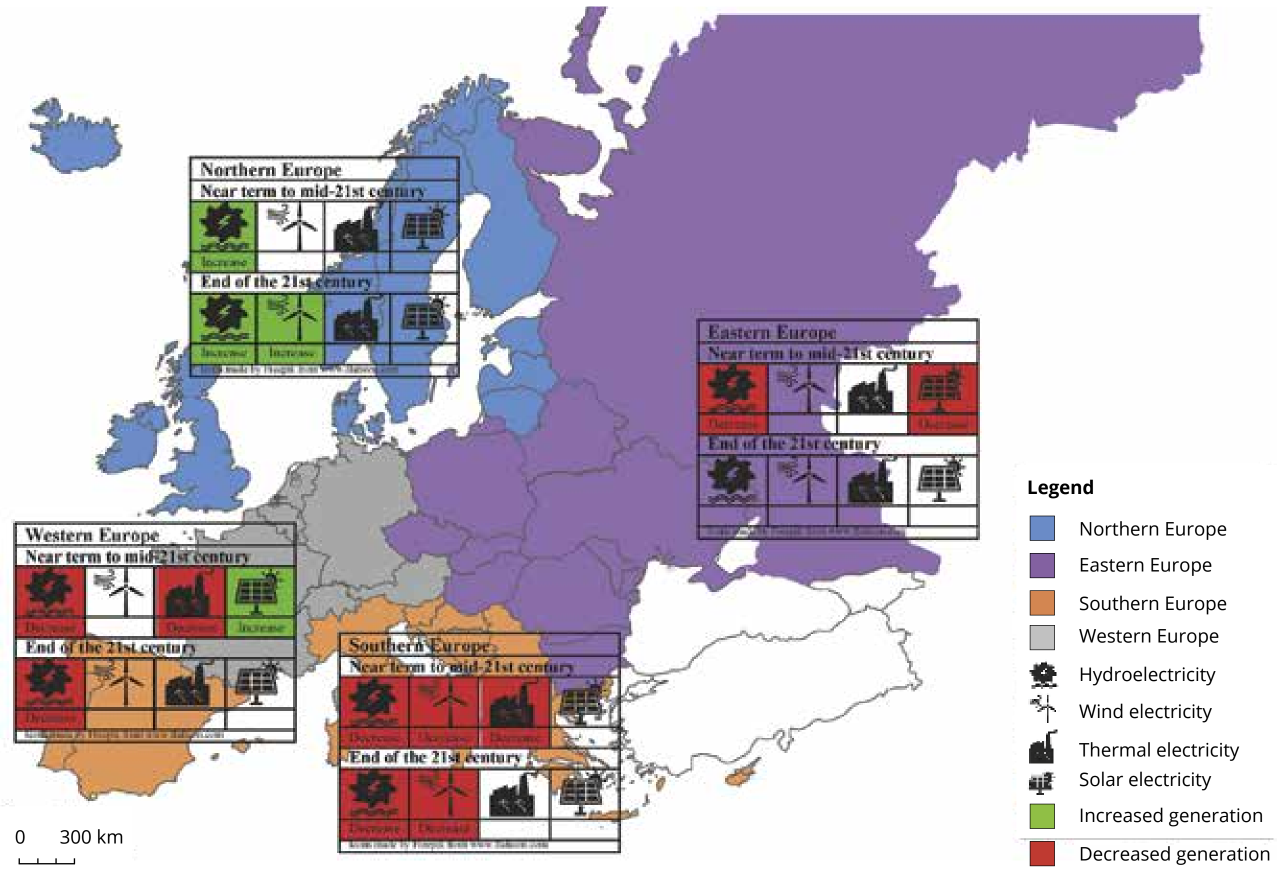
5.4.4 Electricity production

The relevance of climate change impacts on electricity generation, particularly through changes in water availability, have been highlighted in a number of studies. Climate change impacts on electricity production will vary depending on the role of different sources in the energy mix and the geographical location. Therefore, there will be a marked difference between southern and northern Europe, with varying impacts depending on the generation technology. Increases are projected for most of Scandinavia and decreases for the rest of Europe (Rübbelke and Vögele, 2012; Hamududu and Killingtveit, 2012; van Vliet et al., 2012, 2013; van Vliet, Wiberg, et al., 2016; van Vliet, van Beek, et al., 2016).

A systematic literature review revealed some robust patterns of climate change impacts on electricity generation. The study points to robust negative impacts on thermal electricity generation throughout the 21st century. Impacts on renewable electricity generation show strong regional variation (Map 5.18) (Bonjean Stanton et al., 2016). Hydropower production may experience significant risks in Alpine countries, whereas conditions in Scandinavia are expected to improve (Lehner et al., 2005; SGHL and CHy, 2011; Rübbelke and Vögele, 2012). Climate change impacts on wind generation in the EU are expected to be limited throughout the 21st century, with a tendency towards a decrease in the wind power potential over Mediterranean areas and an increase over northern Europe (Tobin et al., 2015, 2016). Regional studies on solar power generation point to very limited or neutral effects (Pašičko et al., 2012; Wachsmuth et al., 2013; Panagea et al., 2014).

Fossil-powered and nuclear electricity generators are sensitive to a reduced availability and increased temperature of cooling water, and to increased air temperature, which reduces their efficiency. Nuclear plants are particularly susceptible, and France is the country facing the highest risk in this regard (Linnerud et al., 2011; Rübbelke and Vögele, 2012). The ToPDAd

Map 5.18 Projected impacts of climate change on electricity production from different sources in four European regions



Source: Adapted from Bonjean Stanton et al., 2016.

project estimated that the economic damage due to the decreased availability of nuclear power in France could be as high as tens of billions of euros per year by 2100 under a high emissions scenario (RCP8.5) and several billion euros under a medium emissions scenario (RCP4.5), if the current infrastructure and policies remain in place (Perrels et al., 2015; ToPDAd, 2015).

Some studies have assessed the system-wide impacts of future climate change on electricity production. Results of the ClimateCost project suggest that there will be significant impacts on electricity generation, with a worsening of operating conditions for thermal, hydro and nuclear power plants. These impacts will translate into losses for the EU energy system that could reach 200 terawatt-hours (TWh) in 2070 for a medium emissions scenario (SRES A1B) and 150 TWh in 2060 and 2080 for a low emissions scenario (E1). The overall economic impacts of changes in the demand and supply side are estimated as a net loss of 0.11 % of EU-28 (Croatia not included) GDP in 2100 for the SRES A1B scenario. This general result hides, however, significant regional disparities; moreover, the study itself points to a considerable degree of uncertainty about these estimates, stemming from the variability of climate projections across the climate models used, particularly in the case of precipitation (and hence water availability), and from the partial coverage of relevant impacts, as wind velocity, insolation, extreme events and droughts may not be included (Mima and Criqui, 2015). Qualitatively similar conclusions were reached in the PESETA II project (Dowling, 2013; Ciscar et al., 2014). The loss in generation efficiency due to increased cooling requirements for thermal and nuclear plants may result in a loss of competitiveness for these sources and, therefore, increase the proportion of renewable sources in the energy mix (Dowling, 2013). Moreover, mitigation policy choices can be a crucial driver of the final impacts on the energy mix.

Box 5.3 ToPDAd case study for Baltic countries

Preliminary results from the ToPDAd (Tool-supported policy development for regional adaptation) project for the Baltic countries in northern Europe indicate that climate change is likely to decrease energy sector investment costs by 2050 owing to reduced heating needs and increased hydropower generation. The presented results are based on an energy sector investment model (the Balmorel ([103]) model soft-linked with the TIMES ([104]) model) that have been run with and without climate change scenarios for the ToPDAd EU project (Perrels et al., 2015).

For the high emissions scenario (RCP8.5), precipitation and consequently river run-off are projected to increase by 5–20 % in all Baltic countries. For the medium emissions scenario (RCP4.5), the projected increase was smaller and focused on Norway and Sweden, which have by far the largest hydropower capacities in northern Europe. While an overall increase in river run-off looks likely, the magnitude and geographical distribution is uncertain. The projected increases in temperature were estimated to decrease electricity demand by 1–2 % and district heating demand by 7–11 %, depending on the emissions scenario.

Owing to emissions restrictions and cost assumptions, the model directs investments mainly to renewable power generation. As electricity and district heating demand decrease and hydropower production increases, there is less need for new investments in the power sector, including new wind power investments. The resulting savings in cumulative energy costs by 2050 for this region range from 2 % to over 5 %, depending on the combination of the RCP (RCP2.6, RCP4.5 or RCP8.5) and SSP (SSP1, SSP4 or SSP5; see Section 1.2).

The energy sector is characterised by large long-term investments. The impacts of climate change and of mitigation requirements are expected to be considered when these investments are made. However, considerable uncertainty in the magnitude and distribution of climate change impacts may lead to some failed investments. The projected cost reductions also depend on adaptation. The reductions in total annual costs range from 1 % to 2 % if no adaptation takes place; the savings are slightly higher, from 1.3 % to 2.5 %, in the case of adaptation. However, these estimates are sensitive to a number of assumptions, in particular emissions constraints and renewable energy targets.

([103]) The Balmorel model is a model for analysing the electricity and combined heat and power sectors in an international perspective (see http://www.eabalmorel.dk).
([104]) TIMES: 'The Integrated MARKAL-EFOM System' (see http://iea-etsap.org).

5.4.5 *Energy infrastructure*

The vulnerabilities of energy production and transmission infrastructure to climate change are becoming increasingly relevant owing to the increasing dependence of societal activities on electricity, and to the shift of the energy mix towards more vulnerable technologies, such as wind power generation (Ligtvoet, et al., 2015). Moreover, the increasing interconnection between national energy networks in the EU, particularly electricity transmission lines, enhances the interdependency across countries and, therefore, the risk of the vulnerability of energy infrastructures spreading across national borders (Vonk et al., 2015) (see also Section 6.4).

There is a dearth of publications on the impact of climate change on the energy infrastructure in Europe. Pipelines and electricity transmission lines are generally built with a relatively high tolerance to extreme climatic conditions, which adds some safety margin for future climate change. They are therefore expected to withstand the threats posed by climate change better than other infrastructures. This, however, does not exclude the need to adapt the design and operating conditions of energy infrastructures used in currently mild climates, by drawing upon the lessons learnt in areas where conditions are usually more severe (Kovats et al., 2014).

Table 5.6 summarises the climate change impacts on energy transmission and distribution infrastructure in Europe (EC, 2013). The table highlights the risks that extreme weather events could pose to infrastructures, such as reduced technical efficiency under higher temperatures. Note that this information is framed qualitatively as the *risks* possibly faced by energy infrastructure in the future. However, a comprehensive quantitative assessment of such impacts for EU energy infrastructure is not available.

The stress test of European nuclear power plants in the aftermath of the Fukushima accident concluded that further improvements can be made to prepare for extreme weather events (EC, 2011; ENSREG, 2012). The International Atomic Energy Agency (IAEA) has developed guidelines that represent good practice to increase robustness against natural hazards and extreme events, which are expected to be implemented in a number of European countries as a result of the stress test (IAEA, 2011). Renewable electricity generators are most susceptible to potential changes in extreme storm gusts, which might damage wind turbines.

A recent assessment of the possible vulnerabilities of coastal energy infrastructures in Europe, comprising oil, gas or liquefied natural gas tanker terminals and nuclear power stations, highlights the risks posed by sea level rise. There are 158 major terminals in the European coastal zone and 71 operating nuclear reactors on the coast, with more currently planned. Planned adaptation and a high level of awareness of sea level rise threats could mitigate, to some extent, the risks to coastal energy infrastructure in north-western Europe (Brown et al., 2014).

Table 5.6 Climate-related vulnerabilities of energy infrastructures in the EU

Type	Climatic pressures	Risks	Time frame of expected impacts	Regions mainly affected
Primarily electrical transmission and distribution networks	Extremely high temperatures	Decreased network capacity	Medium-negative (2025) to extreme-negative (2080)	EU-wide
	Snow, icing, storms	Increased chance of damage to energy networks and, thus, blackout	Medium-negative to low-positive (2050)	North-western EU
	Heavy precipitation	Mass movements (landslides, mud and debris flows) causing damage	Time frame, magnitudes and frequencies uncertain	Mountainous regions in particular
Primarily transmission networks (oil and gas)	Melting permafrost	Tie-ins of gas pipelines in permafrost ground cause technical problems (this is related only to Arctic supply pipelines and not to the east–west gas pipelines, as the latter are not grounded in permafrost)	Low for 2025 and gradually increasing	Arctic Eurasia
	Higher temperatures	Reduced throughput capacity in gas pipelines	Low for 2025 and gradually increasing	EU-wide
Primarily storage and distribution	Storms in connection with high tides and sea level rise	Threats to refineries and coastal pipelines owing to sea level rise, high tide and storms	Low for 2025 and gradually increasing	EU-wide

Source: EC, 2013 (Annex 2, p. 34).

5.5 Transport

Key messages

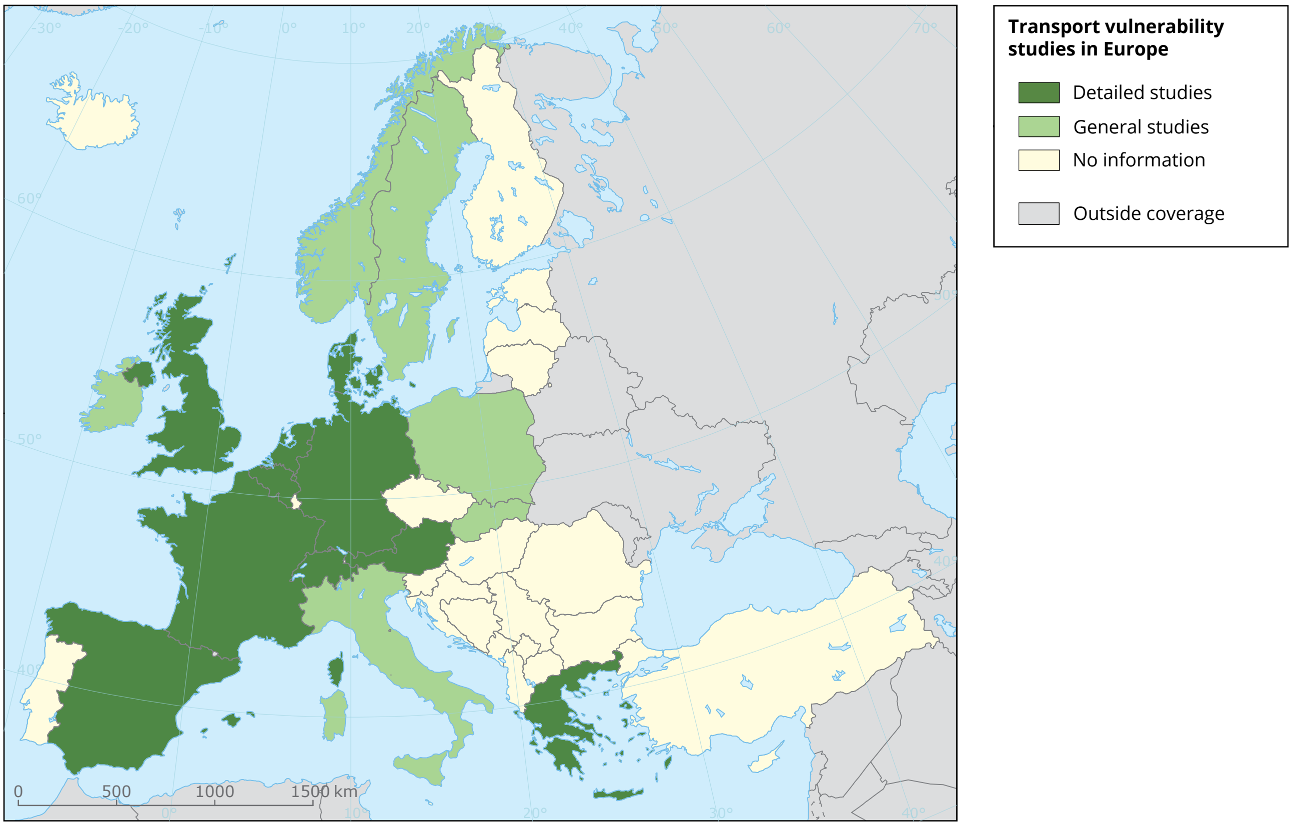
- Past and present weather-related impacts on transport are mostly related to individual extreme events. The main climatic stressors for transport are heat waves in southern and eastern Europe, cold spells and snow in northern Europe, and heavy precipitation and floods in most of Europe.
- The impacts projected by 2050 are expected to be limited and manageable if proper adaptation measures are taken. However, available assessments of climate change impacts on transport, including the costs from extremes, do not give a comprehensive overview of climate-related risks for transport across Europe owing to their widely different methodological approaches.
- The impacts of climate change on transport vary depending on the region and the transport modes considered. Transport systems in mountainous regions, coastal areas and regions prone to more intense rain and snow are generally expected to be most vulnerable to future climate change. Available projections suggest that rail transport will face particularly high risks from extreme weather events, mostly as a result of the projected increase in heavy rain events and limited route alternatives.

5.5.1 Overview

The European society and its economy remain highly dependent on the availability of reliable and efficient transport systems. Transport infrastructure and operations are sensitive to the impacts of climate change, and the effects of those impacts fall well beyond the transport sector, causing enormous disruption in human activities and considerable indirect economic damage, particularly if they affect critical links such as the few transnational connections serving international traffic in Europe and beyond. The long life span of many transport components, including not only infrastructure but also some vehicles, reaches well beyond 2050 and in some cases even beyond 2100, and wherever possible, their design characteristics should take into consideration the expected climate conditions in those years.

Of the 33 EEA member countries, 17 have developed some kind of climate-related vulnerability assessment of their transport systems, and 10 of them have conducted detailed studies for at least some transport modes (Map 5.19). It is worth noting that transport is not considered a priority sector for vulnerability assessment in the majority of these countries. There is a wide variety in the approaches followed by the countries that have developed detailed vulnerability studies. In some cases, such as Greece (Giannopoulos et al., 2011) and Spain (CEDEX, 2013), a common approach has been followed to analyse all transport modes; in other cases, such as France (République Française, 2011) and the United Kingdom (DEFRA, 2012; Thornes et al., 2012), the key stakeholders for each transport mode (generally infrastructure managers) have received a mandate to conduct their own vulnerability studies. Depending on each country's priorities, some transport modes have been particularly active compared with others: this is the case, for example, for rail and road transport in mountainous areas such as in Austria (Steininger et al., 2015) and Switzerland (FOEN, 2012).

Map 5.19 Availability of transport vulnerability studies in Europe



Source: Climate-ADAPT.

5.5.2 Impacts of climate and weather extremes

Changes in average weather conditions will be influential for transport mostly in the long term. For example, semi-permanent frost structures in the far north may become unusable for larger portions of the year owing to permafrost warming and melting. However, changes in climate also result in variations in the conditions and frequency of extreme weather events, which could cause increasing infrastructure damage, longer delays for passengers, disruptions, additional safety risks and higher operational costs.

In the past, most of the damage was caused by heavy precipitation. Heavy rain causes flash flooding, which disrupts transport connections, inhibits inland waterway traffic and damages roads, bridges, rail embankments and other earth structures. Heavy snowfall complicates road traffic, rail transport and airport operations in all of Europe (Leviäkangas et al., 2011; Nemry and Demirel, 2012). Heavy precipitation events have increased in many regions of Europe and these trends are expected to continue (see Section 3.2.5). What makes a difference is the preparedness and the availability of resources to deal with unexpected weather conditions and to solve problems, for instance sufficient availability of maintenance equipment and appropriate contingency plans.

Recent research on climate-related impacts on transport has focused on extreme weather events. The European research projects EWENT ([105]), WEATHER ([106]), ECCONET ([107]) and MOWE-IT ([108]) have explored the geographical distribution of the transport impacts of extreme weather effects and the vulnerability of transport systems. MOWE-IT provides a recent summary of key extreme weather events and their impacts on the various transport modes, building

([105]) EWENT: 'Extreme weather impacts on European networks of transport' (http://ewent.vtt.fi).
([106]) WEATHER: 'Weather Extremes: Impacts on Transport Systems and Hazards for European Regions (http://www.weather-project.eu).
([107]) ECCONET: 'Effects of climate change on the inland waterway networks' (http://www.ecconet.eu).
([108]) MOWE-IT: 'Management of Weather Events in the Transport System' (http://www.mowe-it.eu).

upon the results of the other projects and further stakeholder consultation (see Table 5.7). The ToPDAd project has also assessed climate change vulnerability and adaptation options of selected transport systems in Europe ([109]) (ToPDAd, 2015).

Some future changes in climate may have positive impacts on certain transport modes or in European regions. This can be true of a decrease in the ice cover of oceans and rivers, particularly in the Arctic, where an increase in average temperature would open up new transport routes. Warmer weather conditions would probably decrease maintenance costs for transport infrastructure in central and northern Europe (Ciscar et al., 2014). However, in Europe as a whole, the decreasing trend in winter extremes is overcompensated by the expected increases in warm extremes and heavy precipitation events (Koetse and Rietveld, 2009). Further warming implies a need for improvements in the heat tolerance of the transport system during summer, especially in countries that already experience high temperatures (Leviäkangas and Saarikivi, 2012).

Although the results provided by climate models do not allow for a detailed geographical identification of transport impacts, all research projects mentioned previously include an attempt to locate key challenges in the different European regions. Map 5.20 summarises the projected changes in the probabilities of adverse and extreme weather events for each climate region until 2050. The threshold values used for the most harmful extreme weather phenomena are available in Table 5.8. Some of those projections are associated with significant uncertainties related to projections as well as related to zonal boundaries. Furthermore, some changes have been made to the original map from the EWENT project in order to improve consistency with the regionalisation used in the Executive Summary of this report. In particular, the Baltic States changed from the Temperate Eastern region to the Northern region, and they may experience features of both regions. Furthermore, the Temperate Eastern and Temperate Central regions have been combined; the further one goes towards East in the combined region, the more likely is the increase of heat waves.

A decrease in cold spells, extreme snowfall and frozen precipitation have a positive impact on road, rail and air transportation, reducing the cost of maintenance and producing beneficial side effects. However, even with a general decreasing trend in winter extremes, winter extremes are still expected to have an impact on transportation owing to interannual variability, and would still need to be considered in maintenance and investment for improving preparedness for many European countries. An increase in warm extremes and heavy precipitation events are likely to have negative impacts on transport. During summer, especially in countries that already experience high temperatures, further warming implies a need for improvements in the heat tolerance of the transport system. Increases in heat waves in the Mediterranean and in eastern Europe and cold spells in northern Europe are the main stressors identified until 2050 (Leviäkangas and Saarikivi, 2012).

Although research on the potential economic impacts of climate change on transport is rapidly expanding, results are still constrained by a variety of sources of uncertainty: the initial uncertainty of future climate, the limited reliability of long-term forecasts on demand for the various transport modes, and the weak basis available to estimate the expected impacts (damage, accidents, travel costs, time delay, etc.) on the future transport system. The WEATHER project (Przyluski et al., 2011) estimated that annual direct transport costs related to extreme weather events in 1998–2010 were EUR 2.5 billion and that annual indirect costs added EUR 1 billion; the project also estimated a 20 % increase until the period 2040–2050. All transport modes and logistics were included in this estimate, with the sole exception being urban public transport. The EWENT project followed a different approach, including estimates on accidents, travel time and costs as well as on transport infrastructure and maintenance. The results found only small differences between 2010 and 2040–2070; the main changes would be a significant reduction in annual accident costs (EUR 3.4 billion) and a significant increase in annual logistics costs (EUR 4 billion); the drivers of these changes were related more to trends in demand and technology than to the impacts of extreme weather events (Nokkala et al., 2012). The PESETA II project provides another estimate, limited to road and rail transport; the impact on transport in terms of welfare loss as a percentage of GDP would be negligible (below 0.1 %) and would be much lower than in other sectors, such as water or health, in all of the scenarios considered until 2050 (Nemry and Demirel, 2012; Ciscar et al., 2014). It is worth noting that discrepancies in the figures estimated by the various projects is a logical consequence of differences in their underlying hypotheses and definitions regarding key concepts such as extreme weather event thresholds and occurrence, or transport system disruption and its consequences.

([109]) http://www.topdad.eu.

Table 5.7 Summary of transport vulnerabilities to extreme weather events

Extreme weather event	Impacts on transport modes			
	Road	**Rail**	**Water-borne**	**Aviation**
Heat waves	Damage to pavements Vehicle failure (tyres) Forest fires Fatigue of drivers	Rail buckling Material fatigue Increased instability of embankments Overheating of equipment Forest fires causing damage to infrastructure	Low river flow (due to drought), imposing restrictions on loading capacity, navigation problems and speed reduction	Damage to runway pavement Forest fires reducing visibility Take-off weight limitations
Cold spells	Reduced surface friction Road maintenance Technical failure of vehicles and infrastructure Deterioration of pavement	Ice on trains and catenary	Warm and early winters followed by a rapid decrease in air temperature may result in rougher ice cover formation and lead to ice jams and damage to navigation signs and infrastructure	Reduced runway friction Runway maintenance Deterioration of pavement Technical failure of vehicles and infrastructure Icing of aircraft
Heavy precipitation (large-scale systems)	Reduced visibility and surface friction Floods and landslides	Flooding and landslides damaging infrastructure Scour to structures Increased instability of embankments	High river flows, resulting in problems for passage of bridges, dike instability (speed limitations) and restrictions to the height of vessels	Reduced visibility and runway friction Floods Reduction in airport throughput Runway clearance
Snowfall	Reduced visibility and surface friction Obstacles on roads owing to snowdrift and broken branches			Reduced visibility and runway friction Snowdrift Runway maintenance Icing of aircraft Ground operations affected
Large-scale storms and winds	Difficult driving conditions due to gusts Obstacles on the road owing to fallen trees and other objects	Damage to infrastructure such as signals, catenary, etc. (e.g. owing to falling trees)	Severe storms and extreme waves may affect maritime navigation	Increased turbulence with strong wind gusts Obstacles on the runways Safety risks for ground operations Safety regulations (wind threshold may lead to runway closure) Disruption to operations

Table 5.7 Summary of transport vulnerabilities to extreme weather events (cont.)

Extreme weather event	Impacts on transport modes			
	Road	Rail	Water-borne	Aviation
Thunderstorms (strong wind gusts, lightning, intense precipitation, hail)	Reduced visibility and surface friction Obstacles on roads Failures in transport control systems	Reduced visibility and surface friction Obstacles on tracks Failures in transport control systems	Extreme storm events may lead to devastation of port infrastructure and disruption of traffic flows at ports	Reduced visibility and runway friction Obstacles on runways Failures in control systems Increased turbulence Safety risks for ground operations Damage to aircraft and equipment Safety regulations (lightning strike may lead to airport closure) Disruption to operations
Blizzards (strong wind gusts, intense snowfall)	Reduced visibility and surface friction Obstacles on roads Failures in transport control systems			Reduced visibility and runway friction Obstacles on runways Runway maintenance Increased turbulence Safety risks for ground operations Safety regulations (wind threshold may lead to runway closure) Disruption to operations
Fog	Reduced visibility			Reduced visibility

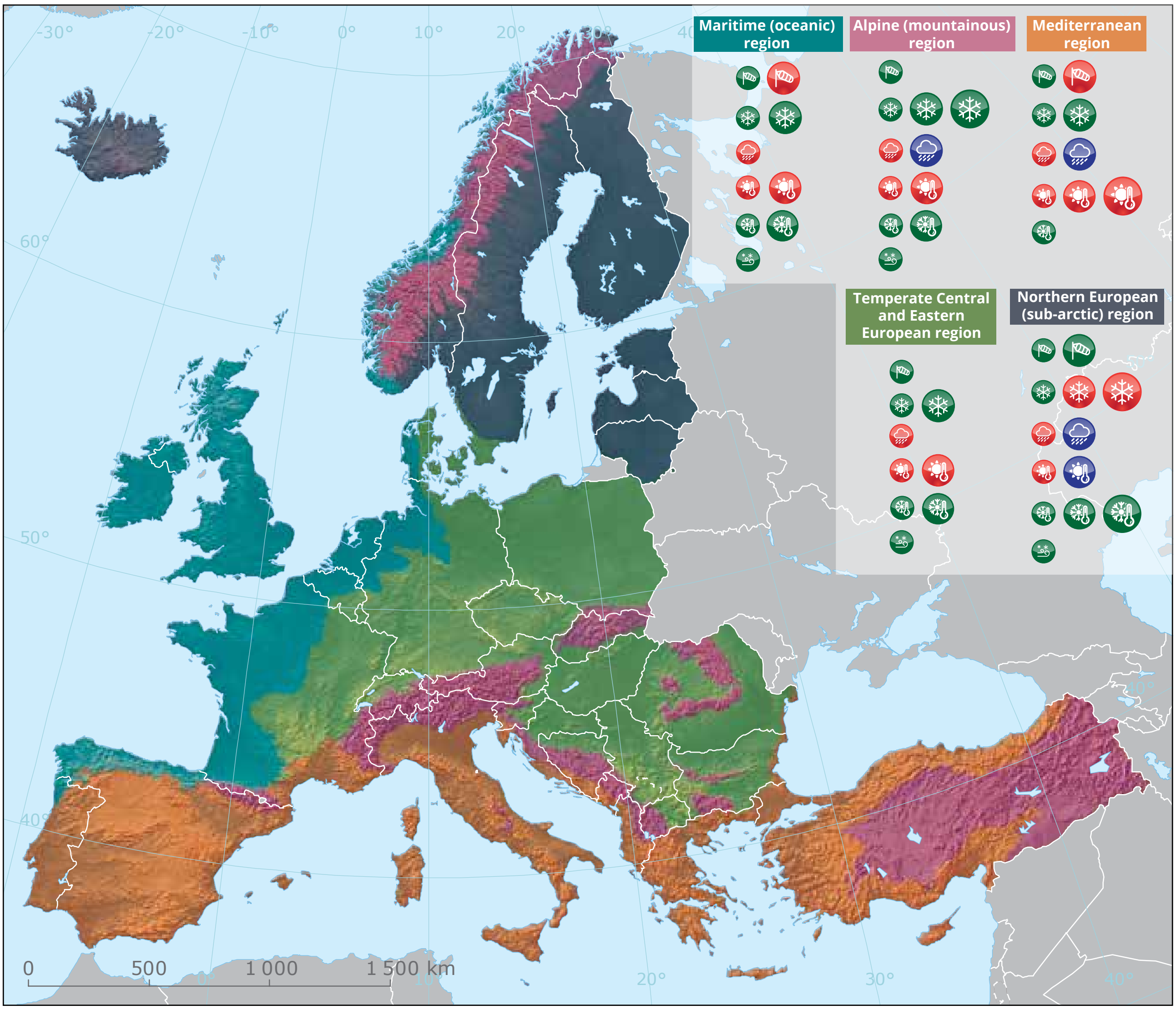
Source: Own compilation based on EC, 2013; Doll et al., 2014, Jaroszweski et al., 2014; Temme et al., 2014; Golikov et al., 2014: Siedl and Schweighofer, 2014; Eurocontrol, 2014) and CEDR, 2011.

Table 5.8 Most harmful extreme weather phenomena and their threshold values

Phenomenon	1st threshold: harmful impacts are possible, 0.33	2nd threshold: harmful impacts are likely, 0.66	3rd threshold: harmful impacts are certain, 0.99
Wind (gust speed)	≥ 17 m/s	≥ 25 m/s	≥ 32 m/s
Snowfall	≥ 1 cm/day	≥ 10 cm/day	≥ 20 cm/day
Rain	≥ 30 mm/day	≥ 100 mm/day	≥ 150 mm/day
Cold (mean temperature of the day)	< 0 °C	< – 7 °C	< – 20 °C
Heat (mean temperature of the day)	≥ + 25 °C	≥ + 32 °C	≥ + 43 °C
Blizzard	A blizzard is considered to occur when the threshold values of wind, snowfall and cold are realised simultaneously		

Source: Leviäkangas and Saarikivi, 2012.

Map 5.20 **Projected changes in the frequency of adverse weather events relevant for transport across Europe**



Projected changes in the frequency of adverse weather events relevant for transport across Europe

Expected mean changes by the 2050s

- Increasing
- Decreasing
- No trend

Ranking

- 1st threshold
- 2nd threshold
- 3rd threshold

Phenomena

- Wind
- Heavy precipitation
- Heat waves
- Cold spells
- Snow
- Blizzards

Source: Adapted from Leviäkangas and Saarikivi, 2012. Reproduced with permission.

5.5.3 *Road transport*

The WEATHER project noted that regional climate models projecting the future cannot reproduce all weather events with the same accuracy, and results partially disagree between the models. Purely temperature-related phenomena (heat waves and cold spells) can be reproduced fairly well, while dynamic phenomena (wind and precipitation) are more challenging. Small-scale phenomena such as thunderstorms, blizzards and fog cannot be fully resolved by current models; thus, changes in these phenomena have to be retrieved using indirect methods, implying additional uncertainties. The impacts listed in Table 5.7 refer to direct, weather-induced consequences, which in turn have the potential to cause delays, increased accident rates and temporary road closures (Enei et al., 2011; Doll et al., 2014).

The WEATHER project estimated the costs of weather events for road transport to be roughly EUR 1.8 billion annually for 2000–2010. Infrastructure costs account for 53 % of those costs, followed by time costs (16 %) and health and life (accident-related) costs (13 %). Costs would increase by 7 % by 2040–2050, mainly driven by higher infrastructure costs; in fact, the other components, related to users' costs and services, would decrease. This increase would not be homogeneous across Europe: the highest increases were estimated for France (72 %) and Scandinavia (22 %) (Enei et al., 2011).

The EWENT project provides different results. EWENT takes into account different patterns in the growth of road transport for passengers and freight, the former growing significantly less than the latter. Weather-related costs in road transport for the reference year (2010) were estimated to be EUR 18 billion; in 2040–2070 road accident costs would be reduced by EUR 4 billion, whereas freight-related costs would increase by EUR 6 billion (Nokkala et al., 2012).

Relevant research activities to support adaptation planning are also occurring at the national level, for example the programme 'Adaptation of road infrastructure to climate change' (AdSVIS) ([110]) in Germany.

5.5.4 *Rail transport*

Rail transport has been identified as particularly vulnerable to changes in climate as a result of the relative complexity of its different sub-systems (infrastructure, energy, communications and signalisation) and their exposure to weather conditions (Nolte et al., 2011). The main threats of climate change to rail transport are higher temperatures and extreme weather events such as floods and storms. The effects of these events are an increased risk of rail buckling, instability of embankments and damage to bridges (Altvater et al., 2011). As the climate warms, milder winter conditions are likely to improve the safety record for railways in some regions.

Annual average costs of extreme weather impacts on rail transport for the reference year (2010) have been estimated by the WEATHER project to be around EUR 0.3 billion, distributed among vehicles (41 %), infrastructure (34 %) and users' costs (25 %). A significant increase of these annual costs (72 %) would be expected by 2040–2050, affecting mainly those regions with a combination of dense networks and particular exposure to higher temperatures and precipitations, such as France (187 %), the British Isles (151 %) and Scandinavia (101 %). It is worth noting that, in spite of this significant relative growth, the absolute values remain modest compared with the total turnover of the rail sector (Przyluski et al., 2011).

The EWENT project reported low economic impacts in 2040–2070 compared with 2010: an increase of EUR 100 million per year in accident costs and EUR 17 million per year on freight and logistics costs, mainly as a result of the effects of extreme weather on the significantly increasing levels of traffic (Nokkala et al., 2012).

5.5.5 *Air transport*

Although aviation already deals with disruptive weather on a regular basis, it will be affected by both future changes in extreme weather events and changes in average climatic conditions such as temperature. The vulnerability of aviation to extreme events will further increase because free capacity, which is currently used to absorb the impact of weather events, will increasingly be occupied by additional flights (McCallum et al., 2013). Sea level rise and flooding could affect airports located in coastal areas across Europe, and increased extreme weather events (mainly increased wind and storms) would mainly affect northern, eastern, western and central Europe and would have operational impacts such as loss of capacity and increased delays (Eurocontrol, 2013). Climate change can also affect the demand for air transport, e.g. if tourists change their destination choice because

([110]) http://adsvis.de/index.php?lang=en.

of climatic changes (see Section 5.6). These conclusions are largely consistent with those provided by the research project MOWE-IT (Temme et al., 2014).

A number of European airports have conducted site-specific vulnerability assessments. For example, London Heathrow Airport conducted a risk assessment in 2011 (HAL, 2011). The review identified a small number of climate risks, related primarily to the need to continue to upgrade the airport's surface water capacity and flood mitigation, as well as reviewing and upgrading the building performance standards. The assessment for Copenhagen Airport found that flooding due to an increase in extreme precipitation patterns would be the most significant threat. Rising sea level was not seen as an important issue for the foreseeable future, despite the coastal location of the airport (Klimatilspassning, 2014). The French airport administration conducted a pilot vulnerability study for Nice Côte d'Azur Airport (DGAC/STAC, 2013), identifying the need for increased protection from storm surges and sea level rise in the future. Some climate risks, such as inundation of ground transport links or loss of utility supply, may not be directly under the control of the organisation (e.g. airports).

A brief overview of climate change risks and adaptation activities at European airports is available in the first European Aviation Environmental Report (EASA et al., 2016, Chapter 7).

5.5.6 Water-borne transport

The ECCONET project assessed the impact of climate change on inland waterway transport as well as possible adaptation measures. The project uses the Rhine-Main-Danube corridor as a case study, with special emphasis on low water situations. Results based on projections from different climate models show no significant effects on low flow conditions for the Rhine and the Rhine–Main–Danube canal until 2050. The upper Danube would experience a moderate increase in low flow conditions. The trend towards drier summers and wetter winters will gain in importance towards the end of the 21st century. Disposition for ice formation on both the Rhine and the Danube will most likely decrease over the whole 21st century (Nilson et al., 2012).

Simulations with the NODUS transport model suggest that projected climate change until 2050 is unlikely to have a sufficient impact on the hydrology of the Rhine to induce a significant shift in modal shares. The study estimates that a 'dry' year leads to approximately a 6–7 % increase in total transport cost compared with a 'wet' year, but these variations are already present under the current climate conditions and will not be influenced heavily by climate change until the 2050s (Bruinsma et al., 2012; Beuthe et al., 2014). Low water levels could also trigger further effects due to interruptions of the coal supply to power stations (Rothstein and Halbig, 2010).

The results from other research projects are consistent with the findings of ECCONET. The German research programme KLIWAS ([111]) did not identify distinctive challenges or restrictions for shipping in inland waterways or in shipping and waterway infrastructure in coastal areas (Moser et al., 2012). The MOWE-IT project concluded that inland waterway transport is expected to remain a reliable and cost-effective mode of transport (Siedl and Schweighofer, 2014).

Water-borne transport is particularly sensitive to river droughts and changes in the ice cover of oceans and inland waters. In the Arctic, the decline in sea ice could open up new transport lanes (see Section 3.3.2). However, the benefits to the regional and global economy would be modest at best: the trade potential of Arctic transport between Europe and Asia would remain rather limited in 2050, at values between 1 to 2.5 million twenty-foot equivalent containers or around 300–900 transits per year. While this represents a small improvement for the global transport of containerised goods, it does not justify any delay in the environmental actions necessary to protect the Arctic's fragile environment (EC, 2012; Perrels et al., 2015).

The seaport community has also been interested in gaining a better understanding of the potential impacts of climate change. Changes in sea level and storm intensity, combined with changes in ice conditions in polar regions, will require responses related to maritime navigation infrastructure and operations (PIANC, 2008). However, this understanding has not resulted in widespread vulnerability studies. A global survey conducted in 2009 among port authorities around the world showed that sea level rise was the key concern for most of them, and that the majority (63 %) of the respondents were discussing climate change-related issues internally, although mainly at an informal level and infrequently (Becker et al., 2011).

There is scarce evidence of vulnerability assessments conducted by seaport authorities thus far. One recent example is the vulnerability study for the port of Rotterdam, as a part of the vulnerability

([111]) Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt — Entwicklung von Anpassungsoptionen (http://www.kliwas.de).

report conducted for the whole metropolitan region (Rotterdam Climate Initiative, 2009). In the recent expansion of the port of Rotterdam (the first and second Tweede Maasvlaktes), higher water levels have been taken into account in the design of the harbour and its main access roads (Vellinga and Jong, 2012). Another example is the city of Hamburg, were an adaptation strategy is in place to, among other things, protect the harbour (Hamburg, 2013). The research project MOWE-IT included a review of operations in the case of extreme weather events in the ports of Limassol (Cyprus) and Southampton (UK) and the National Grid Grain LNG terminal in London (Golikov et al., 2014).

5.6 Tourism

Key messages

- Climatic suitability for general tourism activities is currently best in southern Europe. The most favourable regions for general tourism are projected to shift northwards as a result of climate change. The touristic attractiveness in northern and central Europe is projected to increase in most seasons. The suitability of southern Europe for tourism will decline markedly during the key summer months but improve in other seasons.
- The widespread reductions in snow cover projected over the 21st century will negatively affect the winter sports industry in many regions. Regions close to the low elevation limit for winter sport will be the most sensitive to the projected warming. Winter sport locations on southern slopes of the Alps are, on average, more vulnerable than those on the northern slopes.
- The projected climatic changes are expected to shift the major flows of tourism in Europe and can have substantial consequences for regions where tourism is an important economic sector. The magnitude of the economic impacts is strongly determined by non-climatic factors, such as the ability of tourists to adjust the timing of their holidays.

5.6.1 Overview

The Mediterranean region is the world's most popular holiday destination. Its European shores attract some 120 million visitors from northern Europe each year, the largest international flow of tourists on the globe (Amelung and Moreno, 2009). Spain, France and Italy are the top three EU destinations for outbound trips made by EU residents in terms of nights spent, with, respectively, 20.5 %, 13 % and 12 % of outbound trips in 2013 (Eurostat, 2015b). The European tourism industry accounts for approximately 5 % of the total workforce in Europe and generates more than 5 % of EU GDP, and this figure has been steadily rising (ECORYS, 2009). International tourism is estimated to contribute about 10 % to both GDP and employment in countries around the Mediterranean Sea. In popular tourist regions in France, Greece, Italy, Portugal and Spain, the proportion that tourism is contributing to both GDP and employment is far above these values (Magnan et al., 2012).

In Europe, tourism shows a strong seasonality, with the main peak in the summer season (June–September) and generally low levels of activity in the rest of the winter season (October–March), except for a short peak around Christmas, and somewhat higher levels in the spring season (April–May) (Eurostat, 2015a). Climate is an important resource for many types of summer and winter tourism, and it is a key factor in the place of origin of tourists and their destination. There are large regional differences within Europe and among seasons in the attractiveness of tourism (Eurostat, 2015c). At present, the predominant tourist flows in summer are from north to south, in particular to the coastal zone.

For economy of space, this section focuses on 'summer and beach tourism' on the one hand and 'winter and mountain tourism' on the other hand. The latter comprises tourism related to winter sport activity, but also tourism taking place in the same locations as winter sport activities, but irrespective of the season, such as summer mountain tourism. The distinction between the various kinds of tourism that are potentially affected by climate change could of course be richer and more nuanced depending, among other things, on location and season.

Climate change mitigation could also affect the tourist sector through increases in fuel costs, which would influence destination choices, travel modes, length of stay, etc. (Gössling et al., 2010). These considerations are not explored further here, given the thematic focus of this report. Furthermore, adaptation options are not extensively discussed here, but a recent assessment at the European level is available from the ToPDAd project ([112]) (ToPDAd, 2015). None of the information in this section is presented as an EEA indicator.

([112]) http://www.topdad.eu.

5.6.2 Summer and beach tourism

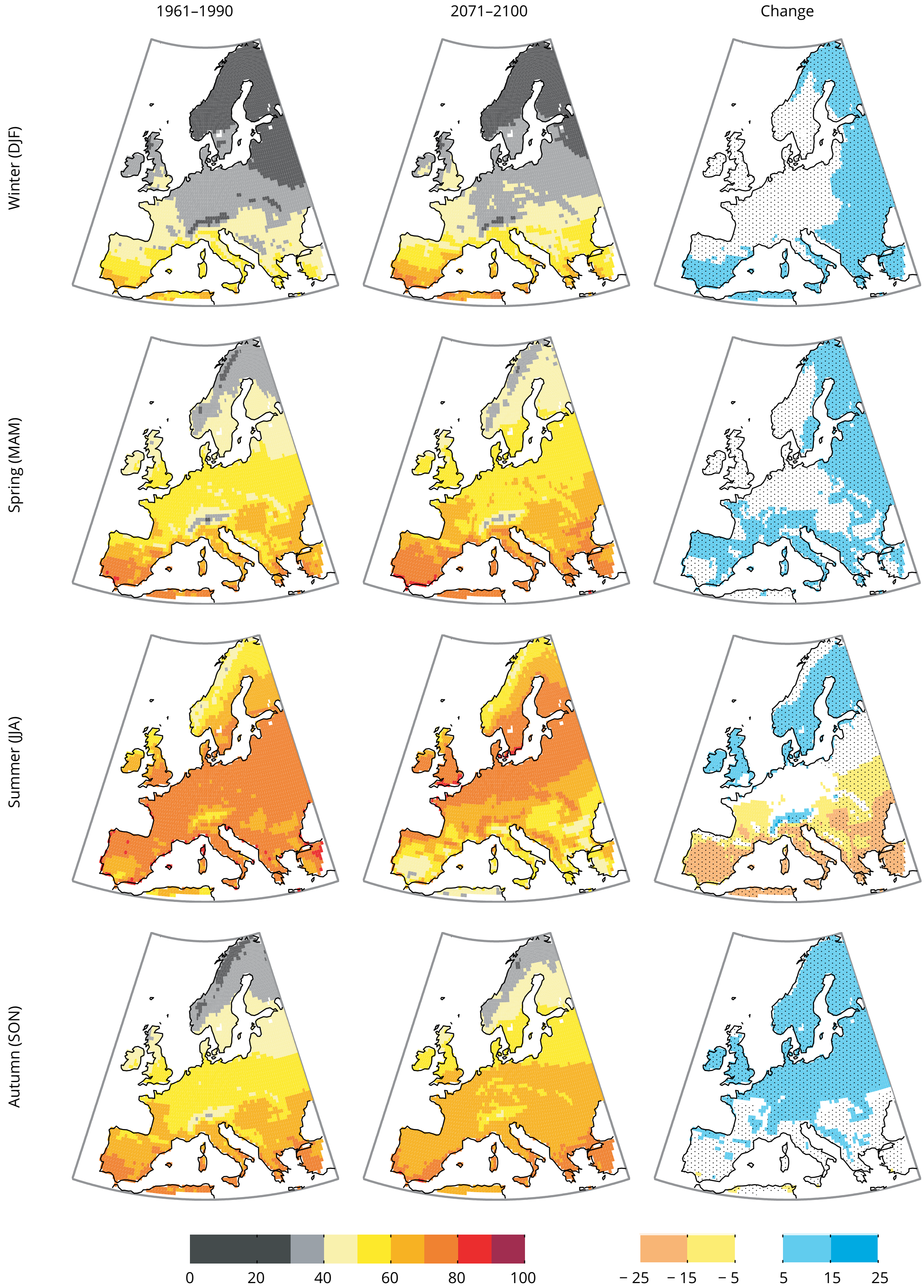
A growing number of studies have assessed the likely impacts of climate change on summer and beach tourism in Europe. Some of these studies have used the tourism climate index (TCI), which is a composite measure for systematically assessing the climatic elements that are most relevant to the quality of the tourism experience for the 'average' summer tourist (Amelung and Moreno, 2009, 2011; Ciscar et al., 2009; Perch-Nielsen et al., 2010; Nicholls and Amelung, 2015). The TCI uses a weighted aggregate of several climate variables (i.e. maximum and mean daily temperature, humidity, precipitation, sunshine and wind) to assess human comfort for general outdoor activities (Mieczkowski, 1985). The TCI has been criticised because of the intrinsic subjectivity of the weighting and the rating of the components of the index (de Freitas et al., 2008); however, it has been partly validated for the Mediterranean countries within the PESETA study (Amelung and Moreno, 2011).

Map 5.21 compares the TCI for baseline and projected future climate conditions in Europe in all seasons. According to these maps, climate resources in the reference period are generally best in southern Europe (left column). Over the 21st century, climate change is projected to shift the latitudinal band of favourable climate northwards, thereby improving climate resources in northern and central Europe in most seasons (central column). Southern Europe's tourism suitability drops strikingly in the summer holiday months; this drop is partially compensated for by improvements in other seasons (right column). Further detailed analysis of the change in the number of acceptable, good and excellent days per month for eight European regions is available in the original study (Perch-Nielsen et al., 2010).

Several recent studies have used econometric approaches and economic modelling approaches to identify the economic impacts of climate change on tourism under different assumptions for adaptation (Barrios and Ibañez Rivas, 2013; Ciscar et al., 2014; Rosselló and Santana-Gallego, 2014; Perrels et al., 2015). Despite somewhat different approaches, all of the available studies come to broadly similar conclusions (Rosselló-Nadal, 2014). Conditions for beach tourism averaged across Europe are expected to improve, as mean temperatures will rise. The beach season will be prolonged, into spring and autumn, in southern regions. Competition between beach destinations in Europe will increase, as climate conditions at the Atlantic and northern European coasts improve, while summer temperatures in some Mediterranean destinations may become too hot in the summer holiday months, leading to a loss of overnight stays. However, the Mediterranean region is expected to remain by far the most popular beach destination (Perrels et al., 2015). In summary, domestic tourism and tourist arrivals at locations in northern and parts of continental Europe may be enhanced at the expense of southern locations, in particular after 2050 (Kovats et al., 2014). The economic impacts of these changes depend largely on whether tourists will predominantly adapt by changing their destination or by changing their timing of travel. In particular, a widespread holiday shift to shoulder seasons would result in reduced gains for northern destinations and lower losses for southern destinations (Ciscar et al., 2014).

The European tourism industry is also highly sensitive to the economic situation in Europe and globally, as well as to demographic change. Furthermore, tourism may compete with agriculture or other sectors for land and water resources, which in turn may be affected by climate change. These interactions are increasingly studied at a regional and national level (in particular in Spain), but they are too complex for systematic inclusion in European-level assessments. Studies considering the direct impact on tourism, together with other climate change impacts, have identified potentially more severe, but also less predictable, impacts.

Map 5.21 Projected changes in the tourism climatic index for the four seasons



Note: The figure shows the tourism climate index for four seasons in the present period (1961–1990, left) and under future climate change (2071–2100, middle), and the change between the present and future periods (right). Future climate conditions are based on the SRES A2 scenario and derived from the ensemble mean of five RCMs that participated in the PRUDENCE project.

Source: Perch-Nielsen et al., 2010. © 2010 Springer Science+Business Media. Reproduced with permission.

5.6.3 Winter and mountain tourism

The winter sports industry across Europe attracts millions of tourists each year, generating nearly EUR 50 billion in annual turnover. The main winter sport destination in Europe is the Alps, where 69 % of Alpine ski areas in Germany, 87 % in Austria, 93 % in Italy and 97 % in France and Switzerland can be considered as naturally snow reliable under the present climate (Agrawala, 2007). However, warm winters have already affected Alpine winter tourism. For example, in the record warm winter of 2006/2007, some low-altitude ski areas in Austria were not able to offer a continuous skiing season from December to April, despite being equipped with artificial snow-making (Steiger, 2011).

The widespread reductions in snow cover projected over the 21st century will affect snow reliability and consequently the length of the ski season (see Section 3.3.5). Substantial reductions in naturally snow-reliable ski areas have been projected for the Alps, the Pyrenees, the Black Forest region in Germany, and Sweden (Agrawala, 2007; Moen and Fredman, 2007; Endler and Matzarakis, 2011; Steiger and Stötter, 2013; Steger et al., 2013; Pons et al., 2015). Low-lying ski areas are the most sensitive ski areas to climate change. Studies have estimated that an increase in mean temperatures of 1 °C will reduce the skiing season by four to six weeks in low-lying regions in the Alps, primarily as a result of earlier spring melting (Hantel et al., 2000; Beniston et al., 2003). An analysis for Switzerland estimates that the altitude limit above which a region is considered 50 % snow reliable will increase from 1 400 m in the 2000s to 2 200 m in the 2080s under a medium emissions scenario (SRES A1B) (Steger et al., 2013). Overall, conditions for winter tourism are expected to worsen in winter owing to reduced snow reliability, with winter sport activities being negatively affected before 2050, particularly at low altitudes and in the presence of limited adaptation options. On the other hand, traditional winter sport areas may become more attractive for tourist activities in summer.

Artificial snow-making is the main technical adaptation option for winter tourism destinations. Its cover has increased significantly in recent years, for example from less than 10 % of the total ski area in Switzerland in 2000 to 36 % in 2010 (Rixen et al., 2011). However, there are both environmental and economic constraints to an expansion of artificial snow-making, which can offer only limited and increasingly expensive protection from climate change impacts (Steiger and Stötter, 2013; Damm et al., 2014; Kovats et al., 2014). Investments in alternative activities during winter or all-year-round tourism may partly compensate for the loss in overnight stays, depending on the attractiveness of the location for non-winter sport tourism.

The economic impact of the worsening snow reliability projected for most European ski resorts depends strongly on tourists' adaptation choices. When tourists stick to skiing but change the month (within the winter season) in which they go and/or the destination, this will affect the competition between skiing areas, with the southern part of the Alps (e.g. in France and Italy) losing overnight stays and the comparatively snow-reliable northern parts of the Alps and Scandinavia benefitting from climate change. If tourists change their holiday type, all skiing areas face a reduction in overnight stays (Perrels et al., 2015).

Socio-economic and demographic changes can also be important factors for future winter sport tourism. One study on the Austrian Alps concluded that declining and/or ageing populations in source countries are a more immediate threat than climate change to winter tourism in the first half of the 21st century, after which the effect of rising temperatures will dominate (Steiger, 2012).

Some winter tourism, in particular in Nordic regions, depends on a snowy landscape, despite not necessarily being related to winter sport activities. Hence, Nordic tourism can be threatened by the loss of reliable snow cover in winter and the related damage to the general perceptions of the northern landscape as a snow-covered backdrop of outdoor and traditional activities, even outside winter sport resorts (Tervo-Kankare et al., 2013; Kaján, 2014).

6 Multi-sectoral vulnerability and risks

The degree to which regions, sectors, population groups and infrastructure in Europe are affected by a changing climate is determined by a complex interplay between climatic and non-climatic factors, as well as by multiple interdependencies and feedback loops across climate-sensitive sectors. The objective of this chapter is to synthesise available information on climate change vulnerabilities and risks in Europe from an integrated perspective. Note that the terms 'vulnerability' and 'risk' are used differently by various scientific communities, practitioners and decision-makers. This requires that care be taken in interpreting and comparing results from different (quantitative) studies using these terms. For a more detailed discussion, see Section 1.4.

'Integration' in this chapter refers, first, to the assessment of vulnerabilities and risks arising from the interaction between changing physical characteristics of the climate system and evolving characteristics of socio-economic systems; such studies have been becoming increasingly common. Second, integration refers to the assessment of climate change impacts on different sectors and systems with a consistent methodology. Third, integration refers to the assessment of the effects that climate change impacts on one sector have on other sectors. Within this framing, the chapter is structured based on different geographical scales: pan-European, European cross-border regions, European macro-regions and urban regions. This structure enables regional differences or commonalities with respect to climate-related risks and vulnerabilities to be identified that are not captured explicitly in other chapters of the report.

Section 6.1 summarises the available information on scenarios for selected non-climatic (in particular socio-economic) factors that are relevant for determining current and future climate change vulnerabilities and risks across Europe. These scenarios complement the global scenarios presented in Section 1.2. Section 6.2 synthesises information from various Europe-wide climate change impact, vulnerability and risk assessments that are consistent in approach and methodology across multiple sectors or systems. This allows for the identification of geographic regions of compound risk in Europe — 'hotspots' — that might be regarded as particularly susceptible to a changing climate. Note that Section 4.5 presents estimates of climate-related changes in ecosystems services, but the results presented here (i.e. in Chapter 6) also consider the coping capacity of socio-economic sectors. Section 6.3 provides an assessment of the economic impacts of climate change across multiple sectors and the wider economy. Section 6.4 provides an overview of cross-border (spill-over) effects of climate change, i.e. climate change impacts occurring outside the European territory that could affect Europe. Section 6.5 summarises climate change risks and vulnerabilities in selected transnational macro-regions that have similar biogeographical characteristics. Finally, Section 6.6 summarises vulnerabilities that are particular to urban regions.

The information presented in this chapter is relevant for European adaptation policy for various reasons, such as its integrative perspective combining both climatic and non-climatic factors and different sectors and systems, and the fact that it considers multiple geographical scales. However, the content is not suitable to be presented as EEA indicators for various reasons, such as the limited availability of observed data, uncertainty about the continuity of project-specific information, information being presented as relative (unitless) values and the availability of information for certain geographical regions only.

6.1 Socio-economic scenarios for Europe

Key messages

- Population size in eastern Europe is projected to decrease considerable during the 21st century, with declines of up to 50 % in some countries and scenarios. Population projections for western Europe vary across scenarios and individual countries. For western Europe as a whole, some scenarios project slight increases in population size until the middle of the century, followed by a decline thereafter, and still others assume a continuous decline throughout the 21st century.
- Ageing of the population is projected to rise substantially in both western and eastern Europe. Total fertility rates are projected to stay below the natural replacement rate.
- Urbanisation is projected to further increase throughout all scenarios. The difference between scenarios in the proportion of the population made up of urban populations is much larger in eastern than in western Europe, where the urban population is expected to increase to more than 90 % of the population in most countries.
- Some economic growth is projected under all scenarios, but the magnitude of growth varies strongly between the scenarios, particularly in western Europe. Available projections suggest that the current substantial gap in GDP per capita between eastern and western Europe is expected to be significantly reduced throughout the century, but not to vanish completely.
- Estimates of trends in adaptive capacity suggest increasing capacities to cope with the consequences of climate change. However, the current pattern of higher capacity in central and north-western Europe and lower capacity in southern and in particular (some of) eastern Europe is expected to prevail to some degree

Non-climatic factors and trends have a significant (and often even dominant) role in shaping the exposure and vulnerabilities of regions, sectors and people, thus contributing to changes in overall climate-related risks. Recent European studies show this for several sectors, such as water, agriculture and forestry (Audsley et al., 2014; Wimmer et al., 2014). For notational convenience, the following text refers to the range of non-climatic developments as 'socio-economic developments'. This section provides information on how these non-climatic factors might change in Europe during the 21st century, thereby complementing the global scenarios presented in Section 1.2.

This section is structured based on two dimensions. First, it summarises projections of key socio-economic variables for the five SSPs (for details see Section 1.2, distinguishing between western and eastern Europe and using additional information from recent assessments by the European Commission (EC, 2014b; EEA, 2015). The second dimension summarises results from studies that attempt to capture the role of different non-climatic factors by combining them into one metric of adaptive capacity (or coping capacity). Estimates of adaptive capacity also include projections, where available.

The use of different scenarios across impact and vulnerability assessments makes comparisons challenging. From a European vulnerability assessment perspective, particularly relevant sets of scenarios are the IPCC SRES scenarios, the SSP scenarios, and four socio-economic scenarios from the CLIMSAVE project that have been developed jointly by the project and stakeholders in a participatory approach (Dunford et al., 2015; Kok, Bärlund, et al., 2015). The SSP, SRES and CLIMSAVE scenarios do not fully match one another, but may be compared to some extent (see Table 6.1).

For example, the SSP3, SRES-A2 and CLIMSAVE 'Icarus' scenarios all assume increasing international fragmentation, characterised by increasing antagonism between countries and within regional blocs, weak international cooperation and governance, low economic and technological development, low social cohesion, low environmental respect, and high carbon intensity. Likewise, the SSP2 and SRES-A1B scenarios share a certain degree of common 'middle of the road' assumptions (i.e. a development where future trends reflect patterns of change from the past decades, while CLIMSAVE has not developed such a scenario). This means that the vulnerability assessments in Section 6.2 that are based on these two scenarios (SSP2 and SRES-A1B) are to some extent directly comparable with respect to their underlying assumptions about future socio-economic conditions.

Table 6.1 Comparison of SSP, SRES and CLIMSAVE scenarios

SSP	SRES	CLIMSAVE	Archetype	Comment
SSP1	B1/A1T	'We are the world'	Global sustainability	
SSP2	B2/A1B	–	Patterns of historical experience	Match is rather poor
SSP3	A2	'Icarus'	International fragmentation	Very good match
SSP4	A2	'Riders on the storm'	Inequality at all levels	Poor match of SSP4 vs. A2
SSP5	A1FI	'Stay or go'	Market-driven development	Poor match of SSP5/A1FI vs. 'Stay or go'

Source: Adapted from van Vuuren and Carter, 2014; and Kok et al., 2015.

Demographic and economic scenarios

A set of quantitative demographic and economic projections has been developed through a coordinated effort across multiple international modelling teams and they are internally consistent based on the five SSP narratives (Kriegler et al., 2014; O'Neill et al., 2014; van Vuuren et al., 2014; O'Neill et al., 2015). Some relevant elements are summarised below, distinguishing between trends for western and eastern Europe (for a list of countries in both regions, see the note underneath Figure 6.1). In addition, semi-quantitative and qualitative information on potential socio-economic developments in Europe for the different SSPs is available in the form of storylines and trends for a variety of variables from the FP7 projects BASE ([113]) (see Section 6.2) and IMPRESSIONS ([114]) (Kok, Pedde, et al., 2015).

There are also other relevant projections including the World Population Prospects (UNDESA, 2015) and a study from the European Commission (EC, 2014b), which do not follow the SSP logic but provide different projections. The European Commission's study uses a single EUROPOP2013 (European Population Projections, base year 2013) convergence scenario (Eurostat, 2013). It is limited to the EU-28 Member States and to a time horizon until 2060, but its results are largely within the range of the SSP scenario family. Note that relevant socio-economic projections for climate change assessments may also be derived from other Commission sources, such as the CAP context indicators (EC, 2014a).

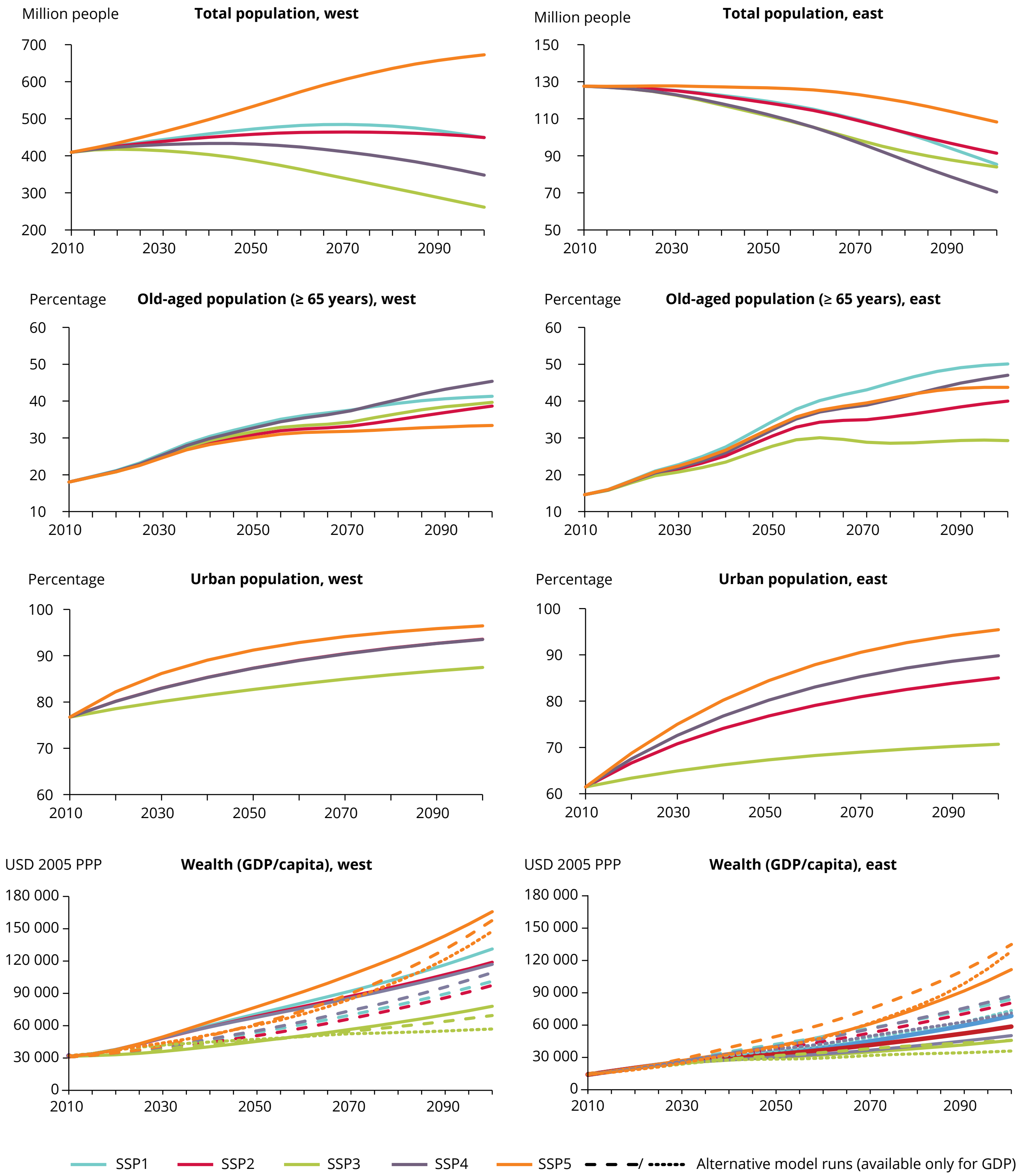
Projections for *population size* for western Europe vary across the five SSPs, ranging from a steady increase from 410 million in 2010 to 670 million in 2100 (SSP5), to significant declines to 350 and 260 million (SSP4 and SSP3, respectively). SSP1 and SSP2 assume initial moderate increases that peak around the middle of the century and decline thereafter. In sharp contrast, the population is projected to decrease for all five SSPs in eastern Europe. The strongest decrease is projected for SSP4, with a drop from 130 million in 2010 to 70 million (about half of its size) in 2100. For Turkey, which currently has about 73 million inhabitants, three SSPs project only slight changes, while SSP2 and SSP3 project significant population increases to 90 or 150 million by 2100, respectively.

According to the European Commission study, the population of the EU-28 is projected to increase slightly from 507 million in 2013 to a peak of about 530 million in 2050, and decline thereafter. Large differences are expected across the EU, with some countries projected to lose more than a quarter of their current population (e.g. Lithuania, Latvia and Bulgaria), while in other countries increases of 25 % or more are expected (e.g. Belgium, Sweden, the United Kingdom). One driver is the *total fertility rate*, which is expected to stay below the natural replacement rate of 2.1 in the coming decades, although rising from 1.59 in 2013 to 1.76 in 2060. Other factors determining population size are *life expectancy* at birth, which is projected to increase from 77.6 years in 2013 to 84.7 in 2060, albeit with substantial variation across Europe, and *net migration*, which is expected to increase further, with the highest levels in countries such as Italy or Germany.

Ageing of the population is projected to increase substantially throughout Europe for all SSPs. For western Europe, the percentage of people aged 65 or older is currently around 18 %, and this proportion is projected to roughly double by 2100 (minimum proportion of older people projected to be 33 % for SSP5; maximum proportion of 45 % for SSP4).

([113]) BASE: 'Bottom-up Climate Adaptation Strategies Towards a Sustainable Europe'.
([114]) IMPRESSIONS: 'Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions'.

Figure 6.1 Projected European trends for key socio-economic factors for the five shared socio-economic pathways



Note: The division between western and eastern Europe was based on the region groupings of the IIASA SSP database (version 1.0). Western Europe comprises the following countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. Eastern Europe comprises the following countries: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, the Czech Republic, Estonia, the former Yugoslav Republic of Macedonia, Hungary, Latvia, Lithuania, Malta, Montenegro, Poland, Romania, Serbia, Slovakia and Slovenia. Turkey was not included in the region 'east', as many of its current and projected socio-economic variables differ significantly from those of the countries included in the region 'east'. Instead, some key numbers for Turkey are provided in the text.

Source: Cuaresma, 2015; Dellink et al., 2015; Jiang and O'Neill, 2015; Samir and Lutz, 2015; Leimbach et al, 2015; data available from the IIASA SSP database (version 1.0).

For eastern Europe, the variation across the SSPs is somewhat larger, and the proportion of older people by 2100 is projected to be between 29 % (SSP3) and 50 % (SSP1). The European Commission study agrees with the ageing development, owing to the dynamics between fertility, life expectancy and migration. The EU-28 old-aged population (65 years and older) is projected to rise from 18 % in 2013 to 28 % in 2060, while the group of people aged 80 years and older is projected to become as numerous as the population aged 0–14 years (both groups projected to be around 12 % of the total population in 2060).

Levels of urbanisation are currently at 77 % in western and 62 % in eastern Europe, and continuous increases are projected for both regions and across all SSPs. Like for the ageing trend, the variation in urbanisation across SSPs is smaller for western Europe, where urbanisation might reach a level of 94 to 96 % in 2100, while urbanisation in eastern Europe depends more on the SSP (ranging from only 71 % for SSP3 to 95 % for SSP5 in 2100). A range very similar to that of eastern Europe is projected for Turkey.

Projections of *economic development* are available from three different models (see Figure 6.1), and similar trends are projected for western and eastern Europe across the five SSPs. All SSPs assume a steady growth in wealth (measured as GDP per capita, adjusted for purchasing power) and a significant reduction in the current gap in GDP per capita between western and eastern Europe. SSP3 assumes the slowest growth throughout the century, whereas SSP5 at the other extreme assumes the strongest increase in wealth, where GDP per capita increases by factors of five (western Europe) and seven (eastern Europe) throughout the 21st century. For Turkey, most scenarios project a similar trend as for eastern Europe, with a significant growth in wealth that converges towards the wealth levels in western Europe. In the European Commission study of the EU-28, the annual average GDP growth rate is projected to remain stable at moderate levels of 1.1 to 1.5 % up to 2060.

Scenarios of adaptive capacity

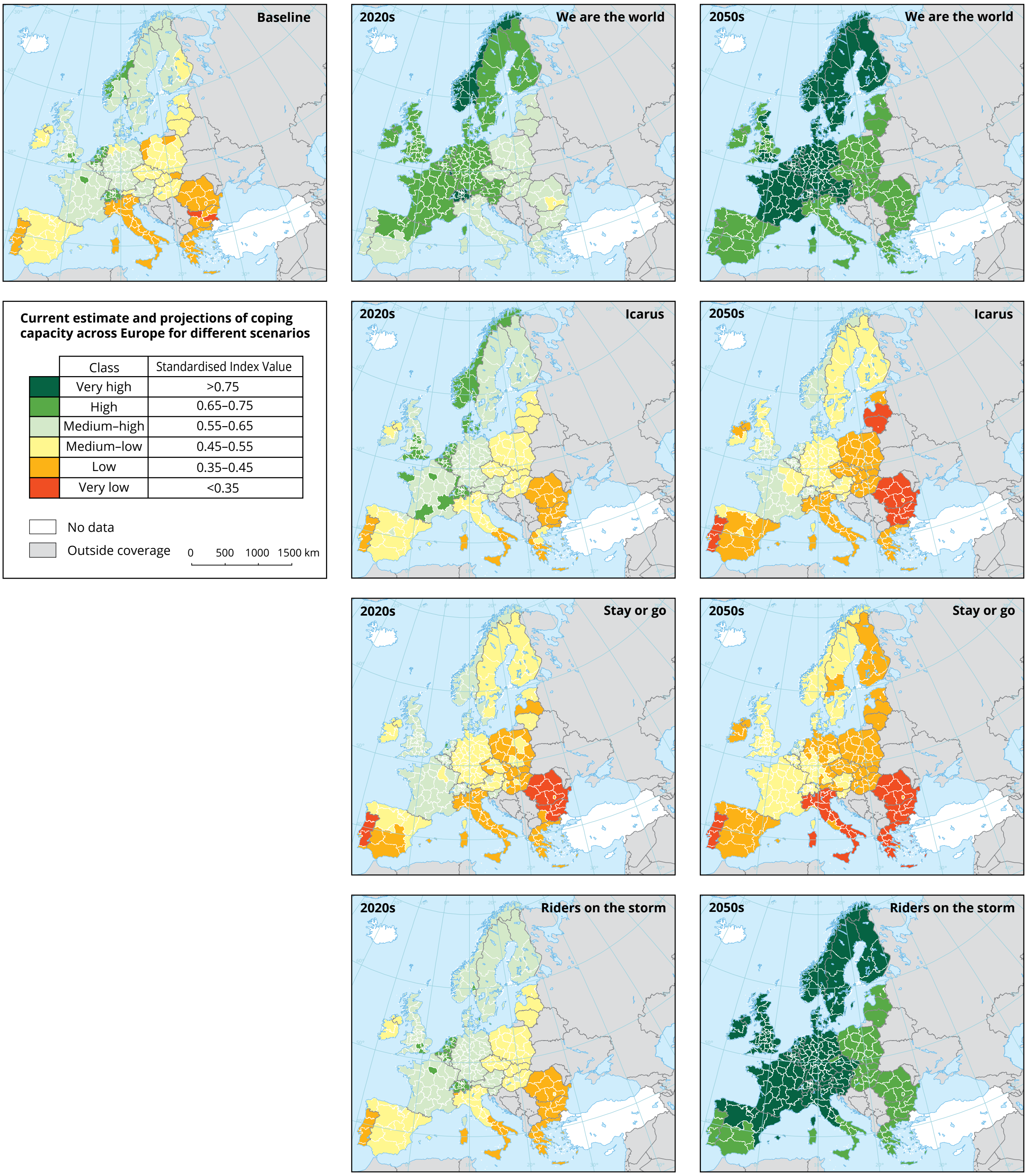
Adaptive capacity is defined in the IPCC AR5 as 'the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences' of climate change (IPCC, 2014, Annex II: Glossary). Some scholars further distinguish between proactive and reactive forms of capacity to adjust, and refer to these two forms as adaptive capacity and *coping capacity*, respectively (Tinch et al., 2015). Regardless of this distinction, the principal idea is to combine the various socio-economic factors that determine the extent to which a sector, society or region is able to deal with the consequences of climate change into an aggregated estimate of overall generic capacity. Indicator-based approaches are often employed to derive quantitative estimates (for their pros and cons, see Section 1.4).

One of the first studies including scenarios on the potential future development of adaptive capacity across European regions used a composite indicator of generic adaptive capacity based on six determining factors: 'equity', 'knowledge', 'technology', 'infrastructure', flexibility' and 'economic power' (the ATEAM ([115]) project) (Acosta et al., 2013). Its spatial coverage was limited to 15 European countries. Recent work from the CLIMSAVE project has supplemented the ATEAM approach by constructing a generic indicator of coping capacity at the pan-European scale based on four capitals: 'human capital', 'social capital', 'manufactured capital' and 'financial capital' (Dunford et al., 2015; Tinch et al., 2015). Each capital is represented by two indicators (e.g. 'life expectancy' and 'tertiary education' as proxies for estimating human capital). The results for the current situation show that the highest coping capacities are in north-western Europe and Switzerland, while many regions in eastern and southern Europe show low or very low coping capacity (see Map 6.1).

The CLIMSAVE coping capacity indicator (based on the four capitals, see previous paragraph) has also been projected into the future, based on four socio-economic scenarios (see Table 6.1). For each of the four scenarios, the direction and magnitude of change for the four capitals of the coping capacity indicator were quantified, together with stakeholders. The results from this exercise show that overall coping capacity is assumed to either improve or deteriorate substantially towards the 2020s and even further towards the 2050s, depending on the scenario. However, the currently prevailing spatial distribution across Europe of a higher capacity in central and north-western Europe and a lower capacity in southern and in particular in (some of) eastern Europe is projected to prevail across all scenarios (see Map 6.1). These general trends and patterns do not give information about particular threats and specific local contexts, and should therefore be used in conjunction with hazard-, sector- and location-specific information.

([115]) ATEAM: 'Advanced Terrestrial Ecosystem Analysis and Modelling'.

Map 6.1 **Current estimation of and projected changes in coping capacity across Europe**



Note: The vulnerability index developed by the European Observation Network for Territorial Development and Cohesion (ESPON) Climate project (ESPON Climate, 2011) and presented in the previous version of this report (EEA, 2012) shows a pattern similar to that of the 'Icarus' scenario.

Source: Adapted from Dunford et al. 2015. © 2014 Authors. This article is published with open access at Springerlink.com.

6.2 Multi-sectoral impacts and vulnerabilities across Europe

Key messages

- The degree to which European regions are vulnerable to climate change is determined by the vulnerability of multiple sectors, and by interdependencies and feedback loops across these sectors. In particular, the water, agriculture, forestry and biodiversity sectors show strong interdependencies with each other and with non-climatic developments, such as changing land-use patterns and population change. These interactions require careful attention with respect to climate adaptation policy development.
- Projections of the spatial distribution of climate change impacts and vulnerabilities across multiple sectors suggest that south-eastern Europe, Italy and France will be hotspot regions with the highest number of sectors severely affected. An assessment with a focus on ecosystem services identifies the same spatial hotspots in south-eastern Europe, but indicates the Alps and the Iberian Peninsula as additional hotspots.
- An assessment that explicitly distinguishes between seven climate hazards, including droughts, fires and sea level rise, identifies southern Europe, but also coastal areas and floodplains in the western parts of Europe, as multi-sectoral hotspots.
- The overall conclusion from available studies of multi-sectoral impacts and vulnerabilities is that the greatest challenges appear to be concentrated in the south-eastern and southern parts of Europe.
- Opportunities for technological and social innovations are greater for scenarios assuming well-functioning governance and international cooperation.

6.2.1 Introduction

In order to facilitate informed policy decision-making about adaptation strategies, it is necessary to understand and quantify how climate change impacts and vulnerabilities in different sectors overlap and interact, and how this might alter climate adaptation pressure. Integrated assessments of climate change vulnerability and risk that are systematic and consistent in approach and methodology are a means to address this need. They provide a more holistic and comprehensive understanding of interdependencies, potential synergies and trade-offs between sectors in a changing climate, thus facilitating the exploration of adaptation options to reduce associated vulnerabilities in Europe.

This section summarises information available from recent integrated assessments covering multiple sectors with a pan-European spatial coverage: the IMPACT2C ([116]) project (IMPACT2C project, 2015), the FP7 CLIMSAVE project (Harrison et al., 2015), a multi-hazard climate risk assessment supported by the FP7 ENHANCE project (Forzieri et al., 2016) and a storyline-based synthesis by the FP7 BASE project (BASE project, 2016). Studies at national or regional level also exist, here illustrated with a study for Germany.

Some earlier integrated assessments of climate change vulnerability and risk across Europe are not included here. The ESPON Climate project (ESPON Climate, 2011) provided one of the first comprehensive pan-European multi-sectoral assessments of vulnerability, which was extensively reported in the previous version of this report (EEA, 2012, Section 5.3). The RESPONSES ([117]) project conducted a quantitative multi-hazard vulnerability assessment for several weather hazards across Europe: heat stress, river floods and forest fires (Lung et al., 2013). This assessment considered the combined effects of climatic and non-climatic factors, such as adaptive capacity. The multi-hazard assessment also allowed vulnerability hotspots to be identified. Owing to space limitations, we focus in this section on the more recent results from the above-mentioned projects.

([116]) IMPACT2C: 'Quantifying projected impacts under 2°C warming'.
([117]) RESPONSES: 'European responses to climate change: deep emissions reductions and mainstreaming of mitigation and adaptation'.

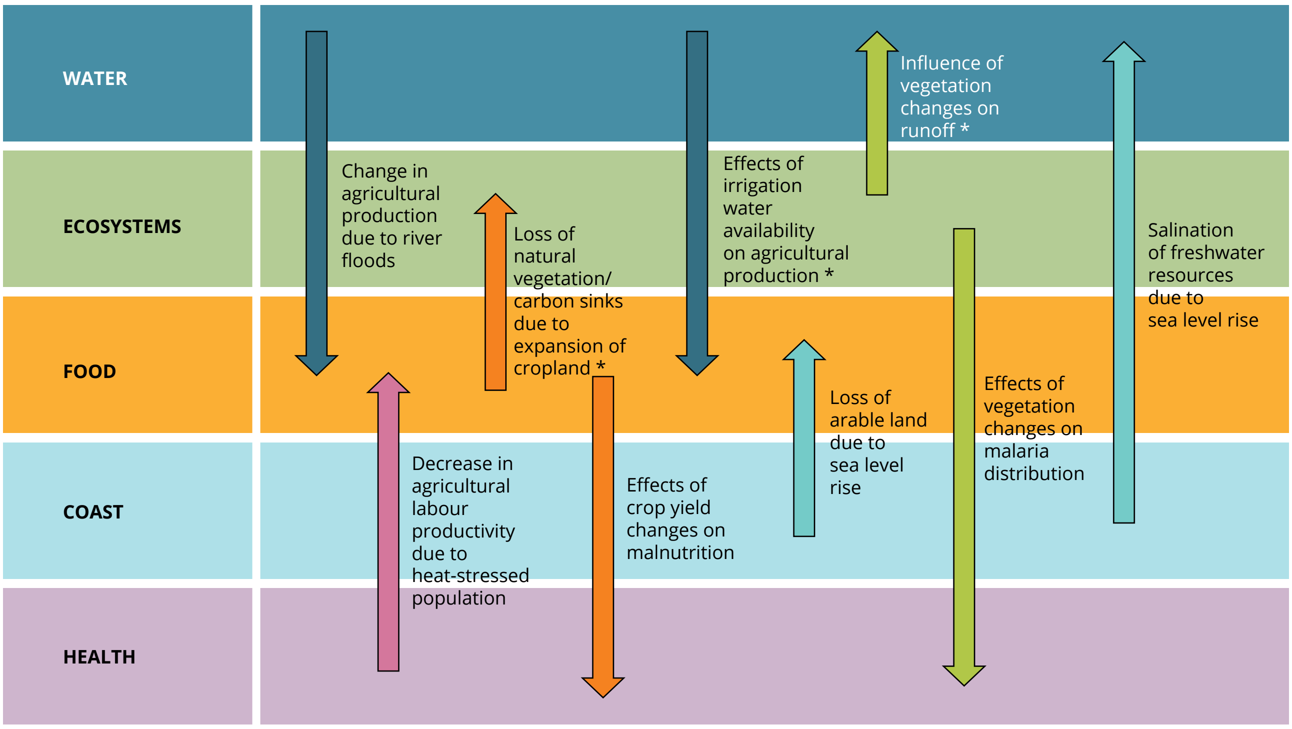
The different pan-European assessments vary considerably with respect to their coverage and specification of sectors and themes, their underlying methodological frameworks and their usage of climatic and non-climatic scenarios. Despite these differences, a compilation and comparison (to the extent possible) of the outcomes of these assessments sheds light on predominant cross-sectoral interactions resulting from the combined effects of climatic and socio-economic scenarios. In addition, it might also help to identify geographical 'hotspot regions' within Europe that are projected to be affected most severely by climate change. Such analyses can serve as a starting point for prioritising supplementary regional case studies on vulnerability, interactions and feedbacks between the affected sectors (Piontek et al., 2014).

In the context of this section, it is helpful to distinguish between multi-sectoral and cross-sectoral assessments. Multi-sectoral assessments, such as the work within the IMPACT2C project, combine the results from separate assessments for various climate-sensitive systems and sectors, e.g. to determine so-called vulnerability hotspots. Cross-sectoral assessments (e.g. the CLIMSAVE project), in contrast, also consider important interdependencies and feedbacks between different sectors (see Figure 6.2), which enables climate change impacts and adaptation to be assessed in the context of climate change mitigation or other policy concerns. Such assessments require careful consideration between the added complexity of explicitly modelling interdependencies between sectors on the one hand and the improved realism of the assessment results on the other (Huber et al., 2014).

6.2.2 Multi-sectoral assesments

Large parts of the Nordic countries and the Baltic countries, as well as some parts of central and eastern European countries (Austria, the Czech Republic Poland, Slovakia), have been identified as multi-sectoral hotspot 'winners' (see left panel of Map 6.2). This means that multiple sectors in these regions might benefit from a warming climate. On the contrary, most regions in

Figure 6.2 Examples of interdependencies between climate impacts on different sectors



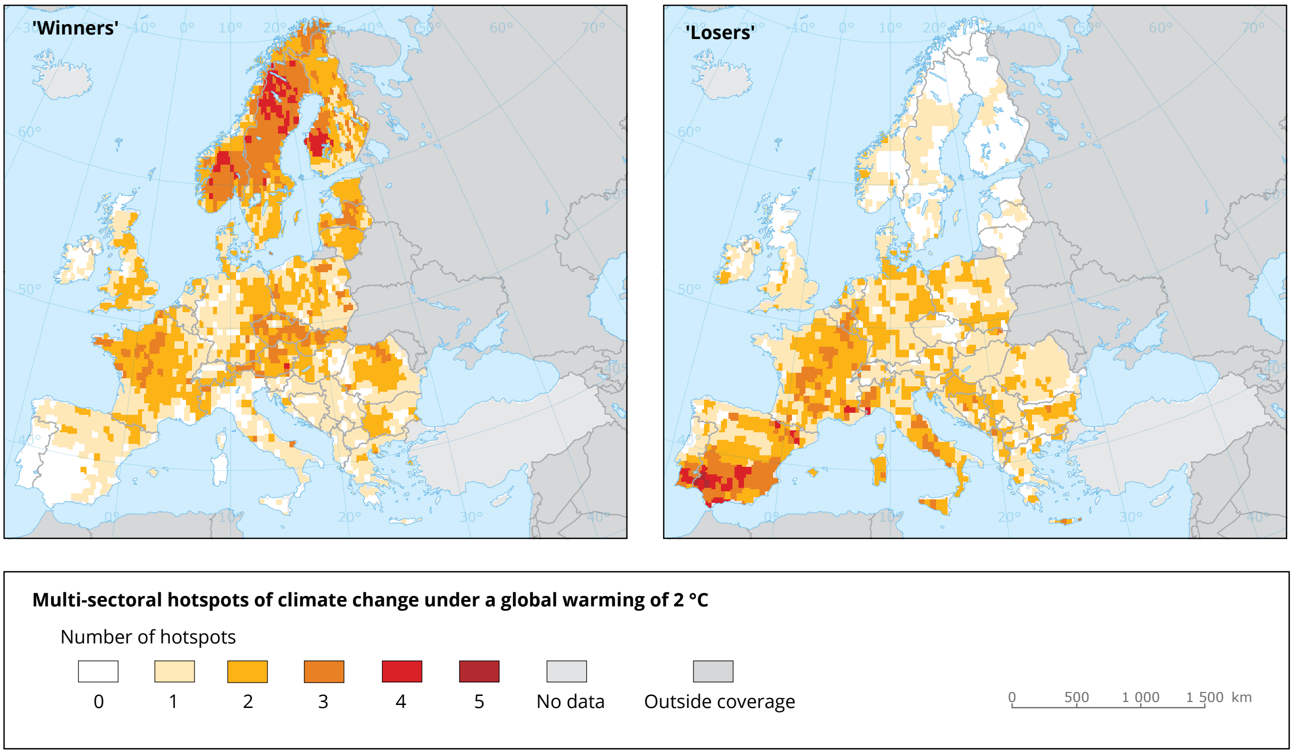
Note: Each arrow, overlain on the standard impact table from the IPCC AR4 (Parry et al., 2007), illustrates an example of inter-sectoral feedback.

* Feedbacks recently studied in the context of ISI-MIP ([118]).

Source: Adapted from Huber et al., 2014.

([118]) ISI-MIP: 'Inter-Sectoral Impact Model Intercomparison Project'.

Map 6.2 Projected 'winners' and 'losers' from climate change



Note: The impacts as shown in the maps refer to a warming of 2 °C above the pre-industrial level. The time period when warming of 2 °C above the pre-industrial level is reached varies depending on the RCP scenario and climate model. For RCP8.5, most climate models project that the 2 °C threshold will be reached in the 2030s, while for RCP4.5 most climate models project the 2 °C threshold to be reached around the middle of the century.

Source: Adapted from IMPACT2C project, 2015.

southern Europe have been identified as multi-sectoral hotspot 'losers', indicating that the impacts from a changing climate on the sectors in these regions are projected to be predominantly negative. Regions with a particularly high number of sectors projected to be negatively affected are found on the Iberian Peninsula, in southern and central France, and in Italy (see right panel of Map 6.2) (IMPACT2C project, 2015). Likewise, a study by the ISI-MIP project has identified southern (and also south-eastern) Europe as the region with potentially the most severe impacts across multiple sectors in Europe (and actually the second largest hotspot region globally) (Piontek et al., 2014).

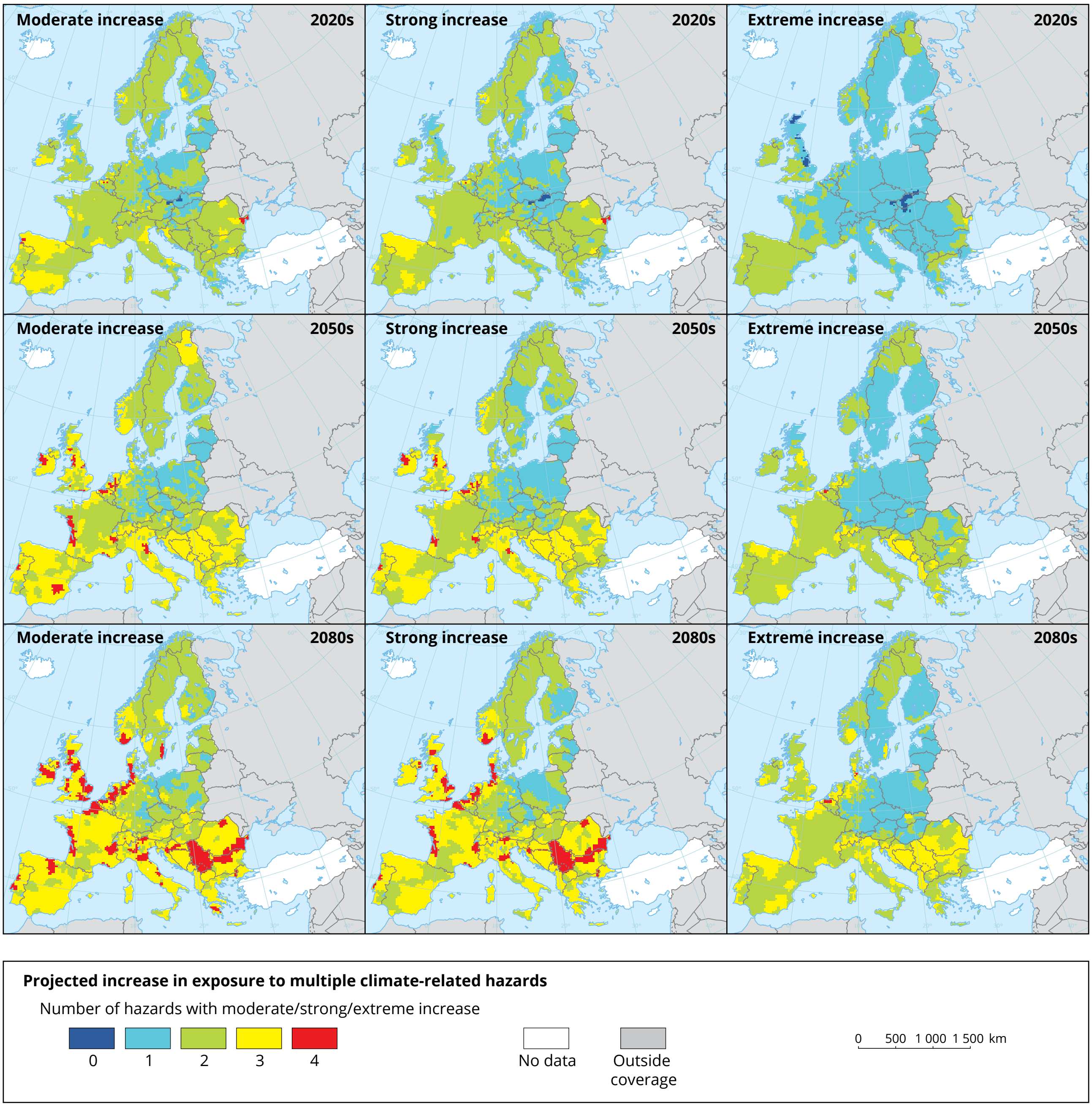
The IMPACT2C results emerge from an assessment of eight impact criteria in relation to the sectors 'water', 'agriculture', 'tourism' and 'ecosystems', and based on up to 10 regional climate models simulating the RCP4.5 and RCP8.5 scenarios. The impact criteria used are cooling water level, hydrological droughts (river low flow level, 10-year return period), floods (10-year return period), crop yield (winter wheat), value at risk for summer and winter tourism (measured as changes in overnight stays), and terrestrial ecosystem function (net primary productivity and soil organic carbon). For each criterion, winner hotspots and loser hotspots were defined based on EU policy thresholds and scientific literature (depending on availability). Robust hotspots were defined either based on a majority rule, such that the majority of models (e.g. 6 out of 10) had to agree that a given grid cell was indeed a hotspot, or, for some criteria, based on the median response over all simulations. In the assessment, however, SSP information (i.e. potential future socio-economic changes, such as demography and economy) was taken into account only for tourism (SSP1, 2 and 3).

6.2.3 Multi-hazard exposure

Multi-sectoral impacts and vulnerabilities can also be studied by explicitly distinguishing between multiple climate-related hazards. Such an approach shows that Europe could face a progressive increase in overall climate-related hazards from the 2020s to the 2050s and further to the 2080s, with a prominent spatial gradient from north-eastern towards south-western Europe (see Map 6.3). This gradient is mainly driven by projected increases in heat waves, droughts and wildfires. Key hotspot areas of particular concern (i.e. with exposure to three or four hazards) are found along the coasts and in floodplains.

By 2080, most areas in Spain, France, Italy, the Balkan countries, Bulgaria and Romania, but also in the Netherlands, the United Kingdom and Ireland, are projected to be affected by increases in the probability of hazard occurrence of at least 20 % for three or even four out of the seven hazards considered. In addition, when assuming a higher increase in the probability of hazard occurrence (i.e. at least 100 %, which means that the likelihood of a hazard occurrence has doubled), most of these regions are projected to be affected by three to four hazards (see Map 6.3). These patterns confirm the critical role of south-eastern and southern

Map 6.3 Projected increase in multi-hazard exposure



Note: The maps show projected increases in hazard exposure (considering climatic events with a statistical return interval of 100 years) for three time slices (2020s, 2050s and 2080s) and for three levels: moderate (increases at least 20 %), strong (increases at least 100 %) and extreme (increases at least 1 000 %).

Source: Adapted from Forzieri et al., 2016.

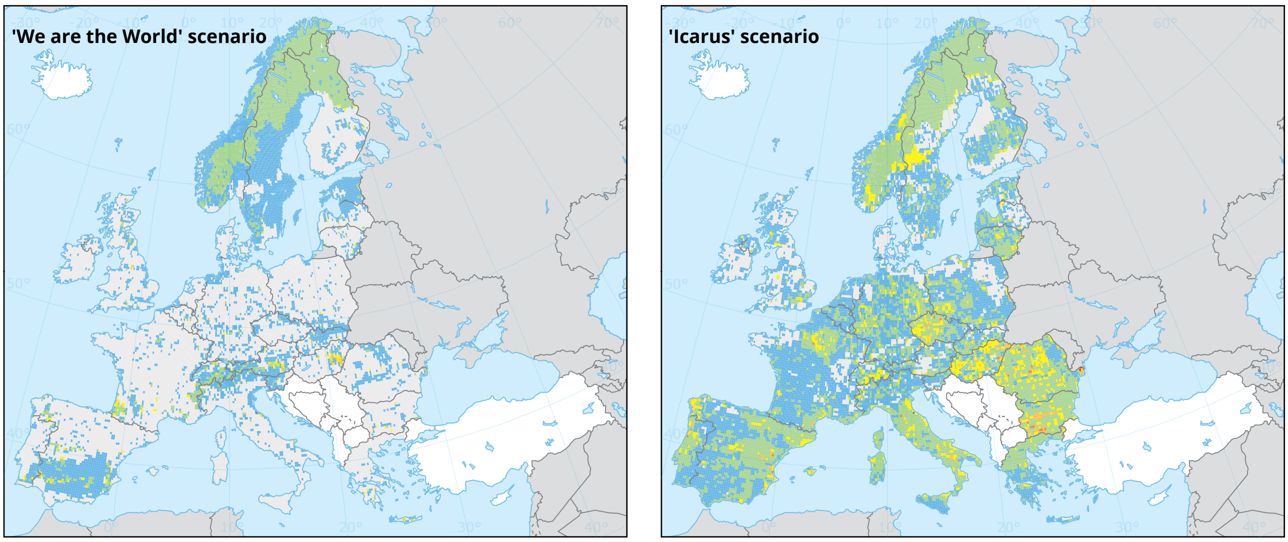
Europe as hotspots of climate change impacts and vulnerabilities. Furthermore, these results also highlight the risk that multiple climate-related hazards will extend northwards to central and western Europe in the coming decades, as has already been pointed out by previous multi-hazard assessments (e.g. Lung et al., 2013).

These results are based on a set of regional climate model simulations under the SRES A1B scenario with a reference period (1981–2010) and three projected periods (2020s, 2050s and 2080s). The approach follows the definition of vulnerability by the disaster risk community (see Section 1.4). Seven climate-related hazards have been covered: 'heat waves', 'cold waves', 'droughts', 'wildfires', 'river floods', 'coastal floods' and 'windstorms' (Forzieri et al., 2016). In terms of exposed assets, the assessment focused on direct damages to physical infrastructure and distinguished between the four key sectors 'energy' (power plants related to coal, gas, nuclear, oil, biomass, hydro, solar and wind; electricity networks; gas pipelines), 'transport' (roads, railways, inland waterways, ports, airports), 'industry' (metal, minerals, refineries, chemical, water and water treatment) and 'social' (education and health institutions). Climate sensitivity was estimated semi-quantitatively based on an expert survey and literature-based evidence. The three components (climate hazards, exposed assets and climate sensitivity) were integrated to derive quantifications of overall risk. Note that the assessment was based on the current configuration of assets (i.e. assuming no change in the current distribution of critical infrastructure) (Forzieri et al., 2016). A related study assessed the economic impacts of the projected changes in hazard exposure on critical infrastructure in Europe (Forzieri et al., 2015).

6.2.4 An ecosystem service perspective

An alternative perspective to assessing multi-sectoral impacts and vulnerabilities is to take ecosystem services as the point of departure, by selecting and modelling, for each sector considered, one or several key ecosystem services that are associated with that sector. The results of the ecosystem service approach are shown in Map 6.4. When assuming a low vulnerability scenario (see left panel of Map 6.4), only very few areas are projected to be vulnerable to multiple ecosystem services, most notably the Alps, parts of Scandinavia (provisioning of food and landscape diversity) and pockets in Hungary and France (food, landscape diversity and biodiversity).

Map 6.4 Aggregated cross-sectoral vulnerability in the 2050s from an ecosystem service perspective



Aggregated cross-sectoral vulnerability in the 2050s from an ecosystem service perspective

Number of sectors found to be vulnerable

0 | 1 | 2 | 3 | 4 | 5 | 6 | No data | Outside coverage

0 500 1 000 1 500 km

Source: Adapted from Dunford et al., 2015.

Under high vulnerability assumptions, almost 90 % of the population is projected to be vulnerable to at least one sector by 2050, and hotspot areas with vulnerability to three or more sectors are found in particular in southern and south-eastern Europe (Italy, Hungary, Romania, Bulgaria, Greece), but also on the Iberian Peninsula and in parts of Scandinavia (see right panel of Map 6.4). The apparent vulnerability of Scandinavia is, however, strongly driven by the assumption that a homogeneous landscape causes vulnerability (Dunford et al., 2015). Therefore, the large forested areas in Scandinavia that do not have food production (agriculture) will appear as vulnerable, even though the human population is not necessarily greatly affected by all changes in the forests.

These results stem from the CLIMSAVE project, which has developed an integrated assessment platform combining models for the six sectors 'agriculture', 'forestry', 'biodiversity', 'water', 'flooding' (coasts and rivers) and 'urban' under different climate and socio-economic scenarios for the 2020s and 2050s. Note, however, that the definition of 'sectors' differs partly from that used in the ISI-MIP study (Piontek et al., 2014) and does not refer purely to economic activities but also refers to particular processes such as urban development, flooding or water availability. The six ecosystem service indicators were selected, with priority given to those that are inherently cross-sectoral (the sector is in brackets): (1) 'food provision' (agriculture), (2) 'water exploitation index' (water), (3) 'flood regulation index' (flooding), (4) 'biodiversity index' (biodiversity), (5) 'land use intensity' (agriculture/forests) and (6) 'landscape diversity' (agriculture/forest/urban) (Dunford et al., 2015).

The platform explicitly models the interdependencies between the six sectors and has been made available to the general public as a web-based explorative tool. It contains climate scenarios for five climate models and four SRES emissions scenarios (A1, A2, B1 and B2), and for four stakeholder-derived CLIMSAVE socio-economic scenarios (Kok et al., 2015). The platform projects impacts for a range of sectoral and ecosystem service output indicators, six of which have been selected to assess vulnerability (representing one key ecosystem service indicator for each sector). For further information on the potential consequences of climate change on ecosystem services, including the CLIMSAVE project and an IPCC literature review from its AR5, see Section 4.5.

Vulnerability as depicted in Map 6.4 comprises the following elements: (1) potential impact, (2) the level of adaptation in place to reduce that impact and (3) the societal coping capacity available to address the impact that remains after adaptation. Thresholds were specified for each element in order to determine when vulnerability becomes an issue. Two summary statistics, 'total vulnerable area' and 'number of vulnerable people', were calculated and maps of 'hotspots' (see Map 6.4) were produced by spatially overlaying the results for the six ecosystem services (Dunford et al., 2015).

An analysis of cross-sectoral interdependencies suggests that the sectors 'water', 'agriculture', 'forestry' and 'biodiversity' in particular are highly sensitive to trends and changes in other sectors (Kebede et al., 2015). This means that these four sectors are very likely to be indirectly affected by climate change through impacts in other sectors. The CLIMSAVE assessment also confirms the crucial role of non-climatic factors, such as changing land-use patterns or population changes, in determining overall vulnerability and risk. For example, while flood risk is projected to generally increase (except in parts of eastern Europe) under climate-only assumptions, the patterns of flood risk are more nuanced or even diverging across European regions when different socio-economic scenarios are taken into account (Harrison et al., 2015). This shows that proactive adaptation can reduce climate change vulnerability (Jäger et al., 2015).

Box 6.1 National case study: the German vulnerability assessment

As requested by the first German national Adaptation Action Plan (APA I) in 2011, a standardised, cross-sector assessment of current and future climate change impacts and vulnerabilities was prepared in 2015 in order to provide official evidence for the second Adaptation Action Plan (APA II). The APA II and the vulnerability analysis are part of the progress report for the German Adaptation Strategy, adopted in 2015. The cross-sector assessment required the cooperation of many actors from various areas of expertise. For this reason, the Federal Ministry for the Environment (BMUB) and the Federal Environment Agency (UBA) started the Vulnerability Network in 2011. This network is composed of 16 Federal agencies and institutes, mandated by their ministries, and was supported by a scientific consortium. By working together, a co-design of the assessment could be reached, which also facilitated the communication and ensured the applicability of the results in the following political process.

First, the Vulnerability Network created a consistent cross-sector methodology based on a joint understanding of vulnerability and of related terms adapted from the concept of vulnerability, as set out in the IPCC AR4 (2007). To visualise the cause–effect relationships between climate drivers and possible impacts, as well as the connections between the 15 areas for action of the German Adaptation Strategy, the network defined 'impact chains'. These represent climate drivers that influence particular climate impacts. Out of the about 170 impacts identified, network partners chose 72 for further analysis and 38 could be at least partly quantified for three time frames: the present, the near future (2021 to 2050) and the distant future (2071 to 2100).

Key sensitivities were subsequently worked out by invited experts and network partners. For the near future, two scenario combinations, one for a strong and one for a weak change based on socio-economic and climate change scenarios, were used to cover the range of possible futures. For the remote future, no socio-economic scenarios were available. Therefore, these results rest only upon the ensemble of climate change projections.

In a final step, the confidence level and the significance of the results for Germany were accessed by the Network. For each area for action, information on its adaptation capacity, based upon expert interviews, was combined narratively by using a matrix with the potential sectoral climate change impact, to give a rough estimation of its vulnerability (low, medium or high). For example, the climate change impact potential of the water sector was calculated as 'medium to high' as a weighted mean of the investigated single climate change impacts in the water sector (see Table 6.2) for the near future under strong change. In combination with the adaptive capacity of the water sector, which was also estimated to be medium to high based on expert interviews, its vulnerability is considered to be medium.

The key impacts of climate change in Germany until the middle of the century will be heat waves in urban regions, fluvial floods, particularly in northern Germany, and flash floods in southern Germany. These climate impacts will threaten mainly human health and infrastructures in urban agglomerations. Gradual climate change is already affecting biodiversity, agriculture and forestry, as well as human health. In the long term, dry spells will also have an important effect on water uses, mainly in rural areas, and sea level rise will affect the coasts. The areas for action that are expected to be strongly affected by climate change in the future are construction and coastal and sea protection. Construction, fisheries and biodiversity are the most vulnerable areas for action.

Box 6.1 National case study: the German vulnerability assessment (cont.)

Table 6.2 Climate change impacts in the water sector in Germany

Climate drivers:	**Temperature**	**Precipitation**	**Dryness**	**Fluvial flood**	**Heavy rain**
Main sensitivity factors:	Land use, population density, water uses				
Climate change impact potential:	Medium to high (near future)				
Adaptive capacity :	Medium to high				
Vulnerability:	Medium (near future)				

Climate change impact	**Data source**	**Significance**		**Confidence level**
Run-off	Process model	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: ++		
Fluvial floods and flash floods	Process model and proxy indicator	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: +		
Effect on canalisation and treatment plants	Proxy indicator	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: + to ++		
Availability of groundwater	Process model	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: ++		
Availability of surface water	Process model	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: ++		
Availability of drinking water	Expert interviews and proxy indicator	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: ++		
Management of dams	Expert interviews	Today		Medium
		Near future: weak change	Near future: strong change	
		Distant future: ++		
Water quality	Expert interviews	Today		Low
		Near future: weak change	Near future: strong change	
		Distant future: ~ to ++		

Legend

Significance of the climate change impact for Germany:

- Low
- Medium
- High

Expected development of relevant climate drivers until the end of the century (distant future):

- ++ Strong change
- \+ Change
- ~ Uncertain

Source: Adapted from Adelphi et al., 2015. Reproduced with permission.

6.2.5 A narrative perspective

The FP7 BASE project has developed storylines of potential socio-economic development and related sectoral vulnerabilities up to 2050 for three different RCP–SSP combinations and four European regions. The scenarios were developed by project researchers using the SSP database (see Section 6.1) on basic socio-economic data, which were complemented with results from sector-based modelling and information from case studies. Interviews with stakeholders were used to verify salient features of the storylines (BASE project, 2016). The following RCP–SSP combinations were used to bring together information on socio-economic development and climate change:

- RCP8.5/SSP5, *market-driven world*;
- RCP4.5/SSP2, *middle of the road*;
- RCP8.5/SSP3, *fragmentation*.

The following regions were used for regional aggregation:

- *northern Europe and the Arctic* (Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden);
- *north-western Europe* (Belgium, Denmark, France, Ireland, the Netherlands, the United Kingdom);
- *central and eastern Europe* (Austria, Bulgaria, the Czech Republic, Germany, Hungary, Kosovo under UNSCR 1244/99, Luxembourg, the former Yugoslav Republic of Macedonia, Poland Romania, Serbia, Slovakia, Switzerland);
- *southern Europe and the Mediterranean* (Albania, Bosnia and Herzegovina, Croatia, Cyprus, Greece, Italy, Malta, Montenegro, Portugal, Slovenia, Spain, Turkey).

One common feature across regions and storylines is urbanisation (see also Section 6.1). This implies that an increasing number of people will be exposed to typical urban impacts such as heat island effects, storm water floods and flash floods (see Section 6.6). In a market-driven world, more assets will be exposed to climate-related hazards and there will be increasing demands to invest in reducing vulnerabilities.

The assumption of significant relative population growth in a market-driven world, especially in northern Europe and the Arctic and north-western Europe, means that new infrastructure will be built, including housing. The development of vulnerabilities will depend on how the new areas accommodating the increasing population are planned and built. In these storylines, the central and eastern regions appear less dynamic in terms of population and economic growth, which means fewer changes than in the current situation, but also relatively fewer resources to address vulnerabilities.

The 'fragmentation' storylines are in many respects the most problematic ones for all regions, as they are characterised by few additional resources but high exposure to climatic hazards owing to the assumed RCP8.5 scenario. Major challenges will include the management of agriculture, especially in the Mediterranean area, which will suffer from an increasing frequency of drought and high temperatures. Under 'fragmentation', financial resources are scarce and the abilities to cope with adverse conditions are weaker; thus, vulnerability increases relative to market-driven development, even under the same scenario, RCP8.5.

One of the main features of progressing climate change is that vulnerabilities will raise new challenges but also some opportunities for both the public and private sectors. These opportunities and challenges will play out differently, depending on the socio-economic pathways that set the general context. To illustrate this, a synthesis has been made of the material with reference to a 'fragmentation' storyline and a 'middle-of-the-road' storyline (see Table 6.3).

The 'fragmentation' storyline illustrates a current business-as-usual scenario: increasing emissions along an RCP8.5 trajectory until 2050, combined with uneven economic growth in which some areas and countries grow rapidly, whereas others face stagnation or even decline. Globalisation progresses unevenly and the free movement of natural resources, technologies, capital and people develops between some countries and regions but not others.

The 'middle-of-the-road' storyline illustrates a scenario that leads to a clear curbing of emissions towards an RCP4.5 trajectory until 2050, combined with modest economic growth that benefits most regions and countries (although obviously with varying rates). Globalisation is assumed to progress in a way that facilitates free and fair movement of natural resources, technologies, capital and people between regions and beyond Europe.

These two storylines were chosen to illustrate the differences between a modest progress in mitigation and a failure to mitigate climate change. The climate-related challenges in the storyline assuming rapid economic growth in combination with high emissions (a market-driven world) would be similar to those experienced under 'fragmentation', but stronger economic growth would provide more positive opportunities for developing adaptation actions.

The overall conclusions of the storylines fit those that can be extracted from the other studies of cross-sectoral impacts and vulnerability: the greatest challenges appear to be concentrated in southern Europe and the Mediterranean regions of the EEA region, especially under a fragmentation storyline. Opportunities for technological and social innovations for adaptation are greater in a middle-of-the-road storyline than under fragmentation.

Table 6.3 Overview of the management challenges related to vulnerabilities to climate change for two storylines and four European regions

Topic	Storyline	Northern Europe and Arctic	North-western Europe	Central and eastern Europe	Southern Europe and the Mediterranean
Management of urban areas	Middle of the road	Yellow	Yellow	Yellow	Yellow
	Fragmentation	Orange	Orange	Red	Orange
Management of rural settlements	Middle of the road	Yellow	Yellow	Yellow	Yellow
	Fragmentation	Orange	Orange	Red	Orange
Management of energy consumption in housing	Middle of the road	Green	Green	Yellow	Orange
	Fragmentation	Yellow	Yellow	Orange	Red
Management of hydropower production	Middle of the road	Green	Orange	Red	Red
	Fragmentation	Orange	Red	Red	Red
Power production with boilers	Middle of the road	Yellow	Orange	Orange	Orange
	Fragmentation	Orange	Red	Red	Red
Water management	Middle of the road	Yellow	Orange	Yellow	Orange
	Fragmentation	Orange	Orange	Orange	Red
Management of agriculture	Middle of the road	Yellow	Yellow	Yellow	Orange
	Fragmentation	Orange	Orange	Orange	Red
Forest management	Middle of the road	Yellow	Yellow	Yellow	Orange
	Fragmentation	Orange	Orange	Orange	Red
Coastal management	Middle of the road	Yellow	Yellow	Yellow	Orange
	Fragmentation	Orange	Orange	Yellow	Red
Management of health care	Middle of the road	Yellow	Orange	Orange	Orange
	Fragmentation	Orange	Orange	Red	Red
Biodiversity management	Middle of the road	Yellow	Yellow	Yellow	Orange
	Fragmentation	Orange	Orange	Orange	Red
Development and diffusion of green innovations	Middle of the road	Green	Green	Green	Green
	Fragmentation	Yellow	Yellow	Yellow	Yellow

Legend
- [Green] Mainly positive opportunities
- [Yellow] Balance between negative challenges and positive opportunities
- [Orange] More negative challenges than positive opportunities
- [Red] Mainly negative challenges

Source: Adapted from BASE project, 2016.

6.3 Projected economic impacts of climate change in Europe

Key messages

- Estimates of the projected economic impacts of climate change in Europe are emerging, but the coverage of these estimates remains only partial and there is considerable uncertainty.
- Recent studies indicate that the economic costs of climate change will potentially be high, even for modest levels of climate change, and these costs rise significantly for scenarios of greater levels of warming. For example, the PESETA II study estimates that the annual total damages from climate change in the EU would amount to around EUR 190 billion (with a net welfare loss estimated to be equivalent to 1.8 % of current GDP) under a reference scenario (SRES A1B) by the end of the 21st century.
- The projected damage costs from climate change are distributed very heterogeneously across Europe, with notably higher impacts in southern Europe.
- Regarding the costs and benefits of adaptation, more information has become available, especially for coastal areas, water management, floods, agriculture and the built environment, but the focus has been on national rather than pan-European estimates.

Climate change will lead to economic costs. These costs, which are often known as the 'costs of inaction', are a useful input to the policy debate. A number of studies have made advancements in pan-European estimates of these costs, using scenario-based impact assessments, and these are the focus of this section. These include the IMPACT2C project (Vautard et al., 2014), which used the RCP and SSP scenarios, the PESETA II project (Ciscar et al., 2014) and the ClimateCost project (Watkiss, 2011), which used SRES. The information from these studies is summarised in Table 6.4.

A large number of caveats are associated with these values, reflecting different scenarios, assumptions and methods and dependent on whether results are reported for the impacts of climate change and socio-economic change together or separately and, for the latter, whether results are reported for current or future socio-economic conditions. There are further issues with the adjustment of values in future time periods and metrics reported (i.e. whether or not they are discounted, annual versus present values; note that the information here generally reports current prices in all future time periods to facilitate direct comparison, over time, and between sectors). Overall, this implies that it is not possible to have a simple aggregated table allowing direct and easy comparison of figures across sectors.

There have been a number of studies that have used these direct sector costs as inputs into wider economic models. The PESETA II study used a computable general equilibrium model to look at the economic effects of direct climate effects and the indirect effects on the economy (Ciscar et al., 2014). Under the reference scenario (SRES A1B), this study estimated that the annual total damages from climate change in the EU would be around EUR 190 billion (with a net welfare loss estimated to be equivalent to 1.8 % of current GDP, see Figure 6.3) by the end of century, with particularly high costs in southern European regions. These impacts would be reduced to EUR 120 billion (equivalent to 1.2 % of current GDP) in a 2 °C warmer world. While a significant proportion of the damages are related to heat-related mortality (noting that cold-related benefits were excluded and that values are driven by the valuation approach used), coastal damages and the agriculture sector are also quite significant. However, the assessment covered only a limited number of sectors (and impacts within these), and the estimates for these sectors can be considered only partial, especially due to the omission of potential impacts on biodiversity and ecosystem services.

There have also been a number of regional assessments. For example, the CIRCE project (Navarra and Tubiana, 2013) estimated the economic costs of impacts in the Mediterranean region. Estimates, using a computable general equilibrium model under SRES A1B emissions, suggest that there will be negative economic consequences for major sectors, such as tourism and energy. Furthermore, all Mediterranean countries could lose, on average, 1.2 % of GDP in 2050. The largest economic costs relate to sea level rise and tourism. Box 6.2 presents results from an assessment of the economic effects of warming on labour productivity in two economic sectors in Austria.

Table 6.4 Overview of cost estimates of projected climate change in Europe

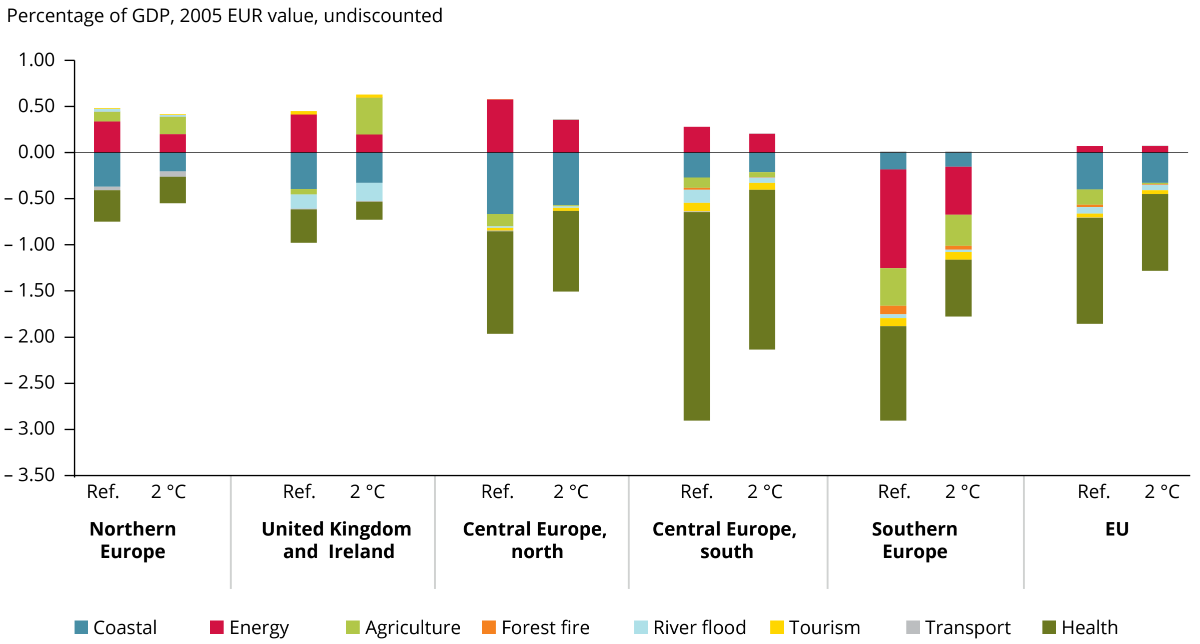
Thematic area (and section in this report)	Pan-European estimates
Coastal zones (see also Section 4.2)	Recent estimates of costs to coastal zones are EUR 6 to 19 billion per year for RCP2.6, EUR 7 to 27 billion per year for RCP4.5 and EUR 15 to 65 billion per year for RCP8.5 in the 2060s in the EU (no adaptation, combined climate and socio-economic change (SSP2), current prices, no discounting, with the range reflecting the uncertainty around sea level rise), based on the DIVA model ([119]) in IMPACT2C (Brown et al., 2015). These costs rise rapidly in later years, ranging from EUR 18 to 111 billion per year for RCP2.6, EUR 40 to 249 billion per year for RCP4.5 and EUR 153 to 631 billion per year for RCP8.5 in the 2080s (Brown et al., 2015). This indicates a disproportionate increase in costs for greater warming scenarios in the second half of the century. There are major differences between Member States, with the greatest coastal zone costs projected to occur in France, the United Kingdom and the Netherlands if no additional adaptation occurs
River flooding (see also Section 4.3)	The expected annual damage is estimated to rise from approximately EUR 4–5 billion/year (currently) to EUR 32 billion/year in the EU by the middle of the century (RCP4.5 for 2 °C of warming) without additional adaptation (median ensemble results, combined effects of socio-economic and climate change, current values, undiscounted), based on the LISFLOOD model ([120]) from IMPACT2C (Roudier et al., 2016). The large range of this estimate is a result of the high levels of climate model uncertainty. Note that around half of the increase reported is attributable to climate change. Analysis at the country level reports high climate-related costs in France, Germany, Italy, Romania, and the United Kingdom and damage costs rise significantly in the subsequent years. While there are Europe-wide assessments of stream-flow drought, soil moisture drought and water scarcity (IMPACT2C project, 2015), these have not been monetised
Agriculture (see also Section 5.3)	The recent Agricultural Model Inter-comparison and Improvement Project (AGMIP) indicates that climate change could lead to a 20 % (mean) food price rise by 2050 globally, with a large range from 0 to 60 % (common reference climate and socio-economic scenario) (Nelson et al., 2014). Yield losses and price impacts rise more sharply in later years under greater warming scenarios. These results cover only a limited number of crops and impacts, and exclude horticulture, livestock and impacts on the wider multi-functionality of agriculture. Values vary widely with scenarios and assumptions (on impacts and autonomous farm adaptation and trade)
Energy (see also Section 5.4)	Climate change will have negative and positive effects on future energy demand, increasing summer cooling but reducing winter heating (an autonomous response). Additional cooling costs have been estimated at around EUR 30 billion/year in the EU-27 by 2050, rising to EUR 109 billion/year by 2100 (A1B, climate change signal only, current values, undiscounted), based on the ClimateCost study using the POLES model (Mima et al., 2011; Mima and Criqui, 2015). However, a similar level of economic benefit was projected as a result of the reduction in winter heating demand owing to warmer temperatures, although with the benefits arising in different countries. Under the E1 scenario, the total costs of the cooling demand due to climate change (alone) were much lower, estimated at approximately EUR 20 billion/year over the period 2050–2100). Climate change will also have effects on energy supply, notably on hydroelectric generation, but also potentially on thermal power (nuclear, fossil) plants and some renewables; these involve additional costs (Mima et al., 2011), although these are low relative to the changes in demand outlined above
Transport (see also Section 5.5)	The PESETA II study (Ciscar et al., 2014) considered impacts on the road and rail networks, estimating the total damages to transport infrastructure due to extreme precipitation to be EUR 930 million/year by the end of the century under an A1B scenario (a ~ 50 % increase from the current baseline damages of EUR 629 million/year) and EUR 770 million/year under a 2 °C warming scenario. More specific estimates also exist for road transport. The future costs are driven by future socio-economic assumptions, i.e. on transport patterns and demand. Further information is available from the WEATHER project (Przyluski et al., 2011) and the EWENT project (Nokkala et al., 2012)
Tourism (see also Section 5.6)	Climate change is projected to make regions less favourable for tourism in the south in summer but more favourable in the north. Several recent studies have used econometric approaches and economic modelling approaches to identify the economic impacts of climate change on tourism under different assumptions for adaptation (Barrios et al., 2013; Ciscar et al., 2014; Rosselló-Nadal, 2014; Perrels et al., 2015). As an example, the PESETA II study (Ciscar et al., 2014) used an econometric analysis, reporting estimated costs of EUR 15 billion/year by the end of the century, driven by reductions in southern Europe and in the southern parts of central Europe, and with particular gains in the northern parts of central Europe. However, other studies report more positive results, noting that the economic impacts depend on whether tourists adapt by changing their destination or the timing of their travel. Climate change will also affect winter tourism, as snow reliability will decrease in the mountainous regions, particularly the Alps, putting the ski resorts that are at lower altitudes at risk, leading to adaptation costs (artificial snow) or changes in destination choices or timing (Perrels et al., 2015). Estimates are heavily influenced by assumptions about changes in global tourism and the underlying global growth in tourism, as well as the autonomous adaptation response of tourists

([119]) Dynamic Interactive Vulnerability Assessment model (http://www.diva-model.net).
([120]) https://www.efas.eu/user-information.html.

Table 6.4 Overview of cost estimates of projected climate change in Europe (cont.)

Thematic area (and section in this report)	Pan-European estimates
Human health (see also Section 5.2)	The costs of heat-related mortality, without adaptation, are estimated to be EUR 11 to 41 billion/year by the middle of the century (mean ensemble estimates for RCP4.5 at 2 °C, climate and socio-economic impact, with range reflecting different approaches for valuation, no current or future adaptation, current prices, undiscounted), with around two-thirds of the increase due to the climate signal alone (this is based on the IMPACT2C project, with impacts estimated by the WHO and valuation undertaken by Lacressonnière et al. (2015)). Values vary widely according to whether current adaptation and future acclimatisation are included or not, and the metric and value used for mortality valuation. The highest impacts were found in the Mediterranean (Cyprus, Greece and Spain) and some eastern EU Member States (Bulgaria, Hungary and Romania). Costs rose strongly in later years with greater warming. The analysis did not consider the potential reduction in cold-related mortality. Additional impacts, including food-borne disease, extreme events (deaths and reduced well-being as a result of coastal flooding) and occupational health (outdoor labour productivity), were valued in the ClimateCost project (Kovats et al., 2011), although the economic costs were low when compared with the heat-related mortality impacts outlined above
Biodiversity and ecosystem services (see also Section 4.4 and Section 4.5)	Climate change poses a potentially wide variety of risks to terrestrial, aquatic and marine biodiversity and the ecosystem services they provide (provisioning, regulating, cultural and supporting services). However, the valuation of the effects of climate change on biodiversity and ecosystem services is extremely complex. While a number of studies have undertaken case studies, this remains an under-explored area, although there is some analysis of ecosystem shifts under climate change, which use restoration costs to assess impacts

Figure 6.3 Welfare impacts of climate change for different EU regions and sectors for two emissions scenarios



Note: The figure shows the projected welfare impacts in the period 2071–2100, compared with 2010. 'Ref.' refers to the SRES A1B emissions scenario; '2 °C' refers to the ENSEMBLES E1 emissions scenario.

Source: Adapted from Ciscar et al., 2014.

Box 6.2 National case study: climate change and labour productivity in Austria

Economic activity is exposed to climate change in several ways. The reduction of workers' productivity as a result of higher outdoor temperatures and/or higher relative humidity and, therefore, a higher heat exposure is one of the core direct impacts. The impacts of climate change on labour productivity in Austrian manufacturing and trade, as well as their macro-economic implications, have been projected in monetary terms up to the middle of the 21st century, drawing on a range of socio-economic and climate scenarios, disaggregated by region, sector, occupation, outdoor/indoor work and work intensity. The productivity losses of workers are estimated on the basis of a quantitative model using a relationship between the Wet Bulb Globe Temperature index and the productivity of workers. The human capital approach (evaluation by wage rates) and a GDP per employee approach were used for monetising the direct productivity losses.

Changing working conditions can have serious effects on the productivity of workers and thus on companies in specific sectors. Depending on the future development of the climate and the degree of existing temperature control and future adaptation, the damage caused can vary significantly. The direct climate impacts observed in the 'manufacturing' and 'trade' sectors — under assumptions of no current or future adaptation — are found to be magnified three- to four-fold by the associated macro-economic feedback effects, as the manufacturing and trade sectors supply intermediate inputs to a wide variety of other sectors. For the mid-range climate scenario and a reference socio-economic development scenario (see Table 6.5, results in bold), a decline in economic welfare of EUR 6 million per year is projected for the period 2016–2045 (and EUR 54 million for 2036–2065). The high-range and low-range climate scenarios add and subtract, respectively, one standard deviation in local temperature change, with the damage-enhancing and damage-diminishing socio-economic scenarios acknowledging higher and lower growth, respectively, of the labour force. For the high-end combination scenario (high-range climate scenario and damage-enhancing socio-economic scenario), welfare losses amount to EUR 58 million for the period 2016–2045 (and EUR 296 million for 2036–2065). As declining demand also triggers price declines, the subsequent losses in GDP are greater, namely about 1.5 times the welfare losses. By the middle of the century, losses will thus equal up to 0.6 % of labour value added (aggregated across all sectors, with lower impacts in sectors such as pharmaceuticals or beverage production, and significantly higher impacts in the production of food, plastics, metals and machinery). However, in practice, the small fraction of these potential costs related to indoor temperature is unlikely to increase because of the current and growing role of temperature regulation (autonomous adaptation) in trade and manufacturing, and this will be needed to ensure quality and also meet occupational health standards. This fraction of the costs will therefore actually increase as a result of additional cooling demand. Note, however, that this analysis refers only to the effects of productivity changes within the manufacturing and trade sectors, and similar productivity changes could affect the remaining sectors of the economy, in particular in relation to outdoor activities in the agriculture and construction sectors.

Table 6.5 Projected impacts of climate change on welfare and GDP owing to labour productivity changes in the manufacturing and trade sectors

		2016–2045			**2036–2065**		
Changes in million EUR per year relative to baseline	**Socio-economic scenarios** / **Climate scenarios**	Damage-diminishing scenario	**Reference**	Damage-enhancing scenario	Damage-diminishing scenario	**Reference**	Damage-enhancing scenario
Welfare (changes in million EUR)	High			– 58			– 296
	Mid		**– 6**			**– 54**	
	Low	+ 4			– 2		
GDP (changes in million EUR)	High			– 95			– 485
	Mid		**– 9**			**– 89**	
	Low	+ 7			– 3		
Change in value added (as % of sectoral total)		+ 0.01 %	**– 0.02 %**	– 0.2 %	– 0.004 %	**– 0.1 %**	– 0.6 %

Note: The table shows the average annual effects relative to baseline (i.e. reference socio-economic development scenario without climate change). The impact as a percentage of the sectoral labour value added (gross including taxes) is the average across sectors, without current or future autonomous or planned adaptation.

Source: Urban and Steininger, 2015.

All the estimates above are partial, i.e. they do not consider interactions between sectors. Even within the sectors covered, the analysis considers a sub-set of the possible effects of climate change, both positive and negative. There are also important sectors for which estimates are not reported above (e.g. business) and some others where valuation remains challenging, notably biodiversity and ecosystem services. There is also little quantitative evidence on how impacts of climate change outside Europe will affect Europe (see Section 6.4). Finally, these estimates involve a high degree of uncertainty, which is not captured by central projections, but is critical when considering adaptation.

Costs and benefits of adaptation

There is a growing knowledge base on the costs and benefits of adaptation. While the number of pan-European assessments for adaptation costs and benefits remains low, and with most that do exist constrained to the coastal sector (see Brown et al., 2015, for the most recent estimates), there are many more studies at the national, regional and local scales.

This information has recently been reviewed and collated as part of the ECONADAPT ([121]) project (Watkiss et al., 2015). In terms of the coverage by sector and risk, estimates have moved beyond the previous focus on coastal zones and now extend to water management, floods, agriculture and the built environment. However, major gaps remain for ecosystems and business/services/industry. There has also been a shift in the analysis of adaptation towards early adaptation investment (early low-regret options, capacity-building and non-technical options) and the use of iterative climate risk management and decision-making under uncertainty.

Estimates are emerging at the national level, which are more relevant than pan-European assessments with respect to adaptation governance and implementation. There are good national-level studies on adaptation costs and benefits in the Netherlands and the United Kingdom, which are using iterative frameworks (Delta Programme, 2010, 2013) and recently developed dynamic cost–benefit analysis (Eijgenraam et al., 2014; Kind, 2014) (in the UK Economics of Climate Resilience and the National Adaptation Programme and the Thames Estuary 2100 project) (EA, 2012; HMG, 2013). There are also studies in other European countries that have estimated the costs of adaptation. The analysis in Sweden (SCCV, 2007) presented investment and financial flow costs for several sectors; the Bank of Greece study (BoG, 2011) assessed costs for an adaptation scenario; and a study in Germany undertook cost–benefit analysis on potential adaptation options (Tröltzsch, et al., 2012).

Interestingly, recent implementation-based and policy-orientated studies indicate that the costs of adaptation are likely to be higher than estimated in the earlier impact assessment literature (ECONADAPT, 2015), as seen in recent estimates of future coastal and river flood risk management in the Netherlands (Deltacommissie, 2008; Eijgenraam et al., 2014) and the United Kingdom (ASC, 2014; EA, 2014). This is because more recent policy-orientated studies consider broader objectives, existing standards and multiple risks, they recognise and plan for uncertainty, and they include the additional opportunity and transaction costs associated with implementation. Finally, while important gaps exist in the empirical evidence, and there are issues over the transferability of estimates, the new evidence base provides an increasing opportunity for sharing information and good practice.

([121]) ECONADAPT: 'The Economics of Climate Change Adaptation'.

6.4 Europe's vulnerability to climate change impacts outside Europe

Key messages

- Several recent studies have suggested that climate change will have much stronger negative impacts on the global economy than previously assumed, with poor countries being disproportionally affected.
- In a highly interconnected and globalised world, Europe is susceptible to spill-over effects from climate change impacts occurring outside the European territory through various pathways. Past extreme events, such as the Russian heat wave in 2010, have had negative economic consequences for Europe (here understood as the EEA member and cooperating countries).
- Six major pathways have been identified from the available literature: trade of agricultural commodities, trade of non-agricultural commodities, infrastructure and transport, geopolitics and security risks, human migration, and finance. Many of these pathways affect the value chains of European products, which are increasingly complex.
- The strongest evidence for Europe's sensitivity to cross-border impacts exists for economic effects through climate-caused global price volatilities; for transportation networks such as ports; and for changes in the Arctic environment, such as new shipping routes. The Mediterranean area has been identified as the most vulnerable to shocks in the flow of agricultural commodities, while small, open and highly developed European economies are regarded as particularly vulnerable to shocks in the flow of non-agricultural commodities.
- An increasing body of recent literature suggests that unprecedented climatic changes in North African regions, such as the Sahel and Maghreb, as well as in the Middle East will increase the strategic importance of these regions for Europe, with respect both to potential climate-induced human migration flows and to geopolitical and security considerations.
- European vulnerability to cross-border effects is expected to increase in the coming decades, although quantitative projections are not yet available.

6.4.1 Introduction

Europe is part of a highly interconnected world that is bound together through multiple systems (EEA, 2015). International trade, travel, telecommunications and other aspects of globalisation increase the likelihood that climate change impacts have consequences beyond the regions or nations in which they occur. Such cross-border effects of climate change (sometimes also referred to as indirect effects, trans-boundary effects or spill-over effects) are highly relevant for European adaptation policy, as they may significantly influence climate change vulnerability of and risks to regions, sectors and people. The effects are, for example, felt in the increasingly complex value and supply chains of European products, which are often linked to distant geographical areas. For instance, a recent assessment suggests that many countries in Africa, South Asia, South East Asia and Latin America might be disproportionally affected by losses in economic production, in particular under high global warming assumptions (RCP8.5). The overall global economic losses are estimated to be much larger than in previous assessments, and this would unavoidably lead to repercussions in Europe (Burke et al., 2015). Several recent studies of the climate–economy relationship using panel methods have also suggested that climate change will have a substantially stronger negative effect on economic productivity than assumed by most economic models, and that poor countries will be much more affected than rich countries (Dell et al., 2012, 2014).

This section explores the available information base on how, and to what extent, cross-border impacts of climate change have (or are projected to have) potential implications in Europe. The combined effects from climatic and non-climatic changes, as illustrated for Europe in Sections 6.2 and 6.3, may have strong impacts in other world regions, with repercussions for Europe. In some cases, a single extreme climate event may be significant enough to cause a chain of reactions through impact pathways, which eventually lead to consequences in Europe, such as the (temporary) disruption of global supply chains due to damaged transport infrastructure. In other cases, gradual climate change or prolonged periods of extreme weather might trigger spill-over effects in Europe.

With respect to the geographical occurrence of the original climate change impacts, two groups of cross-border effects can be distinguished:

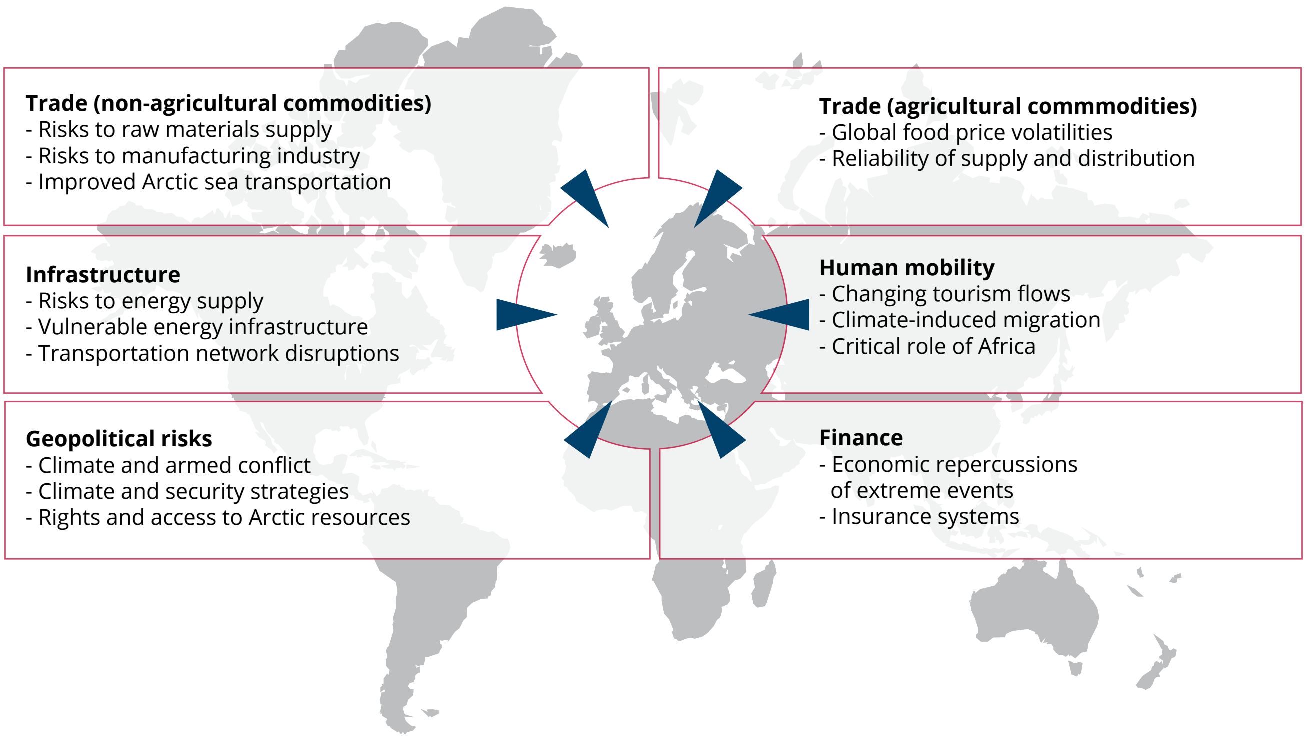
- Climate change impacts occurring outside Europe, but with indirect cascading effects for regions, sectors or people in European territory. An example is the 2008 severe crisis of Australia's rice production after six consecutive years of drought. That crisis strongly contributed to a doubling of the global market price for rice (Stephan and Schenker, 2012), in turn affecting European markets and consumers.

- Climate change impacts within Europe that cross national or regional borders, such as flood events along major European rivers. The example of recent floods events along the Danube show that the severity of flood impacts and damages in one location or European country is determined not only by increasingly severe heavy precipitation events but also by measures to reduce flood risk in other locations or countries (Mabey et al., 2014).

The primary focus of this section is on the first group, i.e. impacts occurring outside Europe but with cascading effects for climate change risk and vulnerabilities in European territory. Cross-border effects within Europe are mentioned only if they directly complement information from other parts of the report, such as Section 4.4 (increasing threat of invasive alien species), Section 5.2 (spread of vector-borne and water-borne diseases) and Section 5.6 (changes in European tourism flows).

The current knowledge on European vulnerability to climate change impacts that occur outside Europe is mostly qualitative or case specific. While much of the existing literature addresses the topic only marginally or indirectly, recently a few assessments with an explicit focus on cross-border impacts have become available, such as a study commissioned by the Directorate-General for Climate Action (DG CLIMA) (Barnett et al., 2013), national studies from the Netherlands (Vonk et al., 2015), Finland (Groundstroem et al., 2015) and the United Kingdom (Foresight, 2011; PwC, 2013; Challinor and Adger, 2016), and some work with a particular focus on coastal areas (Nicholls and Kebede, 2012) and the Adaptation Without Borders project (Benzie et al., 2016). In addition, the IPCC AR5 provides information in several of its chapters (Hewitson et al., 2014; Oppenheimer et al., 2014). This section summarises the current knowledge and is structured based on six major pathways for which sufficient information is available (see Figure 6.4).

Figure 6.4 Overview of major pathways of indirect impacts for Europe



Note: The impact pathways have been placed arbitrarily on the map; therefore, the arrows do not indicate any predominant geographic direction from which these impacts might affect Europe.

Source: EEA.

6.4.2 Trade: agricultural commodities

In most parts of the world, the observed impacts of climate change on terrestrial food production have been predominantly negative, in particular for maize and wheat (Porter et al., 2014). Over the past decade, there have been several periods of rapid food and cereal market price increases following extreme weather events in key producing regions, highlighting the sensitivity of world markets to climate extremes (Trostle et al., 2011; Nicholls and Kebede, 2012; Porter et al., 2014). These events have shown that climatic changes can have substantial consequences beyond the regions in which they occur through the global food trade system. Climate-induced changes in global price levels for food and feed are of great importance for Europe, which relies to a considerable extent on imports to meet domestic demand for food and feed (EEA, 2015). Increasing price volatility could eventually lead to supply disruptions for agricultural commodities with high import dependency (e.g. soybean), whereby price changes for animal fodder would further affect meat production (Barnett et al., 2013).

Several recent examples illustrate how climate impacts on agricultural production outside Europe (EEA member and collaborating countries) have affected Europe via regional and global markets and along international supply chains. The severe heat wave in Russia in the summer of 2010 destroyed 5.4 million hectares of crops, equivalent to about 30 % of Russia's grain harvest. This led to an export ban on wheat by the Russian government that contributed to an increase of 60–80 % in global wheat prices (Foresight, 2011; Coghlan et al., 2014). Similarly, a severe crisis in Australia's rice production in 2008 after six consecutive years of drought contributed, in conjunction with other factors, to a doubling of the global market price of rice in 2008 (Stephan and Schenker, 2012). It is important to note that, in both examples (Russian wheat and Australian rice), the observed global price volatilities resulted from a combination of the extreme weather events and the associated response measures (i.e. export ban and hoarding stocks). This highlights the role that countries and markets play in either amplifying or managing and minimising the effects of climate impacts on food supply.

The Mediterranean region in Europe has been identified as the most susceptible to shocks in the flow of agricultural commodities, owing to its relatively high dependence on food imports from regions outside Europe and the more prominent role of the food sector in its economy (Barnett et al., 2013). Moreover, low-income population groups in all parts of Europe (and elsewhere in the world) are likely to be disproportionally more affected by food price volatilities (Porter et al., 2014; Vonk et al., 2015). An IPCC review of projected climate change impacts on crop production shows that negative impacts on yields are assumed to increase during the 21st century, especially in low-latitude regions (e.g. in Asia and Africa), and that interannual variability of crop yields is assumed to increase as well, including in Europe (see also Section 5.3.4) (IPCC, 2014). Therefore, Europe's susceptibility to price volatilities of agricultural commodities and disruptions of trade flows might further increase in the future.

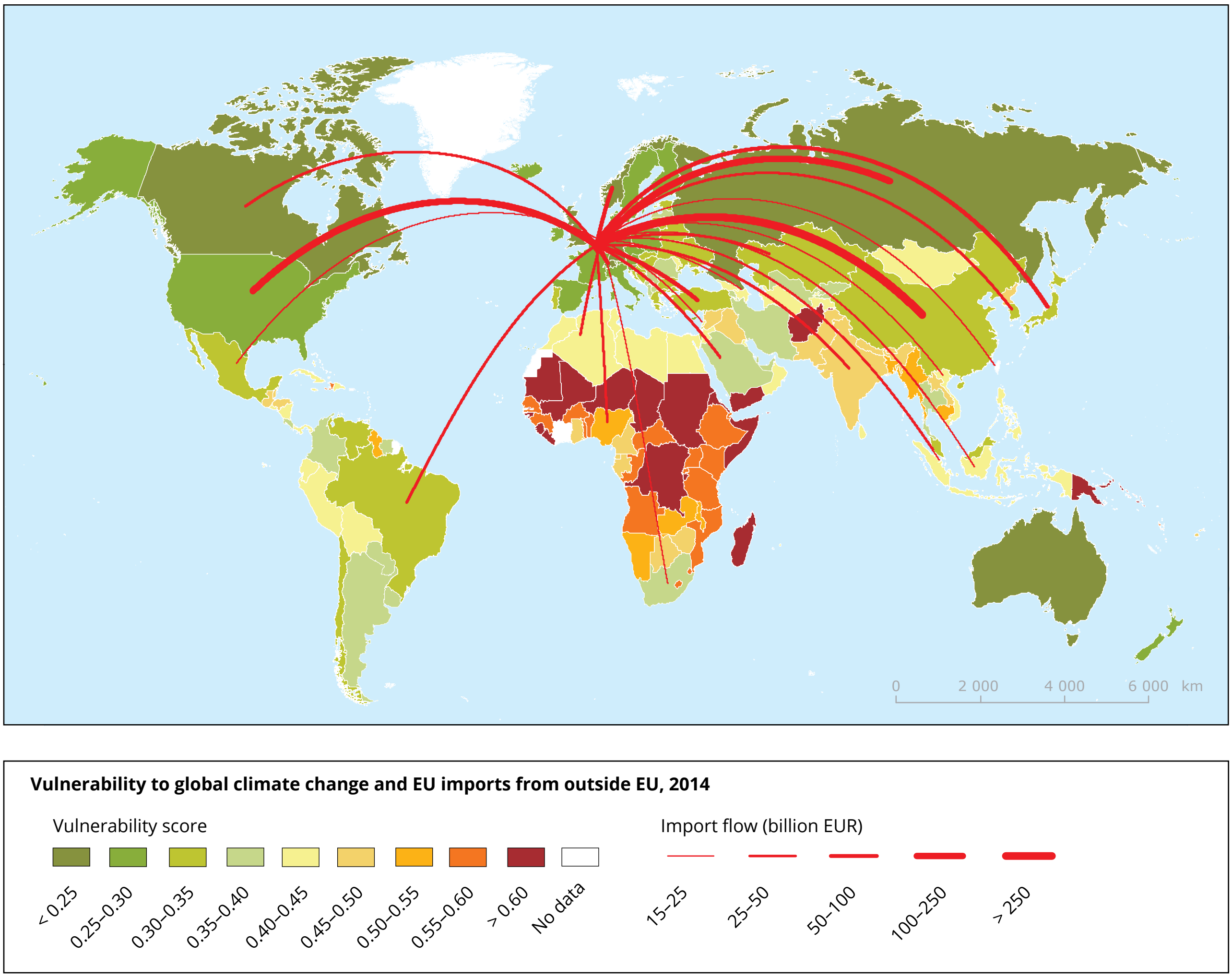
6.4.3 Trade: non-agricultural commodities

Europe is highly dependent on imports for many key resources; for example, 59 % of metal ores consumed in the EU-28 in 2013 were imported (EEA, 2015). This means that Europe's access to many resources and raw materials relies on exploitations in other world regions and associated international supply chains, which in turn may be significantly affected by climate change impacts (Nicholls and Kebede, 2012). As seen in Map 6.5, a substantial number of Europe's major trade partners (e.g. India, Indonesia, Nigeria and Vietnam) are estimated to exhibit an overall vulnerability to climate change ([122]) that is larger than in any European country. For example, primary and manufacturing industries can be affected by extreme climate events through impacts on infrastructure or transport (see Section 6.4.4).

An example of an indirect effect through a supply chain to Europe is the shortage of hard drives and the associated increase in price levels caused by a severe flood event in Thailand in 2011 (Nicholls and Kebede, 2012). Another recent event that disrupted international trade and commodity flows was the flood event in eastern Australia in 2010/11, which restricted various mining activities and damaged key transport infrastructures. This led to drastic declines in coal

([122]) The vulnerability score of the Notre Dame Global Adaptation Index (ND-GAIN; Chen et al., 2015) follows the outcome-based conceptualisation of vulnerability as used by the IPCC AR3 and AR4 (see Section 1.4 for details). The index consists of 12 indicators on projected biophysical climatic exposure (mostly for a time period around the middle of the century and the RCP4.5 scenario), 12 indicators on climatic sensitivity and 12 indicators on adaptive capacity, each associated with six different sectors (food, water, health, ecosystem services, human habitat and infrastructure). Another example of an indicator-based global assessment is the World Risk Index (Birkmann and Welle, 2015; Welle and Birkmann, 2015).

Map 6.5 **Largest European trade import flows from outside the EU and global climate change vulnerability, 2014**



Source: EEA, based on data from Chen et al., 2015, and Eurostat, 2016.

exports, causing world market prices to rise sharply over a period of three months (Hewitson et al., 2014). In Europe, small, open and highly developed economies with intense global trade and investments such as the Netherlands are regarded as particularly susceptible to these types of cross-border impacts (Stephan and Schenker, 2012), but large European economies such as the United Kingdom are also expected to be affected. One study suggests that indirect external effects of climate change on UK trade (and also food supply) could be even larger than domestic risks (PwC, 2013). A potentially major climate-related impact on global trade relates to the shrinkage of the Arctic sea ice. Under a high-emissions scenario (RCP8.5), a nearly ice-free Arctic Ocean in September is likely to be a reality before the middle of the 21st century (IPCC, 2013). Specific studies on the future accessibility of the Arctic region for shipping suggest that there will be increasing access throughout the 21st century with moderately ice-strengthened vessels (Polar class 6) for both the Northwest Passage and the Northern Sea Route, with almost complete access in summer (July–September) by the end of the century under three out of the four RCP scenarios (RCP4.5, RCP6.0 and RCP8.5) (Smith and Stephenson, 2013; Stephenson et al., 2013). This would mean a reduction of 5 500 km and 10 days compared with the traditional 20 000 km shipping routes from East Asia to Europe. In addition, the shrinking of sea ice might also provide (better) access to potentially vast amounts of mineral resources and potentially undiscovered sources of raw materials and fossil fuels in the exclusive economic zones of the countries bordering the Arctic (Hewitson et al., 2014). These new opportunities for transport and resource extraction are associated with numerous risks to the environment in the whole of the Arctic.

6.4.4 Infrastructure and transport

Climate impacts affecting transport, energy and communication infrastructure outside Europe, such as roads, pipes, railways, bridges, ports, airports and tunnels, can have spill-over effects (e.g. supply disruptions) in Europe. Increased weather- and climate-related extremes in the future are expected to increasingly cause damage to key infrastructures in most parts of the world (IPCC, 2012). In addition, infrastructures are also at risk from more gradual climate changes such as sea level rise or thawing of Arctic permafrost. Infrastructure features such as the connectedness of electricity grids are of particular significance, as they can both spread and reduce indirect impacts (EC, 2015a).

Impacts on coastal infrastructure are of particular concern for international transport and trade (Oh and Reuveny, 2010; Nicholls and Kebede, 2012). For example, ports are key nodes of international supply chains, as more than 80 % of global trade in goods (by volume) is transported over the sea. Likewise, over 35 % of all oil refineries globally are located in coastal zones. An example of indirect effects for Europe via impacts on coastal infrastructure outside Europe is the case of Hurricane Katrina. This event destroyed large parts of the port of New Orleans, which caused a temporary shortage in global oil supply and thereby triggered a temporary increase in the global oil price (Nicholls and Kebede, 2012).

Indirect effects from climate change for Europe's energy and material supply are also expected in relation to the projected thawing of Arctic permafrost. Increasing temperatures in the Arctic are expected to cause major threats to transportation routes on frozen ground, thus posing challenges to multiple economic activities such as forestry or mineral extraction, and they might also increasingly affect energy infrastructure (especially oil and gas pipelines) (Arent et al., 2014; Hewitson et al., 2014).

6.4.5 Geopolitical and security risks

Research is not conclusive about the extent to which global warming contributes to armed conflict (Theisen et al., 2013). Nevertheless, there is justifiable concern across many studies that climate change, and in particular changes in climate variability and extreme events, can increase the risk of armed conflict and geopolitical tensions in certain circumstances and when occurring in conjunction with other factors, such as poverty and economic shocks (Hsiang et al., 2013). As poverty and economic shocks themselves are sensitive to climate change (i.e. both factors may be amplified by climate change), climate change may become a key risk factor. Indeed, the IPCC identified violent conflicts and insecurity associated with the effects of climate change as being emergent risks and research priorities (Oppenheimer et al., 2014).

In Europe, climate change can be seen as a threat multiplier that may exacerbate existing trends, tensions and instability both within Europe and across European borders. Consequently, the effects of climate change are mentioned explicitly in the recent European Commission communication on the EU's approach to external conflicts and crises (EC, 2013). Likewise, the US national security strategy of 2015 has integrated climate change risks as a key geopolitical concern (US Government, 2015), and the G7 members have recently commissioned a report on this topic, 'A new climate for peace — Taking action on climate and fragility risks' (Rüttinger et al., 2015). It has been suggested that an increase in conflicts and natural disasters owing to climate change is likely to lead to a greater demand for relief in regions outside Europe and to a need for more European humanitarian aid (Vonk et al., 2015).

Of particular concern for Europe are the Mediterranean countries in North Africa and the Middle East (Brauch, 2010). Indeed, recent research suggests that an unprecedented drought in the southern Mediterranean has been one of many drivers (e.g. economic situation, governance) shaping local conflicts that triggered the Syrian civil war, which ultimately led to the current substantial increase in refugee flows to Europe. The study concludes that the likelihood of such an extreme drought in the southern Mediterranean has increased by a factor of two to three because of anthropogenic climate change (Gleick, 2014; Kelley et al., 2015). Likewise, recent results from regional climate modelling suggest that temperatures in large parts of the Middle East will exceed a threshold for human adaptability towards the end of 21st century under high emissions assumptions (RCP8.5) (Pal and Eltahir, 2016).

The impacts of climate change on the Arctic region (see above and Section 6.5) illustrate the multiple interactions between human security and geopolitical risks, even though they are not currently associated with direct geopolitical conflicts. For example, the projected changes (melting of sea ice, etc.) may affect claims concerning the borders of the exclusive economic zones in the Arctic and they may trigger conflicts about rights and access to new deposits of natural resources or transportation options (Houghton et al., 2010).

6.4.6 Human migration

Historical evidence suggests that climate variability is a contributing factor to migration (Lilleør and Van den Broeck, 2011). Extreme weather events, such as floods or extreme drought, are the most direct link between climate impacts and the displacement of people and migration, but more gradual changes (e.g. sea level rise) may also play a key role. In many cases, climate-related migration occurs within a country (from affected areas to safer zones) and is temporary. However, past incidences show that migration can also be international and permanent, whereby climate impacts at one location are indirectly transmitted to societies and states that receive the migrants from that location (Hallegatte, 2012). A global analysis encompassing all types of displacement (national, international, short-term and long-term) and adjusted for population growth suggests that the risk of being displaced by a weather- or climate-related disaster has increased by more than 50 % since the 1970s. Moreover, it is estimated that, since 2008, an annual average of 22.5 million people have been displaced globally owing to weather- or climate-related hazards (IDMC and NRC, 2015).

A rapidly growing body of literature examines migration patterns in relation to future environmental and climate change (EC, 2015b). Numerous studies have concluded that an increasing frequency and magnitude of extreme weather events as a result of future climate change will increase human migration, particularly for high rates of warming (Gemenne, 2011). There is largely agreement that the most vulnerable regions in terms of climate-induced emigration include low-lying island states, coastal and deltaic regions, and large parts of Asia and Africa, but quantitative projections about the number of people potentially displaced by region are not available (Gemenne, 2011; Nicholls and Kebede, 2012; Oppenheimer et al., 2014).

Of particular strategic significance for Europe is North Africa, for which decreasing precipitation levels and associated increases in drought risk during the 21st century are considered very likely (Niang et al., 2014). Furthermore, sea level rise is expected to increasingly threaten populous coastal areas such as the Nile Delta, where a large proportion of the Egyptian population and agricultural land is concentrated. It has been suggested that a sea level rise of 1 m could affect more than six million people in the Nile Delta (Mulligan et al., 2014). Likewise, the Sahel region has been identified as a hotspot region of climate change (Diffenbaugh and Giorgi, 2012). In that region, unprecedented mean annual temperatures (i.e. temperatures continuously outside historical bounds) have been projected to occur as early as the 2030s (Mora et al., 2013), with potentially significant consequences for local ecosystems and associated rural livelihoods (UNEP, 2011).

These trends, together with other driving forces, may cause a further increase in regional instability and increased migration northwards to Europe (Rodrigues De Brito, 2012). Likewise, climate change impacts in the Middle East may play an increasing role in migration flows to Europe (Kelley et al., 2015). In the face of these challenges, a global governance system to protect climate refugees has been proposed (Biermann and Boas, 2010). Such a regime for the recognition, protection and resettlement of migrants would build on principles such as international burden sharing and an international financing mechanism.

6.4.7 Finance

The financial pathway refers to those climate change impacts that may lead to disruptions in global financial markets or that may have repercussions for financial flows in various countries, such as overseas investments, remittances or global insurance (Groundstroem et al., 2015). An example of such a spill-over financial effect for Europe is Hurricane Katrina in 2005, for which a substantial amount of the insurance costs fell on the London stock markets (Nicholls and Kebede, 2012).

In particular, extreme weather events may lead to disruptions in global financial markets and constitute a significant burden for the insurance industry, as previously demonstrated by hurricanes along the south-east coast of the United States (Kron, 2012). The projected increase in the occurrence and intensity of extreme weather events in many parts of the world will challenge insurance systems, and it may trigger increases in insurance premiums and decreases in coverage (Arent et al., 2014). On the other hand, climate change provides opportunities for European insurance companies to invest in the developing world through, for example, micro-insurance programmes, climate index-based insurance products for both private clients and governments, and multi-country insurance risk pools (Herweijer et al., 2009).

6.5 Vulnerability to climate change in European macro-regions

Key messages

- Under continued climate change, the Arctic environment will, owing to the faster than average rising air and sea temperatures, undergo major changes affecting both ecosystems and human activities. Many traditional livelihoods are likely to suffer, but conditions for exploiting in particular non-renewable natural sources may become more favourable.
- The Baltic Sea region, in particular its southern part, is expected to experience an increased risk of storm surges owing to sea level rise, changing precipitation and run-off regimes, and biota shifts as a result of warmer coastal sea waters.
- All mountain regions are expected to be negatively affected in relation to their water resources and ecosystems in the next decades. Changing river flow regimes are expected to increasingly affect hydropower production capacities in most mountain regions, winter tourism is projected to be negatively affected by a reduced snowfall period, and increased slope instabilities may affect infrastructure and settlements.
- The Mediterranean region is projected to be increasingly affected by severe impacts on several sectors, in particular water resources, agriculture, forestry, biodiversity, tourism and energy.
- The European Union outermost regions and the overseas countries and territories, which are characterised by very rich biodiversity and high concentrations of endemic species, are recognised as particularly vulnerable to climate change impacts mainly because of sea level rise and extreme weather and climate events.

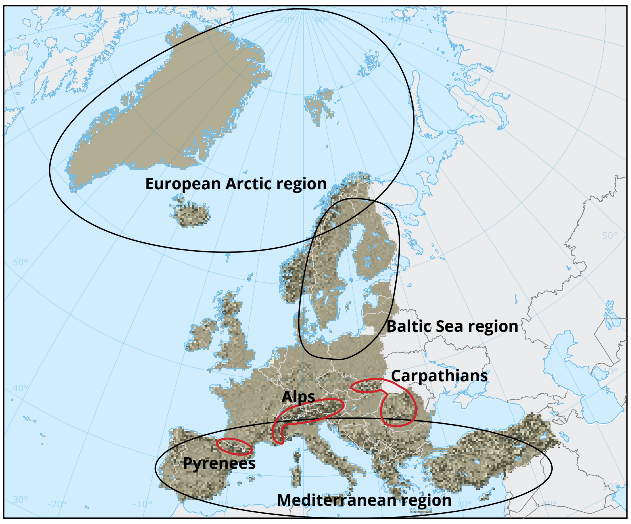
6.5.1 Introduction

This section reviews recent and projected climate change impacts and vulnerabilities for selected European macro-regions. A macro-region in this context is understood broadly to be a transnational region crossing administrative boundaries with common biogeographical characteristics, thus exhibiting particular climate change impacts and vulnerabilities. Only the macro-regions for which comprehensive assessments of climate change impacts and vulnerabilities are available have been considered.

The purpose of this section is to give a synthesis of the most recent regional assessments available for these macro-regions. As a result, there are some differences in the presentation of the various regions. In particular, some assessments focused on climatic and environmental changes, whereas others gave more attention to social and economic vulnerability. For an overview of adaptation policy development in European macro-regions, see Section 2.5.

The following macro-regions will be covered: the European Arctic, the Baltic Sea region, three mountain regions (the Pyrenees, the Alps and the Carpathians), the Mediterranean and the EU overseas entities (EU outermost regions and the overseas countries and territories) (see Map 6.6). For the Arctic region, the following text mainly addresses Arctic regions within (or associated with) EEA member and collaborating countries, i.e. Greenland, Iceland, Svalbard and the northern parts of Norway, Sweden and Finland. Furthermore, this section addresses only the northern part of the Mediterranean region that is within EEA member and cooperating countries.

Map 6.6 Overview of macro-regions in Europe



Note: The map broadly delineates various macro-regions in Europe that are covered by climate change impact assessments in this section. The map is provided for illustrative purposes only, and it does not intend to provide a legal definition of any of these regions.

Source: EEA.

6.5.2 The Arctic region

The Arctic is commonly defined as the region above the Arctic Circle (approximately 66 °N), but other definitions exist, such as 60 °N or using temperature or biological thresholds. The Arctic hosts a set of unique ecosystems and also plays an important role in the global climate system. Politically, the Arctic has been defined through the Arctic Council, whose members are Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, the Russian Federation, Sweden and the United States of America (see Section 2.5).

Temperatures have increased about twice as fast in the Arctic as in the mid-latitudes in an 'Arctic amplification' (Overland et al., 2014). In the absence of a strong reduction in the Atlantic Meridional Overturning, the Arctic region is also projected to continue to warm more than other regions (Collins et al., 2013) (see Section 3.2.2). The faster than average increase in temperatures is a strong driver of climate-related changes in the Arctic. The Arctic is vulnerable to these temperature increases because they affect key features, such as sea ice extent and seasonal variation in ice and snow, the ice sheet mass balance, glaciers and permafrost, and snow cover (see Section 3.3) with knock-on effects on the hydrology of Arctic waters (AMAP, 2011). The dynamics of the freshwater systems with increasing precipitation and thawing permafrost will be reflected in water courses and altered patterns of lakes and wetlands and the ecosystems they support (CliC et al., 2016). Research furthermore suggests that there are strong positive ice–temperature feedbacks in the Arctic, and thus the rapid warming and reduction in sea ice are likely to continue (Screen and Simmonds, 2010). Overall, the Arctic is becoming warmer and wetter (Boisvert and Stroeve, 2015).

The physical changes will in turn affect Arctic aquatic and terrestrial ecosystems, and a wide range of human activities, ranging from the exploitation of fossil fuel reserves, transportation and the building of infrastructure to reindeer herding (Arctic Council, 2013). For example, the loss of permafrost increases the risk of damage to infrastructure. At the same time, longer ice-free seasons and shorter periods of snow cover provide new opportunities for the use of natural resources and for sea transportation (see Section 5.5).

The Arctic Monitoring and Assessment Programme has produced an overview of key issues related to climate change in the Arctic (AMAP, 2013). Human development, biodiversity and oceans are directly vulnerable to the consequences of climate change, but, as the Arctic is a complex socio-ecological system, there are also many interactions between human activities, biodiversity and oceans (Arctic Council, 2013).

Arctic ecosystems have evolved under climatic conditions that have been characterised by long periods of sub-zero temperatures, snow, ice and permafrost and are, therefore, sensitive to an increased duration of above-zero temperatures. With progressing climate change, winters will become shorter and permafrost will thaw. The thawing of permafrost may also accelerate climate change (Schuur et al., 2015).

In the Arctic, specific habitats for flora and fauna (including sea ice, tundra and permafrost peatlands) have been partially lost over recent decades. Arctic vegetation zones are likely to shift, causing wide-ranging secondary impacts. Some species of importance to Arctic people as well as species of global significance are declining. Climate change is emerging as the most far-reaching and significant stressor on Arctic biodiversity (Meltofte, 2013). Moreover, marine ecosystem acidification may become a serious threat, as acidification can progress more rapidly in Arctic oceans owing to low temperatures and considerable influx of freshwater (Chierici and Fransson, 2009; AMAP, 2014). Hitherto unexpected consequences such as mixing of Pacific and Atlantic fish species may also be a result of warming (Wisz et al., 2015).

The Arctic differs from many other parts of Europe by having a relatively large proportion of indigenous people. Livelihoods that depend directly on ecosystem services are still common. Consequently, a range of climate change impacts have already been experienced by local residents in different communities of the Arctic (Gofman and Smith, 2009). Although some communities lack the appropriate resources for effectively adapting to the projected changes, it is also known that many Arctic communities have, because of the naturally harsh and variable conditions, developed a considerable capacity to deal with climatic variability (Stepien et al., 2014). Climate change is, however, not an isolated phenomenon, and the traditional livelihoods, such as reindeer herding, that are under pressure from a range of socio-economic and political developments may suffer (Pape and Löffler, 2012).

The Arctic has abundant renewable and non-renewable natural resources that hitherto have been difficult to exploit. Progressing climate change with shifts in the distribution and seasonal occurrence of snow and ice cover affect transport options and infrastructure, and thus access to resources (CliC et al., 2016). Climate change may therefore increase pressures on fragile Arctic environments but also on traditional livelihoods of indigenous people through competition for space or through environmental impacts caused by the exploitation of natural resources (AMAP, 2013). The changing socio-economic landscape interacts with climate change impacts and can erode cultural traditions, have an impact on food sources and influence migration, leading to shifts in the demography in the Arctic (UNESCO, 2009).

Climate change both offers opportunities for and threatens human use of Arctic ecosystem services and the exploitation of Arctic natural resources. However, for the unique ecosystems and species that are adapted to long periods of sub-zero temperatures, global warming is exclusively a threat, which can be reduced only by mitigating climate change.

6.5.3 The Baltic Sea region

This section is based on the Second assessment of climate change in the Baltic Sea basin (The BACC II Author Team, 2015), which describes observed and projected climatic changes in the atmosphere, on land and in the sea, and their observed and projected impacts.

Despite large multi-decadal variations, there has been a clear increase in surface air temperature in the Baltic Sea basin since the beginning of the observational record in the region in 1871. Linear trends in the annual mean temperature anomalies from 1871 to 2011 were 0.11 °C per decade north of 60 °N and 0.08 °C per decade south of 60 °N in the Baltic Sea basin. No long-term precipitation trend was observed for the whole region, but there is some indication that there was a tendency towards increasing precipitation in winter and spring during the latter half of the 20th century. No long-term trend has been observed in annual wind statistics since the 19th century, but there have been considerable variations on (multi-)decadal time scales. A northwards shift in storm tracks and increased cyclonic activity have been observed in recent decades, with an increased persistence of weather types.

No statistically significant long-term change has been detected in total river run-off to the Baltic Sea during the past 500 years. However, increased annual, winter and spring stream flow values, as well as earlier snowmelt floods, were observed in the northern regions, whereas a decrease in annual discharge from southern catchments of the Baltic Sea of about 10 % has been observed over the past century. For river ice, a decreasing trend was observed over the past 150 years, with an even clearer trend for the past 30 years, indicating a reduction of ice cover duration and a shift to earlier ice break-up. Decreasing trends have also been observed for snow cover and frozen ground.

The annual mean sea surface temperature of the Baltic Sea increased by up to 1 °C per decade in the period 1990–2008, with the greatest increase in the northern Bothnian Bay. Overall, a clear trend in salinity cannot be detected. Sea ice shows large interannual variability, but a change towards milder ice winters has been observed over the past 100 years. Both the annual maximum ice extent and the length of the ice season have decreased.

Sea level rise of around 1.5 mm/year, comparable to the global sea level rise, has been measured in the Baltic Sea. However, recent data have indicated a rise of around 5 mm/year (± 3 mm/year) with the central estimate thus higher than the recent global mean of 3.2 mm/year (The BACC II Author Team, 2015). There is some evidence that the intensity of storm surges may have increased in recent decades in some parts of the Baltic Sea, and this has been attributed to long-term shifts in the tracks of some types of cyclone rather than to long-term change in the intensity of storminess.

Future climate change in the Baltic Sea region has been assessed by means of dynamic downscaling (results from 13 RCM simulations of the ENSEMBLES project) and of statistical downscaling studies (The BACC II Author Team, 2015). Air temperatures in the Baltic Sea area are projected to increase further for all seasons under all of the different SRES levels, with a warming rate generally greater than the corresponding global one. The greatest level of warming is projected for the northern part of the region in winter. Under all SRES levels, winter precipitation is projected to increase across the entire Baltic Sea region, while summer precipitation is projected to increase only in the northern half of the basin and to change very little in the southern part of the region. Extremes of precipitation are also projected to increase. Model projections for wind diverge so there is no robust evidence on the direction of future changes.

Snow cover extent, duration and amount have been observed to be decreasing in the region, although with large interannual and regional variation. The amount of snow is projected to decrease considerably in the southern half of the Baltic Sea region, with median reductions at the end of the century of about 75 % with respect to the period 1961–1990 (as simulated by RCMs using the SRES A1B scenario) (The BACC II Author Team, 2015, Chapter 6, 11). A decrease in river run-off is possible, even in areas with increased precipitation, if it is overcompensated for by increasing evaporation (The BACC II Author Team, 2015, Chapter 21).

The water temperature of the Baltic Sea is projected to increase significantly, and sea ice cover is projected to decrease significantly under all of the greenhouse gas emissions scenarios used (covering the range between SRES B1 and A2) (The BACC II Author Team, 2015, Chapter 13). Sea level in the Baltic Sea may rise at a similar rate as is projected globally (The BACC II Author Team, 2015, Chapter 14). Sea level rise also has a greater potential to increase storm surge levels in the Baltic Sea than increased wind speed (Gräwe and Burchard, 2012).

The projected warming may affect the northwards migration of terrestrial and aquatic species resulting in longer reproductive periods for coastal fauna and flora in the Baltic Sea region and a northwards shift of the hemiboreal and temperate mixed forests. The effects of climate change facilitate invasions by non-indigenous aquatic bird species, such as cormorants (Herrmann et al., 2014), as well as mammalian predators, which could cause major changes in coastal communities (Nordström et al., 2003). There are indications that the transport of dissolved organic matter and total nitrogen fluxes to the Baltic Sea may increase considerably (Omstedt et al., 2012).

In the deep waters of the Baltic Sea, increasing areas of hypoxia and anoxia are anticipated owing to the increased nutrient inputs due to increased run-off, reduced oxygen flux caused by higher air temperatures, and intensified biogeochemical cycling, including mineralisation of organic matter. Cyanobacteria (blue-green algae) blooms are expected to start earlier in summer (Neumann, 2010; Meier et al., 2012; Neumann et al., 2012). A change in seasonal succession and dominance shifts in primary producers in spring is projected, as well as a general shift towards smaller sized organisms. A potential climate-induced decrease in salinity, together with poor oxygen conditions in the deep basins, could negatively influence Baltic cod and may lead to a reduction of marine fauna (Hinrichsen et al., 2011). A reduced duration and spatial extent of sea ice may cause habitat loss for ice-dwelling organisms and may induce changes in nutrient dynamics within and under the sea ice. A model simulation of future marine acidification in the Baltic Sea implies that rising atmospheric CO_2 levels dominate future pH changes in sea surface water, whereas eutrophication and enhanced biological production are not affecting the mean pH value. The projected decrease in pH of surface water by 2100 ranges from about 0.26 (best scenario) to about 0.40 (worst scenario) (Omstedt et al., 2012). In addition, overfishing and eutrophication may erode the resilience of the ecosystem, making it more vulnerable to climatic variations.

Climate change impacts on forestry and agriculture differ with location. Growing conditions tend to improve in the northern boreal zone owing to higher temperatures, increased CO_2 and increased water availability, while reduced precipitation (in the growing season) and higher temperatures would lead to deteriorating growing conditions in the southern temperate zone.

In general, the southern part of the Baltic Sea basin, with its low-lying coasts and higher anthropogenic pressure than the northern part, is expected to be more vulnerable to the above-mentioned impacts of climate change: an increased risk of storm surges owing to sea level rise, droughts in the summer as a result of a potential change in the precipitation and run-off regime, and possibly more frequent extreme precipitation events.

6.5.4 Mountain regions: the Pyrenees

This section is based on recent assessments by the Pyrenees Climate Change Observatory (OPCC) (OPCC and CTP, 2013; OPCC, 2015).

In the whole Pyrenees region, an increase of the mean surface air temperature of the mountain range of 0.21 °C per decade and a decrease in precipitation by 2.5 % per decade have been observed in the period 1950–2010 (OPCC, 2015). Climate projections indicate that the mean air temperature across the mountain range of this region will increase in the range of 1–2 °C by 2030 and 2.5–5 °C by 2100 compared with the current situation. Furthermore, the frequency and intensity of heat waves is projected to increase, in particular in the north-western and south-eastern parts of the region (AEMET, 2008; López-Moreno et al., 2008). These changes will have an impact on spatial expansion, persistence and thickness of snow cover. Projections according to the SRES A1B scenario suggest a reduction in snow cover of about 1.5 months at an altitude of 1 800 m in the south-western part by 2030, with respect to the reference period 1961–1990 (Déqué, 2012).

A reduction of 10–20 % of accumulated annual precipitation is projected by 2100, with the largest decline (about 40 %) in summer and largely unchanged precipitation patterns in winter (AEMET, 2008; López-Moreno and Beniston, 2009). Moreover, more frequent and intense droughts are projected owing to the reduction in summer precipitation and temperature rise, causing an increase in evapotranspiration (EEA, 2012).

The major river basins (the largest of which are the Ebre, the Garonne and the Adour), situated downstream of the region, are supplied from the

Pyrenees water resources. Reductions of up to 40 % of the flow of the Garonne river (MEDDE, 2013), 0–35 % of the flows of the Catalan rivers (ACA, 2009) and 20 % of the flow of the Ebre river in the summer season are projected for 2060 (Confederación Hidrográfica del Ebro, 2005). On the other hand, climate change is projected to lead to increased water demand (e.g. increase in irrigation needs and in drinking water demand in hot periods), which could further amplify the pressure on the water sector (SOGREAH, 2011).

Climate change is also projected to have an impact on forests — particularly conifers, as they are less adaptable to dry conditions — and agriculture, potentially leading to a decrease in average yields close to 12 % by 2025 (see Sections 4.4 and 5.3). On the other hand, the foothill grasslands and mountain summer pastures are expected to increase their biomass production in spring (maximum production period) and autumn, and to lengthen their production period, which will increase their exploitation possibilities (hay or pasture) (Felten, 2010; Brisson and Levrault, 2012). The risk of forest fires is expected to increase, especially in the summer, as temperature rises and precipitation declines.

Hydroelectric power generation in the Catalan Pyrenees has already decreased by 40 % in the 2003–2007 period, compared with average generation, and a further decrease in hydraulic power potential of 20–50 % is projected by 2070 (CTP and OPCC, 2012).

Tourism, which is a major economic sector for the Pyrenees, will be affected by future climate change (see Section 5.6). In particular, winter tourism is projected to be affected by a reduction in the length of the snowfall period (see Section 3.3.5), ranging between 40 and 55 days in 2030 at an altitude of 1 800 m and between 50 and 85 days in 2100 (for scenario A1B with respect to the period 1961–1990) (CTP and OPCC, 2012). This reduction of the snowfall period will be the result of a large decrease in snowfall and higher air temperatures, which will also move the altitude at which snow is stable from 1 800 m to 2 200 m in the region. This might lead to a potential reduction of the snow cover area by more than 50 % on the southern slopes of the Pyrenees region (ACA, 2009). Even though there will be a high local variability on the level of the impacts, an overall decrease of the season length and an increase of the snowmaking necessity is projected for most of the Pyrenean ski resorts (Pons et al., 2014, 2015). Finally, in the future, increases in the frequency and intensity of heat waves are expected to lead to increased health risks for the Pyrenees population, owing not only to heat but also to heat waves increasing peak air pollution in the main urban areas of the Pyrenees (CTP and OPCC, 2012).

6.5.5 Mountain regions: the Alps

Analysing the climate change impacts and vulnerabilities of this region is particularly relevant, as the Alps are the living and working space for more than 14 million people and are characterised by fragile ecosystems and specific topographical conditions, which determine not only climate sensitivities, but also non-climatic aspects such as settlement practices (Permanent Secretariat of the Alpine Convention, 2011).

The main climatic drivers of vulnerability to climate change in the Alps can be summarised by an increase in temperature higher than the global average, an observed increase in annual precipitation in the north-west and a decrease in the south-east of the Alps (Auer et al., 2005, 2007, 2014), a past and present decrease in seasonal precipitation during summer over all of the Alps and an increase in precipitation in winter in the north-west, as well as a pronounced variability in precipitation patterns, and an expected change in the intensity of extreme weather events.

From the late 19th century until the end of the 20th century, the Alpine region experienced a total annual mean temperature increase of about 2 °C, nearly twice the average in the northern hemisphere (Auer et al., 2014; Gobiet et al., 2014). As regards precipitation, despite the differences deriving from seasonal and geographical conditions (Gobiet et al., 2014), a general shift in precipitation peaks from summer to winter is projected for most of the Alps (BMU, 2008; Schöner et al., 2010), while the south and south-east will become significantly drier in all seasons (EEA, 2009; Haslinger et al., 2015). Owing to warmer temperatures, winter precipitation is projected to fall more frequently as rain. Moreover, an increase in the intensity and frequency of extreme weather events (heavy rainfall, drought periods, heat waves and possibly also storms) is expected in the whole Alpine region.

Since 1900, the Alpine glaciers decreased in their ice mass by about 50 % (Zemp et al., 2008; Huss, 2012) and a recent study (Radić et al., 2013) has estimated a loss between 84 % and more than 90 % of their current volume by 2100 under RCP4.5 and RCP8.5 scenarios, respectively (see Section 3.3.4).

The main non-climatic drivers of vulnerability derive from the specificities of the Alpine topographical conditions, and are, in particular, the limited settlement space available and the subsequent intensification of land use. The ongoing development of settlements — including their expansion into hazard zones — enlarges the surface area, population and material assets exposed to risk and hazards, resulting in the need for ad hoc planning and building practices, such as densification (Permanent Secretariat of the Alpine Convention, 2015). This can aggravate the pressure on the territory and can lead to adverse spill-over effects on environmental quality. Owing to the subsequent fragmentation of habitats, this can also have an impact on biodiversity and species distribution, which are likely to be adversely affected by climate change.

Decreasing water availability in the dry period — as a consequence of expected changes in the precipitation patterns and the melting of the glaciers — will reinforce the competition between different water usages, such as drinking water, irrigation, energy production and tourism-related uses, as well as between upstream and downstream territories (see Section 4.3). Moreover, the hydrological system is projected to become more sensitive to extreme weather events. The impacts of changing river flow regimes on hydropower production capacities are a key issue for energy production in the Alpine region, in particular in the longer term (Ballarin-Denti et al., 2014) (see Section 5.4). The development of new renewable energy production units will be the key adaptation measure, but could face possible conflicts with nature and landscape protection and with other activities such as tourism, agriculture and forestry.

The Alpine region is regarded as highly susceptible to mountain-specific climate-related hazards, such as gravitational mass movements (e.g. debris flows and landslides), torrential processes and floods (Gobiet et al., 2014). These risks from natural hazards are likely to increase as a consequence of different effects, such as changes in precipitation patterns, increased soil erosion, permafrost degradation and the destabilisation of mountain slopes. This reduces the suitable areas for settlement, reinforcing the competition between the different forms of land use and directly affecting infrastructures for transport and energy distribution.

Global climate change causes additional threats to Alpine biodiversity (EEA, 2010; Engler et al., 2011; Dullinger et al., 2012; Gottfried et al., 2012). Their high degree of specialisation makes Alpine species less tolerant and more vulnerable to changes in ecological conditions. Owing to shifting climatic zones, many plant and animal species face extinction risks because upwards or northwards migration is not possible, especially for high-altitude species. Observations show that the specialised species growing at high altitudes are replaced by more competitive species from lower regions (see Section 4.4).

Forest ecosystems are already affected and are expected to face increased losses and damage costs from multiple climate-induced effects, e.g. higher tree mortality, more pest species calamities, higher water stress and greater forest fire frequency. This will have a negative impact on both the regulative ecosystem services of forests and the entire forest wood-production chain (Umweltbundesamt, 2007, 2013).

In the agriculture sector, the impact of climate change will vary in different parts of the Alps (Fuhrer et al., 2006; Tamme, 2012; Mitter et al., 2015). In some regions, the average yield potential will increase, and some crop species, such as grapevine, may find new opportunities in areas that were not suitable to them before. In the southern part of the Alps, the change in precipitation could increase the risk of droughts.

Tourism is another important sector in the Alps that, on the one hand, is likely to be subjected to pressures deriving from climate change, owing both to lower snow reliability in winter (see Section 3.3.5) and to an increase in risks from natural hazards. On the other hand, there may be a new touristic opportunity for the Alps in a revival of summer cool-seeking tourism (see Section 5.6).

6.5.6 Mountain regions: the Carpathians

This section is mainly based on the final report of the CARPIVA ([123]) project, in which the results of the CARPATCLIM ([124]) and CarpathCC ([125]) projects are integrated (Werners et al., 2014).

Rising temperatures have been observed in all seasons for the period 1961–2010, with the strongest warming of up to 2.4 °C (depending on location and altitude) in summer seasons. The lowest rates of warming have been measured in winter, with temperature increases mostly lower than 0.4 °C. Model projections according to the SRES A1B scenario suggest an increase in temperature of up to 1.8 °C for the period 2021–2050 compared with the reference period 1961–1990, with greater temperature increases in the southern parts of the region (see Section 3.2.2). Regarding precipitation patterns, observations have shown increasing annual precipitation in most of this region in the last 50 years, except for the western and south-eastern areas, where precipitation has been decreasing. Projections suggest

([123]) CARPIVIA: 'Carpathian integrated assessment of vulnerability to climate change and ecosystem-based adaptation measures'; see http://www.carpivia.eu.
([124]) CARPATCLIM: 'Climate of the Carpathian Region'; see http://www.carpatclim-eu.org/pages/home.
([125]) CarpathCC: 'Climate Change Framework Project'; see http://www.carpathcc.eu.

further precipitation increases (up to 10 %) in winter but a decrease of about 15 % in the summer period (Werners et al., 2014).

The Carpathians include eastern Europe's largest contiguous forest ecosystem, which provides habitat and refuge for many endangered species. The native flora of the Carpathians is among the richest on the European continent. It is composed of almost 4 000 species, representing approximately 30 % of the European flora. The Carpathians contain Europe's largest populations of brown bears, wolves, lynx, European bison and rare bird species. The promotion of sustainable agriculture, forestry and tourism are crucial for safeguarding the diversity, continuity and robustness of these ecosystems, allowing species to migrate under changing climatic conditions to areas that better meet their living conditions. The seven countries with a share of the Carpathian territory are characterised by large socio-economic differences, which in turn shape climate change vulnerability and response capacities (Werners et al., 2014).

The factors projected to most affect the water sector are increasing temperatures, increasing winter precipitation and decreasing summer precipitation. Decreasing summer flows would have negative impacts on ecosystems and ecosystem services. Periods when ecological water demands will not be met are projected to increase, with potentially irreversible damage to aquatic and riparian ecosystems. Settlements, agriculture and industry are projected to be affected by more frequent periods of water shortages. At the same time, increasing wintertime flows are likely to exacerbate existing flood problems (see Section 4.3.3). The vulnerability of water resources shows a clear south–north gradient, with higher risks in the south, owing to a combination of climatic, topographical and economic factors (Werners et al., 2014).

In the context of the CarpathCC project, integrated forest vulnerability to climate change has been assessed on the basis of exposure and sensitivity components and adaptive capacity. This study shows that the vulnerability of forest ecosystems is highest in the southern and western parts of the Carpathian region (see Map 6.7). This is attributed to the fact that the condition of the trees has deteriorated and the composition of the forests has changed owing to increased drought events, with the result that pests can occur more easily (Werners et al., 2014).

The Carpathian wetlands and grasslands are also vulnerable to the combined pressure from climate change and human activities. The most vulnerable wetland habitats are peatlands, owing to their limited resilience to climate variability and human activities, such as changes in land use. Less vulnerable are halophytic habitats, steppes and marches. These habitats can adapt to climate fluctuations, yet are highly sensitive to human activities and changes in land use. The lowest vulnerability is found in habitats already subjected to regular flooding, such as subterranean wetlands and some riverbank and water habitats. Grasslands in the region have strong cultural associations, provide a wide range of ecosystem services and associated economic benefits, and are rich in wildlife and biodiversity. The species-rich *Nardus* grasslands in (sub-)mountain areas, where management possibilities exist, are less vulnerable, while the (sub-)Alpine grasslands on calcareous sites are more vulnerable to changing climatic conditions (Werners et al., 2014).

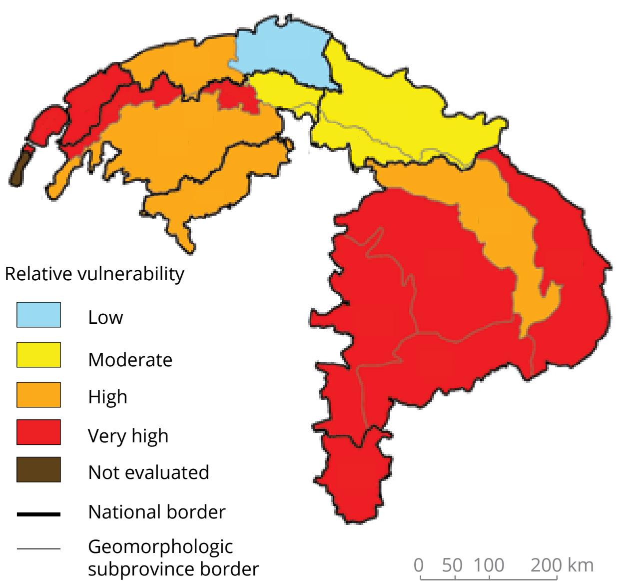
Currently, changes in the turnover of the tourism sector are much more dependent on general economic performance than on climate change. On the other hand, several tourism activities may potentially be positively affected by future climate change (e.g. ecotourism, summer tourism, health tourism, vocational tourism), while other activities such as fishing, hunting and winter sports are expected to be affected negatively (Werners et al., 2014).

6.5.7 The Mediterranean region

This section is mainly based on the first two volumes of the Regional Assessment of Climate Change in the Mediterranean (Navarra and Tubiana, 2013a, 2013b) as part of the FP6 CIRCE project. This is so far the only comprehensive regional assessment of climate change observations, projections, impacts and vulnerabilities for the Mediterranean region that applies an integrated interdisciplinary approach to assess how climate is expected to affect ecosystems, key economic sectors and societies.

The large environmental diversity and unique biotic and abiotic characteristics of the Mediterranean Sea, the largest of the semi-enclosed European seas, are undergoing rapid changes owing to increasing natural and human pressures (EEA, 2015). In particular, the physical dynamics and hydrological structure of the Mediterranean are influenced by climate change impacts and the increasing nutrient and pollutant loads discharged into several areas of the basin. Furthermore, the Mediterranean has been identified as one of the main climate change hotspots in Europe, where potential impacts may be particularly severe, with a large number of sectors affected (see also Section 6.2) (Giorgi, 2006).

Map 6.7 Vulnerability of the forest sector in the Carpathian region



Note: The map shows the vulnerability of forests in the Carpathian region (see Map 6.6 for the location) to climate change, evaluated in the frame of geomorphological units on the basis of several indicators of climatic exposure, forest climatic sensitivity and adaptive capacity.

Source: Adapted from Barcza et al., 2013.

Climate observations show that there has been a progressive and substantial drying of the Mediterranean land surface since 1900 (e.g. a change of the Palmer Drought Severity Index by – 0.2 units per decade), consistent with an increase in surface air temperatures and a decrease in precipitation. The analysed sea level data show a rise of about 150 mm in the last two centuries, and a 20-year-long reanalysis (1985–2007) of marine temperature and salinity detected long-term temperature variability and a positive salinity trend in the ocean layers from the surface to a depth of 1 500 m. Regarding extreme climate and weather events, heat wave durations and frequencies have been observed to have increased more than six-fold since the 1960s (Kuglitsch et al., 2010).

A significant surface warming of about 1.5 °C in winter and about 2 °C in summer and a decrease in mean annual precipitation (about 5 %) is projected in this region for the period 2021–2050 compared with the period 1961–1990 under SRES A1B emissions, with the largest changes projected for the summer months (Gualdi et al., 2013). Sea level rise in the Mediterranean Sea is expected to be in the range of 6.6–11.6 cm in the period 2021–2050 with respect to the reference period 1961–1990. Furthermore, more frequent very hot days and nights, longer warm spells and more intense and frequent heat waves are projected for the whole Mediterranean region (Navarra and Tubiana, 2013b) (see also Section 3.2.3).

Climate change also interacts with other non-climatic drivers in the Mediterranean (Navarra and Tubiana, 2013a, Chapter 2), such as urbanisation and other socio-economic modifications, land-use changes (Santini and Valentini, 2011) or changes in tourism flows. All these factors combined are likely to cause significantly increasing climate-related risks and vulnerabilities in the region (see also Section 6.2). Of the range of different climate impacts in the Mediterranean region, water availability is considered the most critical (EEA, 2012). The new expected climate regime, under the combined effects of precipitation decrease and near-surface air temperature increase, is expected to affect the hydrological cycle with a general decline in water availability in terms of groundwater recharge, superficial water flow and soil moisture (Santini et al., 2014). Furthermore, the decrease in water resource reliability is related to the increased variability of streamflow, including an earlier decline in high flows from snowmelt in spring, an intensification of low flows in summer, more irregular discharges in winter, and changes in reservoir inputs, including reduced availability of or less reliable discharges from dams to meet the water demand from irrigated and urban areas. These factors act in conjunction with other drivers such as changing patterns of land use, population increase, increasing water demands for agricultural, industrial, energy and domestic consumption, and inappropriate water management (García-Ruiz et al., 2011), all of which make the Mediterranean water sector highly vulnerable under future climate change (Navarra and Tubiana, 2013b).

The projected reduction in mean precipitation and the increase in interannual and intra-annual precipitation variability, alongside inefficient water resource management in some areas of this region, will negatively affect water availability for a large number of people. In particular, shortages of water resources are projected in some northern areas of Spain (Arias et al., 2014) and Italy (Senatore et al., 2011; Gunawardhana and Kazama, 2012), where some water production is currently non-sustainable (overexploitation of renewable and non-renewable water reserves) (Navarra and Tubiana, 2013b).

The Mediterranean region is projected to be affected by losses of agricultural yields and carbon storage potential, increased fire risks and biome shifts (Navarra and Tubiana, 2013a; Santini et al., 2014). Mediterranean ecosystem services are particularly sensitive to extreme events or seasons, such as very hot and dry summers

(Ciais et al., 2005; Reichstein et al., 2007; Vennetier et al., 2007; Navarra and Tubiana, 2013a, Chapter 3) and mild winters or windstorms and heavy rains (IPCC, 2014). Ecosystem services are also threatened by long-term climate-driven changes such as aridification and degradation, eventually leading to irreversible desertification (Rubio et al., 2009; Santini et al., 2010). Future climate change is also projected to affect typical Mediterranean crops, e.g. grapevine, durum wheat and olive (Ponti et al., 2014; Tanasijevic et al., 2014; Saadi et al., 2015). In particular, the area suitable for olive trees is projected to undergo a northwards and eastwards shift owing to the projected warming and drying (Mereu et al., 2008; Navarra and Tubiana, 2013a, Chapter 4). Agriculture also includes the farming of animals, which will be exposed to increased heat stress during summer (Navarra and Tubiana, 2013a, Chapter 7).

Impacts of climate change on the Mediterranean forests (see Section 4.4) are already evident in ecophysiology, productivity, dieback and some shifts in species distributions (Bréda et al., 2006; Vennetier et al., 2007; Allen et al., 2010), and these impacts are projected to further increase as a result of the projected climate change. In particular, the distribution range of typical Mediterranean tree species is likely to decrease in the region, but it could expand to new areas with new Mediterranean-like climatic conditions (Jump et al., 2006; Ruiz-Labourdette et al., 2012). Projected climate change for the Mediterranean region is likely to increase fuel dryness and reduce relative humidity, which will thus lead to a higher forest fire risk, longer fire seasons and more frequent large, severe fires, along with more difficult conditions for ecosystem restoration after fire (Navarra and Tubiana, 2013a, Chapter 6).

The Mediterranean marine ecosystems, which are already experiencing pressures ranging from eutrophication to dumping of waste and fish farming, are expected to suffer additional pressures owing to increased marine temperatures (see Section 4.1).

The Mediterranean is the largest tourism region in the world owing to its unique natural and cultural heritage. Higher air temperatures in northern European countries are expected to reduce the north-south tourism flow (see Section 5.6). Furthermore, the attractiveness and competitiveness of Mediterranean coastal areas could be reduced for tourists because of increasing air temperatures during summer peak seasons and increasing coastal erosion. Further studies on understanding the regional differences within the Mediterranean touristic areas and the role of the non-climatic factors are needed in this sector (Navarra and Tubiana, 2013a).

Higher air temperatures, more frequent and longer heat waves, reduced air quality (mainly PM and ozone), and changes in the distribution patterns of climate-sensitive infectious diseases are expected to lead to an increased risk to human health in Mediterranean countries if adaptation measures are not planned and taken in due time (see Section 5.2).

Table 6.6 provides a summary of the stresses, impacts, sensitivities and critical thresholds for the different ecosystem services and the sectors they support (Navarra and Tubiana, 2013a, Chapter 2).

6.5.8 EU overseas entities

This section covers the EU overseas entities, which comprise nine EU outermost regions (ORs) and 25 overseas countries and territories (OTCs). Both types of region are characterised by their remoteness, specific climatic conditions, very rich biodiversity, high concentration of population and economic activities along the coastline, and economic dependence on a small number of products and services.

The ORs comprise remote regions that belong to an EU Member State and that are an integral part of the EU. There are nine ORs: five French overseas departments (Guadeloupe, French Guiana, Martinique, Réunion and Mayotte), one French overseas collectivity (Saint Martin), two Portuguese autonomous regions (Madeira and the Azores) and one Spanish autonomous community (the Canary Islands). The OTCs comprise 25 regions that are not part of the EU but are constitutionally linked to an EU Member State (in particular to Denmark, France, the Netherlands and the United Kingdom). The type of association with the EU varies across OTCs. The OTCs are a particularly diverse group, as they range from small islands in the tropics to huge territories in the Arctic (Greenland) and the Antarctic (the British Antarctic Territory).

Several research activities and policy initiatives have covered ORs and OTCs jointly, despite their different legal statuses. A first comprehensive overview of the potential impacts of climate change on biodiversity in ORs and OTCs was provided in a report by the International Union for Conservation of Nature (IUCN) in collaboration with the Observatoire National sur les Effets du Réchauffement Climatique (ONERC; the French national observatory about climate change impacts) (Petit and Prudent, 2010), based on the 2008 IUCN conference 'The European Union and its Overseas Entities: Strategies to Counter Climate Change and Biodiversity Loss'. Further relevant information was provided in an IUCN-led review of the implementation of the convention on biological

Table 6.6 Vulnerability of ecosystem services in the Mediterranean

Sector	Ecosystem services	Stress (climate, others)	Impacts/ sensitivities	Critical thresholds for ecosystem services
Agriculture, grazing, agroforestry	Food (crop and livestock) production	• Higher temperatures • Changing precipitation patterns • Water stress • Disease • Erosion • Urban encroachment	• Higher irrigation demand • Reduced productivity • Crop failure • Livestock mortality	• Precipitation threshold beyond which rain-fed systems fail • Fallow groundwater level threshold below which pumping fails
Agriculture	Carbon sequestration	• Higher temperatures • Changing precipitation patterns • Water stress • Disease • Erosion • Urban encroachment	• Higher irrigation demand • Reduced productivity • Soil organic matter decomposition	• Precipitation threshold beyond which rain-fed systems fail • Irrigation water allocations below which permanent cultures die • Fallow groundwater level threshold below which irrigation water pumping fails • Grazing pressure beyond stocking capacity above which productivity sharply declines • Climatic or land-use change threshold beyond which systems turn into carbon sources
Agriculture, forestry	Biofuels, carbon offset	• Higher temperatures • Changing precipitation patterns • Water stress • Disease • Fire • Erosion/overexploitation • Urban encroachment	• Reduced productivity • Crop or tree mortality	• Precipitation threshold below which biofuels can no longer be produced • Water or land scarcity threshold below which food security is threatened
Forestry	Timber production	• Higher temperatures • Changing precipitation patterns • Water stress • Disease • Fire • Erosion/overexploitation	• Reduced productivity • Tree mortality	• Temperature or management threshold beyond which many more fires occur
Forestry, terrestrial ecosystems	Carbon sequestration	• Higher temperatures • Changing precipitation patterns • Water stress • Disease • Fire • Erosion	• Reduced productivity • Tree mortality • Soil organic matter decomposition	• Climatic or land-use change threshold beyond which systems turn into C-sources
Terrestrial and aquatic ecosystems	Water provision/ regulation	• Higher temperatures • Changing precipitation patterns • Water stress • Land cover changes • Landscape degradation • Erosion	• Reduced water availability • Higher water demand • Water quality degradation • Sediment yield	• Precipitation threshold below which groundwater recharge fails • Minimum vegetation cover threshold below which moisture recycling from land surface to atmosphere fails • Minimum vegetation cover threshold below which rapid erosion/siltation starts

Source: Adapted from Hoff, 2013.

diversity (Benzaken and Renard, 2011), even though this review did not focus on climate change. The current NetBiome-CSA project ([126]) is an EU-funded coordination and support project aiming to strengthen European research cooperation for smart and sustainable management of tropical and subtropical biodiversity in ORs and OCTs.

EU outermost regions

The information presented here builds mainly on the final report of a study commissioned by DG-CLIMA on the impact of climate change and adaptation measures in the ORs (EC, 2014a, 2014b). Further information is available in sectoral assessments, e.g. for coastal areas (EC, 2009a, 2009b).

The ORs, which have been recognised as particularly vulnerable to climate change impacts in the recent EU Strategy on climate change adaptation, have the following features in common that contribute to their general high degree of vulnerability:

- high sensitivity to extreme weather and climate events, e.g. hurricanes, cyclones, storm surges, flooding and droughts;
- high sensitivity of water resources to sea level changes, with a related risk of saltwater intrusions, and also to droughts;
- very rich biodiversity and a high concentration of endemic species that are sensitive to changes in temperature and precipitation and to the introduction or increase in numbers of pests and invasive species;
- high exposure of coastal zones, owing to dense urban areas, socio-economic activities and infrastructures, making them highly sensitive to sea level rise and coastal flooding;
- an economy dependent on a small number of sectors (e.g. fishing and tourism), which makes them highly vulnerable to any potential changes.

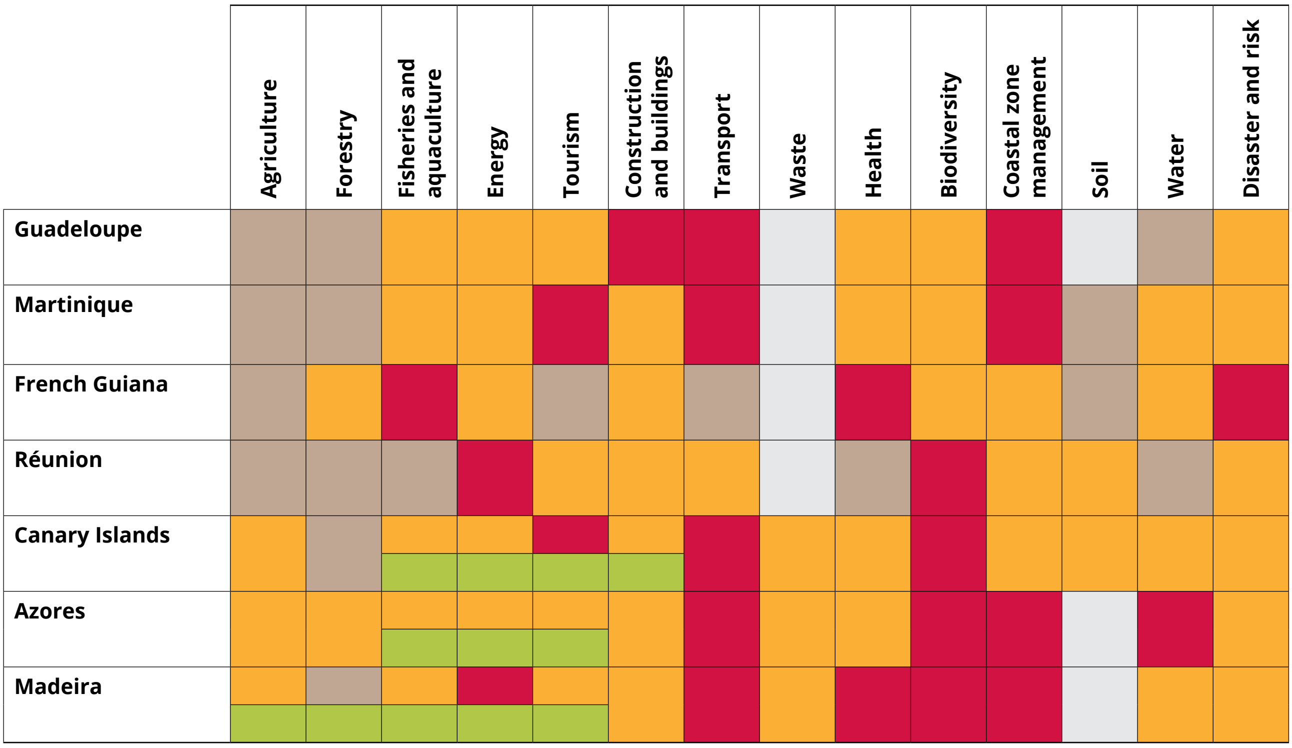
Owing to the limited number of specific modelling and impact assessment studies, information about climate change impacts relevant to ORs is mainly based on the IPCC reports. The following are the key impacts of climate change in the ORs (IPCC, 2014):

- a change in annual precipitation patterns (e.g. wetter winters but drier summers);
- increasing sea temperatures and ocean acidification leading to coral bleaching;
- an increasing frequency of inland and coastal floods owing to extreme precipitation events and storms as well as sea level rise;
- increasing saltwater intrusions into freshwater aquifers, with related negative effects on water quality;
- impacts on the health sector as a result of rising temperatures and heat waves causing increasing mortality and related human diseases;
- increasing soil degradation, droughts and wildfires, with increasing related impacts on agriculture and food production due to rising temperatures and heat extremes;
- increasing impacts on the few relevant economic sectors of these regions.

In a study on the impact of climate change and adaptation measures in the ORs, the impacts and vulnerabilities of most of the ORs ([127]) were scored and combined to give an assessment of the level of risk or opportunity arising from climate change for each OR (EC, 2014a, 2014b). Table 6.7 summarises risks and opportunities across seven selected economic sectors and six human and environmental systems relevant for all the ORs.

([126]) http://www.netbiomecsa.netbiome.eu.
([127]) This assessment was performed for only seven ORs, because Mayotte and Saint Martin lack detailed specific information on impacts and vulnerabilities.

Table 6.7 Risks and opportunities arising from climate change to the EU outermost regions by sector



Note: The colour coding of the cells in the risk matrix represents the following: red, high risk; orange, moderate risk; brown, low risk; green, opportunity; grey, the risk is relevant to the sector but could not be assessed. Some sectors in some regions experience both risks and opportunities.

Source: EC, 2014a (Table 1).

Overseas countries and territories

The most recent overview of the potential climate change impacts in OCTs is available from the OCTs Environmental Profiles 2015, which comprise a main report and five regional reports (EC, 2015a). These reports highlight the wide range of observed and projected climate change impacts across OCTs, which reflect their climatic and environmental diversity. A concise summary is available in the main report:

> *'Greenland, the British Antarctic Territory and TAAF* [French Southern and Antarctic Territories] *are well placed to study and understand the effects of global climate change. Ongoing processes in these territories have worldwide impacts: changes in melting of glaciers, sea ice extent, water mass formation. Several OCTs are particularly vulnerable to sea-level rise, and some effects are already visible. Many OCTs lie on the path of hurricanes and increased violence storms are expected more frequently, but also changes in precipitation patterns. Besides, changes in ocean temperatures, salinity and currents will bring changes in marine ecosystems, endanger coral reefs which play a key role in the physical defence and economies of many territories, and have unpredicted effects on fish stocks. Jointly, the OCTs have a comparative advantage in studying first hand these phenomena, and in testing adaptation and mitigation measures that can then be transferred to other neighbouring countries'.*
>
> (EC, 2015b, page 10)

6.6 Vulnerability to climate change in urban regions

Key messages

- The climate resilience of Europe's cities, which accommodate almost three-quarters of the European population, is decisive for their functioning and for Europe's growth, productivity and prosperity.
- Cities face specific climate threats. The urban heat island effect exacerbates the impacts of heat waves and is increasingly also affecting cities in central and north-western Europe.
- Almost 20 % of the 411 cities that were considered were continuing to spread into areas potentially prone to river floods during the period 2006–2009, thus increasing their sensitivity to the impacts of flooding.
- Urban sprawl with low-density housing has led to a growing intermingling of wild land and urban areas, which has increased the risk of forest fires in many residential areas over recent decades, in particular around cities in Portugal, Greece, southern France and Italy.
- European cities in general are less vulnerable to climate change than cities in other regions of the world owing to them having a relatively high response capacity. However, further action is needed in line with the changing climate to sustain this high degree of preparedness.

Cities are important for Europe. They accommodate around three-quarters of its population and produce a major proportion of Europe's wealth. Metropolitan regions alone generate almost 70 % of Europe's GDP. The proportion of the European population that is urban is likely to increase further to 80 % by 2050 (EC, 2014). Among other challenges, climate change impacts can substantially affect the quality of life in and productivity of cities. Well-functioning and climate-resilient cities are therefore key for a climate-resilient Europe.

6.6.1 Climate risks to urban areas

While, in principle, cities face the same climate risks as their surrounding regions (see Chapters 4 and 5), they also face specific risks, which can be altered by urban design.

The impact of heat waves is felt particularly intensely in cities and towns. The 'urban heat island' (UHI) effect increases the temperature of urban air compared with the air of rural surroundings. The temperature difference can be up to 10 °C (Oke, 1987). The UHI effect is particularly significant at night, when high temperatures are generally most problematic for human health (Grinze et al., 2005). Zhou et al. (2013) found that the effect is positively correlated with city cluster size, but there are considerable deviations in size and experience of UHI effect. This suggests that factors other than size can influence the UHI effect, such as topography, the form and size of green infrastructure, building material or ventilation corridors. Furthermore, in terms of health effects, thermal comfort is more relevant than air temperature. Outdoor thermal comfort is linked to the UHI effect, but also depends on wind speed, humidity and radiation, factors that are influenced by urban design (van Hove et al., 2015).

Map 6.8 shows city-specific values of the outdoor thermal comfort index, which combines air temperature, the relative humidity of the air and average wind speed (EEA et al., 2015). The average values for the current period show that most cities in Europe experience nights of thermal discomfort, in particular in the south. The UHI effect causes a significant increase in the number of nights of thermal discomfort compared to using standard rural data without UHI correction (EEA, 2015). The number of nights of thermal discomfort is projected to increase, and the part of Europe where people experience nights of thermal discomfort is projected to extend further. A specific regional analysis for cities in the Randstad area in the Netherlands (Amsterdam, Rotterdam and The Hague) indicates that, even in cities currently experiencing hardly any warm nights, heat stress at night could add up to more than a month per year in the period around 2050 (KPSA, 2014). As many buildings in these cities are not yet adapted to keep the heat out or cool effectively, indoor thermal discomfort is likely to increase and could threaten people's health. In addition, energy consumption for cooling might increase.

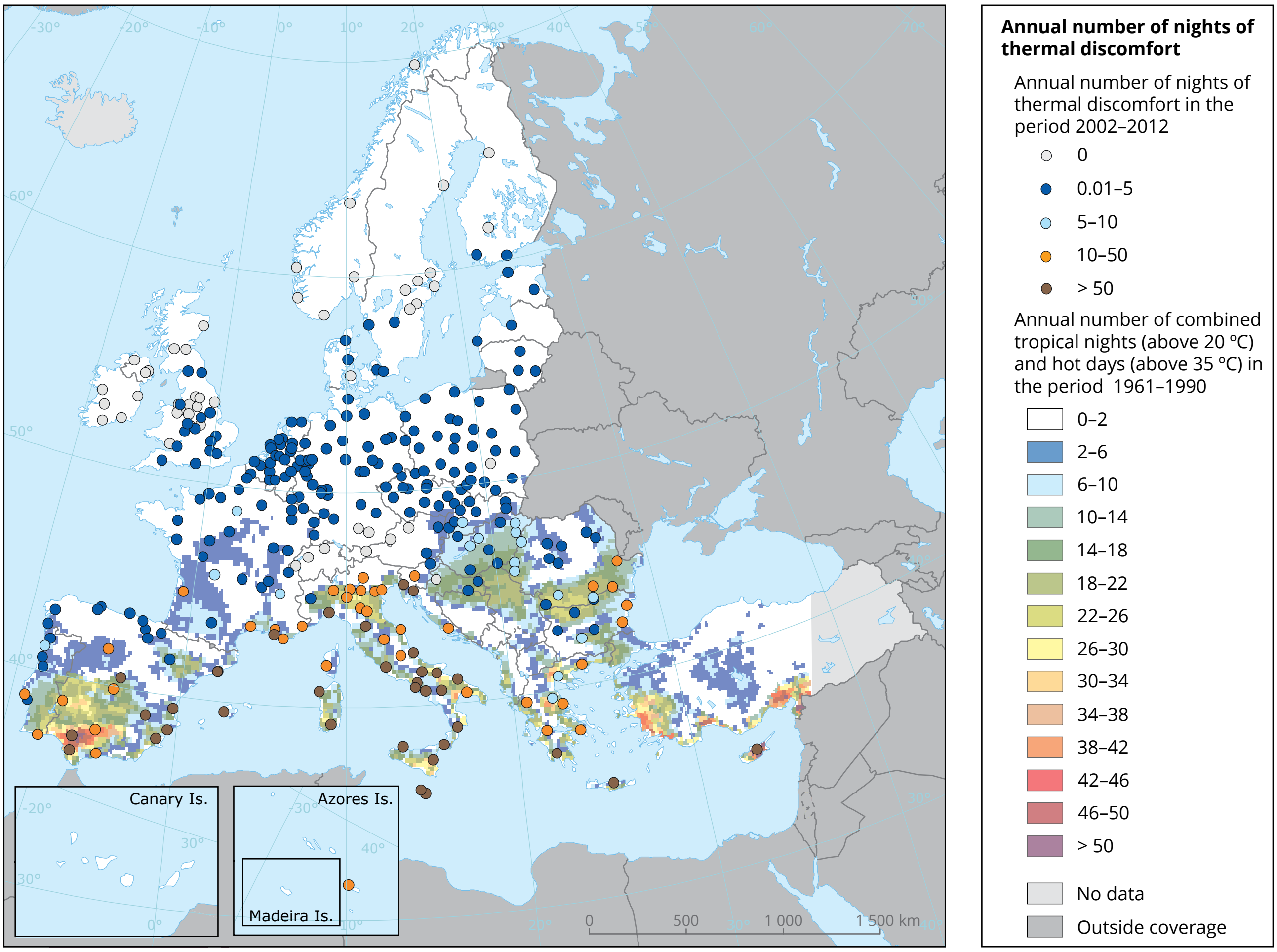
A recent assessment in the EU RAMSES project used heat wave risk scores that also included socio-economic information to assess vulnerability.

It suggested that cities at higher risk are mainly located over the central continental European belt, extending from central France to Romania and Bulgaria, with a few higher risk cities also in the United Kingdom, southern Greece and the Baltic countries. Interestingly, the Mediterranean cities show medium to lower levels of risk. These urban areas have historically suffered recurrent heat wave episodes and thus have already developed adaptation measures to tackle heat waves (Tapia et al., 2015).

Higher temperatures, more sunlight and dry conditions can also increase air pollutants such as PM and ozone, adding to health problems under heat waves. Hot, dry summers with long-lasting periods of high air pressure over large parts of Europe, such as the 2003 heat wave, lead to elevated summer ozone concentrations. Cities in the south of Europe are already showing higher ozone levels and are expecting further temperature increases in the future (see also Section 5.2.4).

Owing to the high soil sealing in cities, any excess water from extreme rainfall cannot drain into the ground and instead is led into the sewage system. Sewage systems are often not designed to take up these amounts of

Map 6.8 Average annual number of nights of thermal discomfort for two indicators



Note: As a proxy for thermal comfort, the dots show the average number of nights of thermal discomfort occurring in the period from April to September. Thermal discomfort is defined as the maximum effective temperature being above 21 °C at midnight (which is different from air temperature), taking into account the UHI effect. The interactive version of this map, including additional layers, detailed technical information and further thematic maps, can be found in the EEA map book on urban vulnerability ([128]).

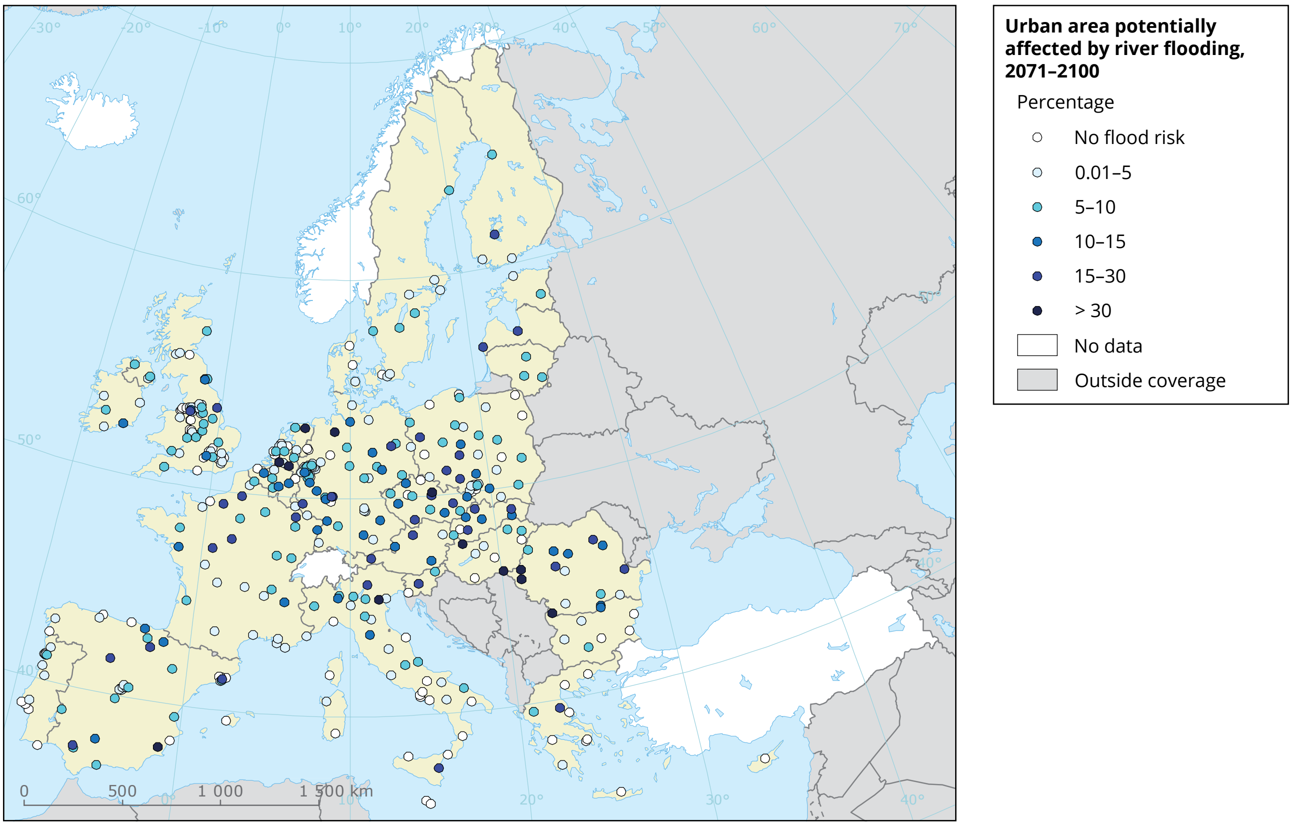
Source: Fischer and Schär, 2010; EEA, 2015; EEA et al., 2015.

([128]) http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction.

water (Kaźmierczak and Cavan, 2011) and pluvial floods develop. In many places, urban sprawl and densification have increased the soil sealing and worsened the situation, while the majority of sewage systems have the same capacity as when they were designed some 100 years ago. Cities of high and low soil sealing can be found in all regions, and do not cluster in a particular region (Prokop et al., 2011; EEA, 2015). In most cities, the level of soil sealing is between 40 and 60 %, with some cities having soil sealing as high as 80 %. However, in the short period from 2006 to 2009, a rapid increase in the level of soil sealing of more than 0.5 % in almost half of the 576 analysed cities has been observed. For 17 cities in southern Europe, an extremely significant increase in soil sealing of more than 2 % has been observed, while only one city, Helsinki, showed a considerable decrease (– 1.4 %) in soil sealing (EEA, 2015).

River and coastal floods are natural phenomena, but a changing climate and sprawling cities are likely to increase the flood risk in Europe. Most cities in Europe were built close to rivers or the coast owing to the good transport connections. Map 6.9 shows the proportion of urban area that will potentially be flooded in a 100-year river flood event in the late 21st century (2071–2100) (Rojas et al., 2012, 2013; EEA, 2015; EEA et al., 2015). Most of the cities for which a high percentage of their areas are at risk of river floods are found along the Danube, Rhine, Rhône, Vltava-Elbe, Po and Vistula rivers. The risk from river floods decreases for cities in north-eastern Europe and decreases partially in the Iberian Peninsula (see Map 6.9). The cities at the highest risk of coastal floods in the late 21st century, driven by a combination of sea level rise and storm surges, are along the North Sea coast in Belgium, the Netherlands and Germany, as well as along the Mediterranean coast of northern Italy. However, the simulations underlying these projections do not consider any flood protection in the form of dykes and dams (EEA, 2015).

Map 6.9 Urban area potentially affected by river flooding, 2071–2100



Note: The overall urban area is calculated as the Urban Morphological Zone based on Urban Atlas land-use data inside the city delineation of Eurostat's Urban Audit database (EEA, 2015). The interactive version of this map, including additional layers, detailed technical information and further thematic maps, can be found in the EEA map book on urban vulnerability ([129]).

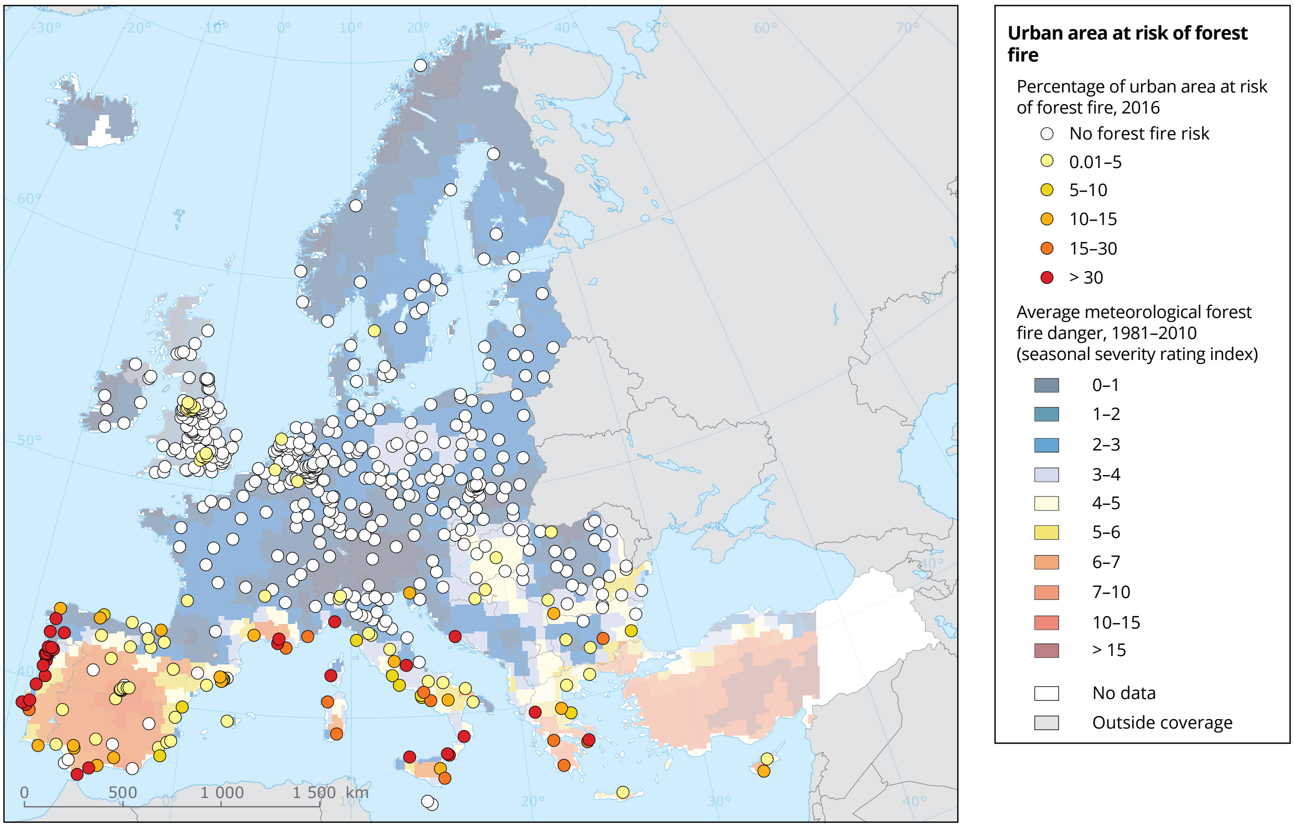
Source: Rojas et al., 2012, 2013; EEA, 2015; EEA et al., 2015.

([129]) http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction.

Vulnerability increases not only because of climate change but also because of socio-economic change. Until 2050, urbanisation levels in Europe will increase and the urban population is projected to grow, in particular in north-western Europe but also in parts of the southern Mediterranean (see also Section 6.1), namely the regions where the majority of Europeans already live, according to the SSP2 'middle of the road' storyline (O'Neill et al., 2015). This will result in higher urban vulnerabilities owing to more city residents being affected by urban climate change. Substantial growth is also expected in the northern Europe and Arctic regions, but starting at lower population levels, while for central and eastern Europe, the projections foresee population declines. Urban sprawl and densification have happened in low-lying areas that are potentially flood-prone. Almost one-fifth of the 411 cities in Europe that were considered have been found to be increasing their urban land use in areas already potentially prone to river floods by values between 10 and 70 % between 2006 and 2009 (EEA, 2015, with content updated in 2016). With these increasing assets, the sensitivity to flood impacts has grown, even if the probability of flooding is low, owing to dikes and flood walls.

Urban sprawl with low-density housing had also led to a growing intermingling of wild land and urban areas, which has increased the risk of forest fires in many residential areas over recent decades. Beyond the burned area, the population is threatened by smoke and ash. For example, forest fires in Greece in 2007 caused thousands of people to lose their homes (Bassi and Kettunen, 2008). The largest proportion of people and residential areas that are vulnerable to fire are in southern European countries. All Portuguese cities have a high percentage (> 16 %) of residential areas that are at high direct risk of fire. Areas in southern France and Greece present the same pattern, while in southern Italy, the situation is more variable (see Map 6.10, which is based on the combination of relevant (peri-)urban areas and the burnt area perimeter). Commercial areas in cities appear to be less vulnerable than residential areas.

Map 6.10 Urban area at risk of forest fire for two indices



Note: The interactive version of this map, including additional layers, detailed technical information and further thematic maps, can be found in the EEA map book on urban vulnerability ([130]).

Source: Camia et al., 2008; EEA, 2015; EEA et al., 2015; JRC, 2015.

([130]) http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction.

Demographic trends can also affect cities' vulnerability to climate impacts. In general, the elderly are more sensitive to a variety of climate-related stressors: extreme weather events (Fernandez et al., 2002; Brooks et al., 2005), high temperatures and the resulting mortality and morbidity (Huynen et al., 2001; Kovats and Hajat, 2008) and respiratory problems related to forest fires (Johnston et al., 2012). The proportion of elderly people in cities is highest in the area extending from Italy to Germany and into northern Spain. In Belgium and Germany, the proportion of elderly people in cities is usually similar to the proportion of elderly people elsewhere in the country, whereas cities in northern Italy tend to have higher proportions of elderly people in cities than the country average. For other countries, such as Bulgaria, France, Romania, southern Spain and the United Kingdom, the proportion of elderly people in most cities is lower than the country average (EEA, 2012, 2015). The projected trend of a continuously ageing European population with particularly high ageing levels in eastern Europe (see Section 6.1) is very likely to apply to cities as well. Therefore, the vulnerability to climate change is likely to further increase.

Additional factors also contribute to the climate vulnerability of cities. Of particular relevance are communities with low socio-economic status and social inequity (Kaźmierczak and Cavan, 2011). Comparative data for cities on a European level are, however, scarce.

6.6.2 Response capacity

Cities across Europe are differently prepared for climate change. Differences in the many economic, technological, institutional and social factors influence the capacity of cities to adapt to climate challenges. Knowledge, values and perceptions pose social limits to adaptation and can severely increase vulnerability, but they are also mutable (Adger et al., 2008). Being unaware of or neglecting risks, or not having the knowledge of how to prepare themselves leaves people, businesses and infrastructures unprotected and more vulnerable to climate change and extreme weather events. The map book on urban vulnerability shows different maps with the different factors affecting the generic response capacity (trust, education, socio-economic status, commitment of city administrations) per city (EEA, 2015). The link between such generic categories and the response capacity is, however, indirect and resources are not always used to their full potential.

Knowledge and funds for initiating adaption action are generally available for cities in Europe. However, the distribution and presentation of knowledge are not always tailored to local stakeholders' needs, which act together with constrained capacities in terms of staff and skills in a number of local governments, to limit the access to and application of the available knowledge and funding. Effective governance is key to overcoming these barriers. This includes horizontal governance in cities that builds on synergies and uses expertise and capacities in related policy areas, as well as complementary action from regional and national governments, the EU and other organisations. These can create a supportive legislative, institutional and financial framework and provide knowledge, such as the EU initiatives and programmes Covenant of Mayors for Climate and Energy/Mayors Adapt ([131]), LIFE+ ([132]), Horizon 2020 ([133]) and ESI Funds ([134]), among others (EEA, 2012, 2016; Revi et al., 2014).

A variety of response options exist; for example, spatial planning can constrain urban sprawl, and urban design and building regulations can support building more climate resilience. Green infrastructure (green areas, green facades, roofs, trees) help to cool cities and drain excess rain water after cloudbursts. Green infrastructure is a key element in adapting cities to climate change, as it provides multiple additional benefits, such as recreational areas, higher attractiveness of the city, health, quality of life, etc. (Bowler et al., 2010; Steeneveld et al., 2011; Rahman et al., 2013). On the other hand, the compact city model is a planning paradigm for many sustainable city approaches. It enables a higher efficiency of energy use and transport, but leaves less space for green urban areas. Thus, an intelligent urban design that uses every available space for green infrastructure is necessary.

Many climate change impact problems cannot be solved at the city scale. In particular, flooding, droughts and forest fires, as well as heat, require joint approaches with the surrounding sub-urban and rural areas. For example, if the retention area upstream is limited, the pressure on dikes downstream under a flooding event will be even higher (see Box 6.3).

([131]) http://mayors-adapt.eu.
([132]) http://ec.europa.eu/environment/life.
([133]) https://ec.europa.eu/programmes/horizon2020.
([134]) https://www.fi-compass.eu/esif/european-structural-and-investment-funds-esif.

From a global perspective, cities in developed countries such as those in Europe are relatively well prepared to cope with most of the current impacts of climate owing to well-established infrastructures, standards, emergency services, access to knowledge, etc. However, climate change requires major upgrades as well as transformational adaption measures, and only a few cities already have the capacity to do this (UN-HABITAT, 2011; Revi et al., 2014).

Box 6.3 The need for regional or international management of urban flood risks

The city of Vac (Hungary) faces severe flooding challenges almost every four years. Flooding is not only a result of increasingly severe impacts of climate change, but is also caused by the construction of flood defences in cities located upstream from Vac in Slovakia, Austria and Germany, which in turn intensifies flooding in Vac (Mabey et al., 2014).

The Dutch river region manages the flood risk in a regional approach with more than 30 projects distributed over the region that work together to reduce the flood risk (EEA, 2014; Ruimte voor de Rivier, no date).

7 Strengthening the knowledge base

Key messages

- The length of the time series, the geographical coverage and the quality of climate change data and indicators have improved over the past years owing to European and global efforts such as the Global Climate Observing System. Atmospheric and ocean observations are well developed, but an integrated approach to terrestrial observations is still lacking.
- Climate change impact indicators have also improved over the past years at EU and national levels, and many countries have performed impact, vulnerability, risk and/or adaptation assessments. Improvements in such assessment are feasible, e.g. by better addressing indirect effects of climate change. Furthermore, there are no agreed common methods for indicator sets across Europe, which makes it difficult to compare information from different countries. It can be useful to explore how existing thematic and sectoral EU legislation and policies could be used to improve climate change impact data and indicators.
- Climate change services are emerging at both national level and EU level (Copernicus). These services provide climate data and information, such as essential climate variables, reanalyses, observations, seasonal forecasts and long-term projections. Emerging adaptation services provide complementary information, e.g. on vulnerability and cost–benefit assessments, policies, tools and case studies. Climate change services and adaptation services are expected to become increasingly integrated in the future, thereby delivering the services needed by the intended users.
- An increasing number of countries, and also city networks, are developing systems for monitoring, reporting and evaluating adaptation policies. An approach that combines quantitative indicators and qualitative information (including process-based indicators) can be a strong basis for assessments. Only a few countries have so far established such approaches.
- The European Commission has developed a process-based 'adaptation preparedness scoreboard' to assess the progress made by Member States, which will be included in its evaluation of the EU Strategy on adaptation to climate change, due to be published in 2018. There is an increasing need to complement this scoreboard with quantitative information at the EU level.
- Within the Sendai Framework for Disaster Risk Reduction, the finalisation of a set of indicators to measure the progress of its implementation is planned by the end of 2016. Countries, including EU Member States, need to establish national databases of the impacts of disasters on ecosystems, human health and the economy. The Sendai Framework indicators for weather- and climate-related hazards are expected to be relevant and useful for climate change adaptation.
- Knowledge gaps identified by the European Commission and countries include gaps in our knowledge on national and sectoral impact, vulnerability and adaptation assessments; economic damages and losses; the costs and benefits of adaptation; adaptation services; interdependencies, synergies and trade-offs; and the monitoring of systems and tools.
- EU-funded research (in particular through Horizon 2020) and national research may address adaptation knowledge gaps, while Horizon 2020 is specifically designed to also stimulate innovation.

This chapter provides an overview of climate change observations, data and services at global and European levels, including the Copernicus climate change service, which was launched in 2015, and the expected products and services that may help to improve indicators on climate change (Section 7.1). It covers climate change impacts, partly based on information provided in Chapters 4 and 5 (Section 7.2). It furthermore addresses the emerging need for monitoring and evaluation of adaptation policies and the required data and knowledge base (Section 7.3). Other relevant EU indicator frameworks are also presented and their relevance for adaptation is discussed (Section 7.4). In addition, the chapter provides a short overview of the knowledge gaps on climate change adaptation (Section 7.5) and how these may be addressed through climate change impacts, vulnerability and adaptation research in Europe, such as that funded through Horizon 2020, the EU financial instrument on future research and innovation (Section 7.6).

7.1 Climate change data and services

7.1.1 Global activities

There are various ongoing efforts to improve the monitoring and availability of data related to climate change at the global level.

The Global Framework for Climate Services (GFCS) ([135]) provides a worldwide mechanism for coordinated actions to enhance the quality, quantity and application of climate services. Its primary focus is to improve access to and the use of climate information by users. The framework addresses needs at three spatial scales: global, regional and national. It gives high priority to the needs of climate-vulnerable developing countries. Meeting the full observational needs of the GFCS would involve substantial investment in establishing and strengthening national climate observing networks in most countries. The WMO, its member countries and other partners have developed an implementation plan and governance structure for the framework.

The Global Climate Observing System (GCOS, 2010a) supports the objectives of the GFCS and is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for:

- monitoring the climate system;
- detecting climate change and attributing causes;
- operational climate prediction on seasonal-to-decadal timescales;
- assessing the impacts of, and supporting adaptation to, climate variability and change;
- application and services for sustainable economic development;
- research to improve the understanding, modelling and prediction of the climate system;
- meeting the requirements of the UNFCCC and other international conventions and agreements.

GCOS has identified 50 essential climate variables (Bojinski et al., 2014) that are technically and economically feasible for systematic observation and that are required to support the work of the UNFCCC and the IPCC (see also Table 7.1). The GCOS Implementation Plan 2010–2015 (GCOS, 2010b) described the path towards an integrated observing system that depends upon both *in situ* and satellite-based measurements.

A 2015 report (GCOS, 2015) shows how well climate is currently being observed, where progress has been made and where progress is lacking or deterioration has occurred. It reviewed overarching and cross-cutting topics, observing networks (using both *in situ* or other non-space-based measurements and space-based measurements) and the observational status of each essential climate variable separately for the atmosphere, ocean and land. It concluded that improvements in many areas were made over recent years, but also that much remains to be done.

Atmospheric observation is the best developed type of observation, with relatively dense, although far from gap-free, networks, clear observational standards, largely open data exchange and international data centres covering most, if not all, variables, and it continues to be refined.

Ocean observation has developed quickly, with international planning and implementation of observational networks, and new technologies that enable more and better autonomous data collection.

Terrestrial observations have traditionally been made on smaller scales, with different standards and methods in different countries. They also have a poor history of open data exchange. Space-based observation is now providing global coverage of an improving quality for a

([135]) http://www.gfcs-climate.org.

number of variables, increasingly with open data access, and there is progress in other areas, through global networks for glaciers and permafrost, for example. Standards, methods and data exchange protocols for key hydrological variables have been developed. An integrated approach to terrestrial observation is still lacking, however. GCOS is developing a new implementation plan, due to be published in 2016, describing further actions that are needed in the coming years.

Specific conclusions from the report include the following for the *in situ* and other non space-based components of the observing system:

- The performance of the Argo network and its floats in profiling temperature and salinity has been outstanding. The network is now expanding into marginal seas and high latitudes.
- There have been improvements in the coverage and quality of measurements for a number of more established *in situ* networks, including the main meteorological networks.
- Several oceanic and terrestrial networks making *in situ* measurements and networks for ground-based remote-sensing of atmospheric composition have been established or significantly expanded in recent years.
- Fewer observations have been provided recently by some atmospheric composition and marine buoy networks.
- Surface meteorological measurements from ships have declined in number over the major parts of ocean basins, but have increased near coasts.
- Some gaps in the coverage of networks over land have been reduced.
- The recovery of historical data has progressed well in some respects, but is still limited in extent and hampered by restrictive data policies.
- The generation of data products, for example on surface air temperature, humidity and precipitation, continues to improve.
- Sustaining observing system activities that are initiated with short-term research funding is a recurrent issue.

Table 7.1 Essential climate variables that are currently feasible for global implementation and addressing UNFCCC requirements

Atmospheric	Surface: ([a])	Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget
	Upper air: ([b])	Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases ([c]) ozone and aerosol supported by their precursors ([d])
Oceanic	Surface: ([e])	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton
	Sub-surface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

Note: ([a]) Including measurements at standardised but globally varying heights in close proximity to the surface.

([b]) Up to the stratopause.

([c]) Including N_2O, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

([d]) In particular NO_2, sulphur dioxide (SO_2), formaldehyde (HCHO), and carbon monoxide (CO).

([e]) Including measurements within the surface mixed layer, usually within the upper 15 m.

Source: Adapted from Bojinski et al., 2014.

The report concludes the following for space-based components of the observing system:

- The newer and planned generations of operational meteorological satellite systems offer improved quality and a broader range of measurements.
- The European Copernicus programme (see Section 7.1.2) is placing additional types of observation on an operational basis, with increased coverage and quality of measurements, and accompanying service provision.
- There have been increases in the numbers of national providers, cooperative international missions and other collaborative arrangements.
- The generation and supply of products derived from space-based observations have progressed well.
- Data access is becoming more open, although there is still progress to be made. Some data remain to be recovered from early missions, and long-term preservation of data, including occasional reprocessing, is not yet fully ensured.

Regarding essential climate variables (e.g. for the atmosphere and cryosphere), the conclusions from GCOS as presented in this section are also relevant for and applicable to Europe.

7.1.2 Copernicus climate change service

Copernicus is the European Union Earth observation programme designed to provide uninterrupted, independent and accurate data and information on environmental and security matters for Europe. The regulation establishing the 'Copernicus' programme was approved and entered into force in April 2014 (EU, 2014c).

The Copernicus Climate Change Service (C3S) ([136]) provides access to information for monitoring and predicting climate change and will, therefore, help to support adaptation and mitigation. It benefits from a sustained network of *in situ* and satellite-based observations, reanalysis of the Earth's climate, and modelling scenarios based on a variety of climate projections.

The launch in April 2014 of Sentinel-1A saw the first spacecraft out of a series of six so-called Sentinel families to go into orbit, all of which should be operational by around 2022. It was followed by the launch of Sentinel-2A in June 2015. The European Space Agency (ESA) is responsible for developing the Sentinels on behalf of the European Union; operation will be shared with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), while other institutions provide products and services based on the data from these and complementary satellites.

The service will provide access to several climate indicators (e.g. temperature increase, sea level rise, ice sheet melting and warming of the ocean) and climate indices (e.g. based on records of temperature, precipitation and drought events) for both the identified climate drivers and the expected climate impacts. Time scales will range from decades to centuries (i.e. based on the instrumental record). The service will maximise the use of past, current and future Earth observations (from both *in situ* and satellite observing systems) in conjunction with modelling, supercomputing and networking capabilities. This conjunction will produce a consistent, comprehensive and credible description of the past, current and future climate.

In November 2014, the European Commission signed a Delegation Agreement with ECMWF (European Centre for Medium-Range Weather Forecasts) for the implementation of the service. The first stage of implementation will be dedicated to the so called 'proof of concept' (2015–2016), that is, capacity-building and testing of the overall architecture. The pre-operational stage will be in 2017, while the operational stage (phase 1) is planned to be reached in 2018.

The portfolio of service products will include:

- consistent estimates of multiple essential climate variables;
- global and regional reanalyses (covering a comprehensive Earth system domain: atmosphere, ocean, land, carbon);
- products based on observations alone (gridded, homogenised station series and reprocessed climate data records);
- a near-real-time climate monitoring facility;
- multi-model seasonal forecasts;
- climate projections at global and regional scales.

([136]) http://www.copernicus.eu/main/climate-change and https://climate.copernicus.eu.

The aim is to support adaptation and mitigation policies in Europe in a number of sectors, including water management, agriculture, forestry, tourism, insurance, transport, energy, human health, infrastructure, disaster risk reduction and coastal areas. By providing datasets, tools and best practices in a free and open way, 'downstream services' are expected to be developed in various thematic areas.

The service will be delivered through a climate data store, a sectoral information system, an evaluation and quality control function, and an outreach and dissemination platform.

The climate data store will contain a series of geophysical climate variables and specific indicators related to climate change (observed, reanalysed and simulated), needed to monitor both drivers and impacts of climate change. Essential climate variables and climate data records will be part of the store, as well as the derived climate change indicators. The sectoral information system will contain information tailored to fit the needs of end users and customers of the service for various EU sector-specific policies (see Chapter 2). The evaluation and quality control function will assess the technical and scientific quality of the service, including the value to users. It will ensure that information is fully traceable and adequately documented, and that sufficient attention has been given to the assessment of uncertainties. The sectoral information system is expected to help improve the quality and availability of indicators on climate change and impacts at the European scale, specifically for the sectors to be covered in the various phases of the service.

C3S is expected to become an important information source for several of the indicators that are included in this report. It will also be linked to the Climate-ADAPT platform. The EEA and ECMWF are discussing how best to establish collaboration in future.

7.1.3 Climate change adaptation services

Climate change adaptation services have so far been developed and implemented differently from climate change services. Climate change services have thus far focused primarily on providing climate information (and to some extent have included impacts), while adaptation services (such as Climate-ADAPT at the EU level) so far have provided broader information including vulnerability and risk assessments, adaptation strategies and options, case studies and policy frameworks. Thus, these types of services can be regarded as complementary.

The recent (2015) 'European research and innovation roadmap for climate services' uses a broader definition and scope (Street et al., 2015). Climate change services and adaptation services are expected to become increasingly integrated in the future, thereby delivering the services needed by the intended users (see also Section 7.6).

An increasing number of adaptation platforms (or services) have emerged over the past years, which are described and analysed in an EEA technical report (EEA, 2015b). In 2015, there were adaptation platforms in place at the national level in 14 EEA member countries, as well as platforms at the transnational level for the Alpine region and the Pyrenees, and at EU level (Climate-ADAPT). The scope of the platforms varies, and many are linked directly to the implementation of national strategies and/or action plans. The type of information that appears most often includes policy action at transnational, national and sub-national levels, scientific research output, guidance, decision-support tools, and experiences from practice and implemented adaptation measures. The implementation and evaluation of national adaptation strategies and also the EU Strategy will probably enlarge the scope of the platforms. The need for relevant information and knowledge at the city level will increase. A lot of new information will become available from national- and EU-funded research (Horizon 2020). It will be a challenge to update platforms accordingly, while maintaining appropriate quality control, and selecting the information that is most relevant for users. Experiences from practice and implemented adaptation measures are expected to receive increasing attention. Enhancing user engagement is key, as the relevance and usability of the platform are strongly linked to the successful uptake of the information that it provides.

7.2 Climate change impacts

The availability of data on the monitoring of the impacts of climate change on environmental systems, society and economy is presented in Chapters 4 and 5 of this report. Here, an overview and analysis is provided.

7.2.1 National assessments

The knowledge base on climate change impacts and vulnerability across Europe has increased over the past years owing to enhanced and/or continued monitoring and EU and national research projects. A range of countries have developed national impact, vulnerability and/or risk assessments (EEA, 2014). Agriculture, water, forestry, human health and biodiversity are the sectors most frequently considered in assessments. Various countries report that an update of the national assessments has begun. A wide variety of methods were used, including qualitative and quantitative methods. Although many climate change hazards are similar, there are so far no agreed common methods for impact and/or vulnerability indicator sets across Europe.

7.2.2 Cryosphere

Snow and ice cover have been monitored since satellite measurements started in the 1970s. Improvements in technology have allowed for more detailed observations and higher resolution. High-quality long-term data are also available on glaciers throughout Europe. Direct historical area-wide data on the Greenland and Antarctic ice sheets are available for about 20 years, but reconstructions give a 200 000-year perspective.

7.2.3 Oceans, the marine environment and coasts

Changes related to the physical and chemical marine environment are well documented, and often time series of these observations are longer than for biological changes. For example, systematic observations of both sea level and sea surface temperature began around 1880. In recent years, these have been complemented by observations from space and by Argo floats that at the same time automatically measure temperature and salinity below the ocean surface. The longest available time series of plankton (about 60 years) is from the Continuous Plankton Recorder..

The rate of ocean acidification and the biological consequences of this on a global scale need to be further monitored and researched. The understanding of how climate change, in combination with synergistic impacts from multiple stressors, can cause systemic shifts is improving, but additional research is still needed to untangle the complex interactions and their effects upon biodiversity. Similarly, ecological thresholds for individual species are still only understood in hindsight, i.e. once a change has occurred.

Reporting under relevant EU legislation and policies, including the Marine Strategy Framework Directive (EC, 2008), has improved data availability and is expected to further enhance the knowledge base in the future.

7.2.4 Water (water quality, floods, water scarcity and droughts)

The main data sources for Europe-wide studies of the impacts of river floods and river droughts are global databases, in particular EM-DAT by CRED ([137]), which focuses on the impacts on human health, and the NatCatSERVICE by Munich RE ([138]), which focuses on economic damage costs. These databases are compiled from various sources. The differences in definitions, thresholds, classification criteria and reporting approaches are to be taken into account when interpreting the data. Over recent years, these global databases have been harmonised, but some important differences remain.

Data on the impacts of floods since 1980, as reported within the preliminary flood risk assessments by EU Member States (that were due to be undertaken by 2011 under the EU Floods Directive), have been collected and published by the EEA (EEA, 2016a). However, time series are not complete and are difficult to compare across countries. The JRC ([139]) has reviewed the status and best practices of disaster loss data recording and prepared guidance for EU Member States, in close collaboration with various Member States. This is expected to help in improving the comparability and consistency of data on the impacts of floods.

Regarding water scarcity and droughts, the EEA is revising the water exploitation index (EEA, 2016b) so that it will be calculated based on the level of river basins instead of on the administrative boundaries of countries. The JRC maintains the European Drought Observatory ([140]) for forecasting, assessment and monitoring. However, despite such activities, there is currently no systematic, comprehensive record of such events in Europe describing their duration, impact and severity, other than meteorological time series for precipitation.

Data and research projects are available regarding water temperature and the impacts of climate change on freshwater ecosystems and water quality.

([137]) http://www.emdat.be.
([138]) http://www.munichre.com/en/reinsurance/business/non-life/natcatservice/index.html.
([139]) http://drr.jrc.ec.europa.eu.
([140]) http://edo.jrc.ec.europa.eu.

Reporting under relevant EU legislation and policies, including the Water Framework Directive and the Floods Directive, has improved data availability and is expected to further enhance the knowledge base in the future (see also the Water Information System for Europe ([141])).

7.2.5 Terrestrial biodiversity and ecosystems

Quantitative information on past trends and impacts of climate change, specifically on soil and the various related feedbacks, is very limited. Europe-wide soil information is absent and there is a need to establish harmonised monitoring networks.

Generally, observations for popular species groups such as vascular plants, birds, other terrestrial vertebrates and butterflies are much better than for those for less conspicuous and less popular species. Phenological changes are better observed and recorded than range shifts. However, for most cases, only a few years of phenological data are available, and these do not cover the entire area of the EU but are restricted to certain well-monitored countries. One of the greatest unknowns is how quickly and closely species will alter their phenology.

In addition, the data for range shifts is better for popular groups of species than for other species. There are large regional differences in the quality of observational data, with better data generally available in northern and western Europe than in southern Europe.

Reporting under relevant EU legislation and policies, including the Habitats Directive, the Birds Directive and the 2020 Biodiversity Strategy, has improved data availability and is expected to further enhance the knowledge base in the future (see also the Biodiversity Information System for Europe ([142])).

7.2.6 Human health

The attribution of health effects to climate change is difficult owing to the complexity of interactions and the potentially modifying effects of a range of other factors (such as land-use changes, public health preparedness and socio-economic conditions). The monitoring of climate-sensitive health effects is currently fragmentary and heterogeneous. In the absence of reliable time series, more complex approaches are often used (e.g. in EU research projects) to assess the past, current or future impacts of climate change on human health.

The WHO has some data and information available ([143]), while the ECDC assesses the effects of climate change on infectious diseases and has also established a pan-European Union network dedicated to vector surveillance ([144]). Such activities of the WHO and the ECDC could enhance the knowledge base in the future. Relevant EU legislation includes the third EU health programme, 2014–2020 (EU, 2014b), which addresses, among other things, serious cross-border health threats.

7.2.7 Agriculture, forestry and fisheries

The effects of climate change on the growing season and crop phenology can be monitored directly. There is no common monitoring network for crop phenology in Europe, and data on this therefore have to be based on various national recordings. Crop yield and crop requirements for irrigation are affected not only by climate change, but also by management and a range of socio-economic factors. The effects of climate change on these factors therefore have to be estimated indirectly using agrometeorological indicators and through statistical analyses of the interactions between climatic variables and factors such as crop yield.

Agri-environmental indicators track the integration of environmental concerns into the CAP at EU, national and regional levels ([145]). The European Commission proposed a set of 28 agri-environmental indicators, which are maintained by Eurostat, in collaboration with the EEA and other partners. Some of these indicators are potentially relevant for climate change and, thus, these indicators may enhance the knowledge base in the future. Eurostat has also performed a survey on agricultural production methods, including data on, for example, tillage methods and soil conservation, which can also be relevant for climate change.

Eurostat collects data on forests from Member States, in collaboration with the United Nations Economic Commission for Europe (UNECE) and the FAO ([146]). The data collected include, for example, the net annual

([141]) http://water.europa.eu.
([142]) http://biodiversity.europa.eu.
([143]) http://www.euro.who.int/en/health-topics/environment-and-health/Climate-change/data-and-statistics.
([144]) http://ecdc.europa.eu/en/healthtopics/climate_change/pages/index.aspx.
([145]) http://ec.europa.eu/eurostat/web/agri-environmental-indicators/overview.
([146]) http://ec.europa.eu/eurostat/web/forestry/overview.

increment in the forests available for wood supply and the production of round wood. Global Forest Resources Assessments are produced every five years (FAO, 2016), and similar reports are also produced for Europe by UNECE/FAO, with the latest report being from 2015 (UNECE and FAO, 2015). The JRC ([147]) collects and assesses data on forest disturbances (including fires), forest ecosystem services, forests and the EU bio-economy, and forests and climate change. The final category includes data on tree species distributions, tree species habitat suitability, forest type habitat suitability, and habitat suitability under scenarios of climate change.

The EU Common Fisheries Policy ([148]) includes fisheries management and aims to achieve maximum sustainable yields for all stocks by 2015 where possible, and at the latest by 2020, and to reduce unwanted catches and wasteful practices to the minimum, or to avoid them altogether, through the gradual introduction of a landing obligation. A Data Collection Framework ([149]) is in place, managed by the JRC. In addition, Eurostat collects data on fisheries ([150]). These data include catches, landings and discards, and some of the data are potentially relevant for climate change adaptation.

7.3 Climate change adaptation monitoring, reporting and evaluation

The interest in monitoring, reporting and evaluation (MRE) of adaptation policies and actions has grown during the past years at the global, EU and national levels. The EEA recently published the report 'National monitoring, reporting and evaluation of climate change adaptation in Europe' (EEA, 2015a). This report covers, among other things, the development and publication of the EU Strategy on adaptation to climate change and the growing number of countries that are developing adaptation strategies and have begun to implement adaptation actions. The demand to understand if these strategies and actions work (or not), in which contexts and why has increased.

7.3.1 National monitoring, reporting and evaluation of adaptation

The EEA 2015 report uses the following definitions. Monitoring is defined as: 'to keep track of progress made in implementing an adaptation intervention by using systematic collection of data on specified indicators and reviewing the measure in relation to its objectives and inputs, including financial resources.' Evaluation refers to 'a systematic and objective assessment of the effectiveness of climate adaptation plans, policies and actions, often framed in terms of the impact of reducing vulnerability and increasing resilience'.

MRE at the national level is challenging owing to many factors, including long time scales, uncertainty, shifting baselines and contexts, unclear and multiple policy goals and objectives, a lack of a causal link between policies and indicators, the diversity of key concepts and definitions, a lack of appropriate data, and resource constraints.

Despite these challenges, 14 EEA member countries have MRE approaches in place or are developing these. For most of these countries, the main aim is to monitor and report on the progress achieved in the implementation of actions and policies included in NASs or NAPs. Only a few countries are in the stage of evaluation, and one of the main reasons for this is that adaptation is still a new policy area in most countries.

The following types of adaptation indicators are in place or are being developed by countries:

- a *process-based* approach defines the key stages in a process that could realistically be expected to contribute to positive adaptation outcomes, without specifying those outcomes at the outset;

- an *output-based* approach follows the direct results of an adaptation policy or action, without assessing if these results actually lead to better adaptation outcomes;

- an *outcome-based* approach seeks to define an explicit outcome, or result, of the adaptation action, indicating reduced vulnerability or increased adaptive capacity.

The EEA 2015 report shows that, in most countries with MRE approaches in place, they are process-based approaches. Some countries assess changes in vulnerability or adaptive capacity, in either qualitative or quantitative ways. There is a need for further development of methodologies that can be used across countries. The report concludes that a 'mixed

([147]) http://forest.jrc.ec.europa.eu.
([148]) http://ec.europa.eu/fisheries/cfp/index_en.htm.
([149]) http://ec.europa.eu/fisheries/cfp/fishing_rules/data_collection/index_en.htm.
([150]) http://ec.europa.eu/eurostat/statistics-explained/index.php/Fishery_statistics.

methods' approach, which combines quantitative (including indicators) and qualitative information (including process-based indicators), provides a strong basis for assessing adaptation progress and performance. So far, only a few countries have developed such 'mixed methods' approaches. The indicators developed in these countries measure the trends in changes to exposure and vulnerability over time, and the observed impacts. It can be expected that, in the future, an increasing number of countries will develop 'mixed methods' approaches and sets of adaptation indicators, while taking into account the national context, including, in particular, resource and data availability.

7.3.2 EU activities on tracking progress on adaptation

At the EU level, the EU Strategy on adaptation to climate change mentions that 'In 2017, based on the Member State (MS) Monitoring mechanism reports (due March 2015) and on an "adaptation preparedness scoreboard", identifying key indicators for measuring Member States' level of readiness, the Commission will assess whether action being taken in the Member States is sufficient.'

To meet this goal, the European Commission in 2015 developed a draft scoreboard in consultation with Member States. It consists of 33 questions covering various domains of relevance, which are grouped into 'performance areas' and subsequently into the 'five steps' of adaptation policymaking: (1) preparing the ground for adaptation, (2) assessing risks and vulnerabilities to climate change, (3) identifying and assessing adaptation options, (4) implementing adaptation action and (5) monitoring and evaluation of adaptation activities.

The European Commission will, where needed, improve the structure and questions in the scoreboard in 2016 and prepare scoreboards for each EU Member State in 2017–2018. The scoreboard will constitute the EU approach to a 'process-based' monitoring system.

So far, very few quantitative 'adaptation indicators' are available at the European level. This is mainly because an understanding of the different types and purposes of adaptation indicators at the national level has only very recently emerged, and collecting and analysing data at the national level is a very complex and resource-intensive activity, which begun only recently. It can be expected that the need will increase in the future for quantitative adaptation indicators at the EU level as part of a mixed approach including process-based indicators.

The Mayors Adapt/Covenant of Mayors ([151]) initiative was initiated in 2015 in order to consider how to develop a monitoring and reporting approach for cities, in consultation with interested cities. The focus so far has been on process-based approaches. In 2016, further discussions will be held, leading potentially to an agreed approach to be implemented afterwards by all signatory cities.

7.4 Other relevant global and EU indicator sets

At the global level and in the EU, various indicator sets exist or are being developed for different policy purposes. The extent to which climate change impact, vulnerability and adaptation aspects have been taken into account in most of these initiatives has so far been limited, but this is changing owing to various policy developments in recent years.

7.4.1 Disaster risk reduction and sustainable development

At the global level, an intergovernmental expert working group under the Sendai Framework for Disaster Risk Reduction was established for the development of a set of possible indicators to measure global progress in the implementation of the framework (UN, 2015); its work will be completed by December 2016. The draft proposals developed during 2015–2016 contain details of many quantitative indicators that aim to measure progress towards achieving the seven targets set in the framework (PreventionWeb, 2016) (see also Section 2.1.2). Countries need to establish new or improve existing national disaster loss databases to be able to record data, which are needed for many of the proposed indicators, and report these to the United Nations Office for Disaster Risk Reduction (UNISDR). The data and indicators collected within the Sendai Framework are expected to also be very relevant for climate change adaptation, in particular regarding the hazards related to weather and climate change. The Sendai Framework also applies to EU Member States, but it is not yet fully clear what the implications are for current EU legislation on civil protection and on the reporting of data by EU Member States to UNISDR.

([151]) http://mayors-adapt.eu.

The EU's civil protection legislation (EU, 2013a) is preparing the ground for a more resilient European society by developing national risk assessments and refining risk management planning. As of 2015, all Member States need to report their risk assessments and risk management capabilities to the European Commission at three-year intervals.

As mentioned above, the JRC has reviewed the status and best practices of disaster loss data recording and prepared guidance for EU Member States and, in 2016, these activities will be integrated into an EU Disaster Risk Management Knowledge Centre ([152]). Currently, no comparable EU data exist on the impacts of disasters, but in the future all EU Member States should have comparable data and, thus, EU indicators on disaster impacts (economic, human health, ecosystems) may be based on data collected and reported by Member States.

UNECE has published a report of 'Recommendations on climate change-related statistics' (UNECE, 2014). It mentions that additional statistics may need to be developed to describe the social and economic impacts of climate change, population vulnerability, and mitigation and adaptation efforts. In 2015, a 'Task force on measuring extreme events and disasters' (UNECE, 2015) was set up, which aimed to provide recommendations in 2016. The work can be expected to provide input and be linked to the work mentioned above under the Sendai Framework.

Regarding the United Nations sustainable development strategy, an inter-agency and expert group (coordinated by UN Statistics) is developing a sustainable development goal indicator set (IAEG-SDG, 2015). Many countries have provided comments, including several EU Member States. The European Commission (Eurostat) and the EEA also provided some comments. The aim is to finalise the work in 2016. It is not yet clear how the sustainable development goal indicators will lead to changes in EU data collection and EU indicators, in particular regarding climate change adaptation. However, it can be expected that, regarding disaster risks, the Sendai Framework activities on indicators and, regarding adaptation, the UNFCCC activities will be more relevant and specific than the sustainable development goals.

The renewed European sustainable development strategy was published in 2006. Since then, Eurostat has prepared a monitoring report every two years, the latest being in 2015 ([153]). The indicators and information regarding climate change and energy are very similar to those published in the annual reports supporting the Europe 2020 strategy (see Section 7.4.2). In 2016, a Communication from the European Commission is expected on the future of the sustainable development strategy, and on if and how the United Nations sustainable development goals will have an influence.

7.4.2 The Seventh Environment Action Programme, EU 2020 strategy and environmental accounts

The Seventh Environment Action Programme to 2020, 'Living well, within the limits of our planet' (EU, 2013b), contains various objectives that are relevant for climate change adaptation. The EEA will prepare annual indicator reports from 2016 onwards, tracking the progress in reaching the quantitative targets of the Seventh Environment Action Programme, which will be based mainly on existing EEA indicators. The indicators of this report on climate change impacts and vulnerability could provide some input, although mainly as contextual information. The only specific adaptation-related indicator that will be included is the 'number of countries with a national adaptation strategy and/or action plan in place'.

Europe 2020 is the EU's growth and jobs strategy (2010), which aims to pave the way to a smart, sustainable and inclusive future. Climate change mitigation is covered through the same targets on greenhouse emissions, renewable energy and energy efficiency for 2020 as in the climate and energy package (see Section 2.2). Climate change vulnerability and adaptation are covered to only a very limited extent. Eurostat has published annual reports (Eurostat, 2015) on the progress made towards these targets, which includes a figure on global temperature and some qualitative information on the impacts of climate change. A Communication from the European Commission is expected by the end of 2016 that will review the Europe 2020 strategy, including if and how the United Nations sustainable development goals may have an influence.

An EU regulation on environmental accounting (EU, 2011) provides the framework. These accounts track the links between the environment and the economy at EU, national, regional and industry levels, and complement environmental statistics and indicators.

([152]) https://ec.europa.eu/jrc/en/news/new-knowledge-centre-help-eu-minimise-risk-disasters.
([153]) http://ec.europa.eu/eurostat/web/sdi/indicators.

Regarding issues of climate change impacts, vulnerability and adaptation, the specific development of water accounts and of future ecosystem accounts could be relevant. The EEA collaborates with Eurostat on ecosystem accounting and is preparing several initial accounts, including on water.

7.5 Knowledge gaps

Gaining knowledge entails much more than research, and the combined efforts and experiences of adaptation practitioners across Europe, together with new research and innovation, are expected to significantly enhance the knowledge base in the coming years.

The EU Strategy on adaptation to climate change (2013) identified four key areas where knowledge gaps exist: (1) information on damage and adaptation costs and benefits, (2) regional- and local-level analyses and risk assessments, (3) frameworks, models and tools to support decision-making and (4) means of monitoring and evaluating past adaptation efforts.

In 2014, the European Commission prepared an internal note that gives an overview of knowledge gaps identified from collecting, summarising and structuring information from different sources, including information collected in preparation for the 2013 EU Strategy on adaptation to climate change, the IPCC AR5 (IPCC, 2014), UNEP Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA) documents such as the 'Guidance on Assessing Vulnerability, Impacts and Adaptation to Climate Change' (PROVIA, 2013), documents and outcomes from the Joint Programming Initiative 'Connecting Climate Knowledge for Europe' (JPI Climate), JRC projects including PESETA (Ciscar et al., 2014), outcomes of the final conference of the FP7 ERA-NET project Climate Impact Research and Response Coordination for a Larger Europe (CIRCLE-2) ([154]), EEA reports and other sources. This compilation did not address the specific needs of Member States or of particular sectoral stakeholders to inform their specific adaptation policies.

The main knowledge gaps are grouped into eight priority areas. Many of them require that research and experience be combined in implementing adaptation policies and actions. This includes demonstration and replication projects that enlarge the pool of case studies and implemented adaptation options. The eight priority areas are:

- *Adaptation and climate services*. Providing the best available climate data and other information to different users is needed to support adaptation. Needs range from general services providing tailor-made information (climate data, scenarios, sectoral climate-dependent variables, etc.) to tools to support adaptation policy and decision-making, to facilitate knowledge transfer and to build capacity (adaptation services).

- *Robust, integrated (across sectors and geographical and governance scales) impact, vulnerability and adaptation assessments*. Fundamental gaps persist in the identification of the expected impacts to and vulnerability of sectors and in framing this knowledge into decision-making systems, which involves careful matching of, for example, spatial and temporal scales to those of planning and/or management. These assessments are essential both for sectoral adaptation and as the basis for evaluations informing adaptation plans (e.g. integrated assessments, economic analyses).

- *Ecosystem-based adaptation measures*. An evaluation of such measures and an assessment of how these can be integrated with other measures is required, with the aim of achieving multiple societal and environmental benefits.

- *Decision-making and policymaking support tools and assessments, including on the costs and benefits of impacts and adaptation.* There is a need to develop tools and decision frameworks that can effectively inform and support adaptation policies and strategies, particularly at the relevant scales and at aggregated levels (municipal, national, European). The integration of reliable short- and long-term economic indicators therein is needed to help shape decision-making, as current uncertainty is limiting adaptation action. In addition, more insights into the adaptation capacity of sectors, systems and society across the EU need further integration into impact, vulnerability and adaptation assessment frameworks.

- *Knowledge on effective adaptation*. An enlarged pool of adaptation case studies is needed to transfer knowledge on topics such as the identification of adaptation options and criteria for their selection, decision-making frameworks and the integration of adaptation within routine planning, cost-efficient combinations of measures, and governance and opportune implementation

([154]) http://adaptationfrontiers.eu.

timing. The potential of ecosystem-based options as effective solutions needs to be further assessed.

- *Regional- and local-level adaptation*. As part of the general need to enlarge the pool of case studies, the EU needs to identify common challenges, such as how to address limitations in data and resolution, cross-sectoral and cross-border interdependencies, spill overs and the governance of adaptation. Vulnerable European regions and systems need enhanced approaches, including topics such as mountains and their influence regions; the Mediterranean region, a climate change hotspot in all existing evaluations; European coastal areas; international rivers and their catchment areas; urban areas, including their wider metropolitan belts; rural areas and their societies; and islands and outermost regions.

- *Interdependencies, synergies and trade-offs with other relevant goals*. This emergent area requires research and knowledge generation, addressing in particular the interactions between mitigation and adaptation, the linkages between adaptation and disaster risk reduction, and the integration of adaptation with other sustainable development goals. In addition, further knowledge is needed on the geographical interactions and spill-over effects of impacts and adaptation at regional and global levels.

- *Monitoring systems and tools*. These are required both for impacts and vulnerability and for adaptation to climate change.

Several of these knowledge gap areas are being addressed through different EU funding and knowledge initiatives. However, it should be noted that many 'knowledge gaps' also need to be addressed through national research programmes.

As a cross-cutting theme, there is a need for enhanced communication, shared learning and co-creation of knowledge. This is relevant, for example, between climate service providers and users, but also between various governmental agencies and communities of practice (e.g. sectoral) within and across countries.

7.6 Climate change impacts, vulnerability and adaptation research

The EU's FP7 (2007–2013) covered climate-relevant research ([155]) across various themes. For an overview of all of the FP7 climate change projects, see the European Commission's website ([156]). Furthermore, Climate-ADAPT contains a database and web pages on the results of many EU FP7 projects dealing with climate change impacts, vulnerability and adaptation ([157]). In addition, the EU CIRCLE-2 ERA-NET project ([158]) has analysed relevant national research activities and developed an extensive database.

Horizon 2020 ([159]) is the EU financial instrument implementing the 'Innovation Union', a Europe 2020 flagship initiative, for the period 2014–2020. The priorities and research focus of Horizon 2020 were agreed within the EU in 2013/2014. It is expected that at least 60 % of the overall Horizon 2020 budget will be related to sustainable development and that climate-related expenditure will exceed 35 % of the budget, including mutually compatible measures improving resource efficiency.

Of the priorities of Horizon 2020, the societal challenge 'climate action, environment, resource efficiency and raw materials' is the most relevant to climate change impacts, vulnerability and adaptation research. However, other 'societal challenges' are also relevant, such as 'secure societies', which includes as one of its aims 'to enhance the resilience of our society against natural and man-made disasters'.

The Horizon 2020 activity 'fighting and adapting to climate change' supports proposals that aim to:

- develop climate modelling and science for climate services to help provide trustworthy science-based information to governments, the public and private decision-makers;

- pool resources to develop better tools, methods and standards to help assess the impact of climate change and adaptation responses;

- improve understanding of the economics of climate change and linkages with sustainable development;

([155]) http://ec.europa.eu/research/environment/index_en.cfm?pg=climate.
([156]) http://ec.europa.eu/research/environment/index_en.cfm?pg=projects&area=climate.
([157]) http://climate-adapt.eea.europa.eu/knowledge/adaptation-information/research-projects/index_html.
([158]) http://www.circle-era.eu/np4/10.
([159]) http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=h2020.

- develop technological options and strategies to improve air quality and reduce the carbon footprint of European cities; and
- create climate change networks to facilitate dialogue among relevant scientific communities, funding bodies and user communities in the EU.

Horizon 2020 has already addressed in its work programmes from 2014 to 2017 many of the knowledge gaps identified in the section above, including the following:

- *Climate services* ([160]). These are an important element of EU-funded research in the area of climate change (see also above). The European Commission has initiated a 'European research and innovation roadmap for climate services' (Street et al., 2015), which aims to develop a 'market' for climate services for both climate change mitigation and adaptation. This roadmap will complement the Copernicus climate services. The definition of climate services in the roadmap is: 'Transforming climate-related data and other information into customised products such as projections, trends, economic analysis, advice on best practices, development and evaluation of solutions, and any other climate-related service liable to benefit, or that may be of use for the society. These services include data, information and knowledge that support adaptation, mitigation and disaster risk management'. This broad definition is not yet used widely but in future the distinction between climate services and adaptation services (see Section 7.1.3) may become less relevant.
- *Decision support tools*. These can facilitate decision-making by different end users (e.g. individuals, businesses, other private sector firms, local authorities and planners, governments), while developing adaptation plans and measures, as well as developing comprehensive economic assessment of climate change.
- *Effective adaptation and implementation*. This requires projects at local, regional or national levels, conducted using innovative solutions, as well as testing and dissemination of technological and non-technological adaptation options, including ecosystem-based approaches.
- *Synergies*. This involves supporting the clustering and close cooperation between initiatives funded internationally, by the EU and nationally in the fields of climate change adaptation and disaster risk reduction, promoting foresight and large-scale dissemination activities, and fostering the science-policy interface across the EU. It also involves examining the link between climate change actions and sustainable development.
- *Nature-based solutions for resilience*. These can address synergies between different objectives such as mitigation, adaptation, disaster risk reduction and sustainable development. Target areas include urban, mountain and coastal areas.
- *Monitoring*. This includes frameworks and methods to assess climate change impacts, vulnerabilities, the performance and effectiveness of adaptation measures, and operational and organisational/governance needs for successful replication and follow-up.
- *Governance, participatory processes and methods*. These can facilitate knowledge transfer and uptake by stakeholders.

Related to this, JPI Climate ([161]) was initiated in 2011 to support multi-national research activities related to improving climate projections, climate services, societal transformation and decision support tools. The aim of Joint Programming is to increase the value of relevant national and EU research and development funding by concerted and joint planning, implementation and evaluation of national research programmes. A new ERA initiative called 'ERA for climate services' (ERA4CS) began on 1 January 2016 ([162]). It is closely linked to JPI Climate. ERA4CS aims to boost research for climate services, including climate adaptation, mitigation and disaster risk management.

Furthermore, the EU has funded Climate-KIC ([163]). Climate-KIC is one of three knowledge and innovation communities (KICs) created in 2010 by the European Institute of Innovation and Technology (EIT). The EIT is an EU body whose mission is to create sustainable growth. Climate-KIC supports this mission by addressing climate change mitigation and adaptation, although most of the activities so

([160]) http://ec.europa.eu/research/environment/index_en.cfm?pg=climate-services.
([161]) http://www.jpi-climate.eu.
([162]) http://www.jpi-climate.eu/aboutERA4CS.
([163]) http://www.climate-kic.org/about.

far are related to mitigation. Climate-KIC integrates education, entrepreneurship and innovation aimed at the transformation of knowledge and ideas into economically viable products or services that help to mitigate or adapt to climate change.

Other EU initiatives that are contributing to filling the knowledge gap include the LIFE Climate Action instrument (EU, 2014a) which aims to promote adaptation in cross-border coastal and flood management; urban land use planning, buildings and natural resources management; mountains and islands; sustainable management of water; and combating desertification and forest fires in drought-prone areas. In addition the instrument promotes green infrastructure and ecosystem-based approaches to adaptation; innovative adaptation technologies and vulnerability assessments and adaptation strategies. Issues such as governance, knowledge transfer and monitoring systems are also potential topics that could be funded.

As climate change concerns have been mainstreamed in all ESIF funding ([164]), Member States have allocated 25 % of these funds to climate change mitigation and adaptation, which will help to increase the amount of effective adaptation experience and knowledge across the EU.

([164]) http://ec.europa.eu/contracts_grants/funds_en.htm.

8 Abbreviations and acronyms

8.1 General abbreviations and acronyms

Table 8.1 presents all abbreviations and acronyms used in this report, except for the acronyms of fixed-time research projects that are presented in Table 8.2.

Table 8.1 Abbreviations and acronyms (except research projects)

Acronym or abbreviation	Name	Reference (*)
A1	See SRES	
A1B	See SRES	
A1FI	See SRES	
A1T	See SRES	
A2	See SRES	
AdSVIS	Adaptation of road infrastructure to climate change programme	http://adsvis.de
AMAP	Arctic Monitoring and Assessment Programme	http://www.amap.no
AMECO	Annual macro-economic database of the European Commission	http://ec.europa.eu/economy_finance/db_indicators/ameco/index_en.htm
AOGCM	Atmosphere–Ocean Global Circulation Models	
AR4	IPCC Fourth Assessment Report	http://www.ipcc.ch/report/ar4
AR5	IPCC Fifth Assessment Report	http://www.ipcc.ch/report/ar5
ASTI	Arctic Species Trend Index	http://www.caff.is/asti
B1	See SRES	
B2	See SRES	
BEAC	Barents Euro-Arctic Council	http://www.beac.st
C3S	Copernicus Climate Change Service	https://climate.copernicus.eu
CAP	Common Agricultural Policy	http://ec.europa.eu/agriculture/capexplained/index_en.htm
CAPE	Convective available potential energy	
CBSS	Council of the Baltic Sea States	http://www.cbss.org
CCIV	Climate change, impacts and vulnerability	
CCSM3	Community Climate System Model version 3	http://www.cesm.ucar.edu/models/ccsm3.0
CDD	Cooling degree days	
CEH	Centre for Ecology and Hydrology	http://www.ceh.ac.uk
CGCM	Coupled General Circulation Model	
CH_4	Methane (gas)	
CIF	Common Implementation Framework of the EU Biodiversity Strategy	http://biodiversity.europa.eu/policy

Table 8.1 Abbreviations and acronyms (except research projects) (cont.)

Acronym or abbreviation	Name	Reference (*)
Climate-ADAPT	European Climate Adaptation Platform	http://climate-adapt.eea.europa.eu
Climate KIC	Climate Knowledge and innovation community (of the European Institute of Innovation and Technology)	http://www.climate-kic.org
CMEMS	Copernicus Marine Environmental Monitoring Service	http://marine.copernicus.eu
CMIP5	Coupled Model Intercomparison Project Phase 5	http://cmip-pcmdi.llnl.gov/cmip5/index.html
CO_2	Carbon dioxide (gas)	
COP21	UNFCCC climate conference in Paris in 2015	http://www.cop21.gouv.fr/en
COSMO-CLM	Consortium for Small scale Modeling — Climate Limited-area Model	http://www.clm-community.eu/index.php?menuid=198
CPR	Continuous Plankton Recorder	
CRED	Centre for Research on the Epidemiology of Disasters	http://www.cred.be
CSI	EEA Core Set of Indicators	http://www.eea.europa.eu/data-and-maps/indicators#c5=&c0=10&b_start=0&c10=CSI
CSIRO	Commonwealth Scientific and Industrial Research Organisation	http://www.csiro.au
CTI	Community Temperature Index	
CTP	Working Community of the Pyrenees	https://ctp.org
CV	Coefficient of variation	
DAISIE	Delivering Alien Invasive Species Inventories for Europe	http://www.europe-aliens.org
Defra	UK Department for Environment, Food and Rural Affairs	https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs
DFO	Dartmouth Flood Observatory	http://floodobservatory.colorado.edu
DPSIR	Drivers–Pressures–State–Impacts–Response indicator framework	http://www.eea.europa.eu/publications/TEC25
EAP	Environment Action Programme (of the European Union)	http://ec.europa.eu/environment/action-programme
EASIN	European Alien Species Information Network	http://easin.jrc.ec.europa.eu
ECDC	European Centre for Disease Prevention and Control	http://www.ecdc.europa.eu
ECHAM5	Fifth generation of the ECHAM general circulation model	http://www.mpimet.mpg.de/wissenschaft/globale-klimamodellierung/echam/echam5
ECMWF	European Centre for Medium-Range Weather Forecasts	http://www.ecmwf.int
ECP	Extended concentration pathway	
EDO	European Drought Observatory (JRC)	http://edo.jrc.ec.europa.eu
EEA	European Environment Agency	http://www.eea.europa.eu
EFFIS	European Forest Fire Information System (JRC)	http://effis.jrc.ec.europa.eu
EIT	European Institute of Innovation and Technology	https://eit.europa.eu
EM-DAT	Emergency Events Database (CRED)	http://www.emdat.be
ENPI	European Neighbourhood and Partnership Instrument	http://ec.europa.eu/europeaid/funding/european-neighbourhood-and-partnership-instrument-enpi_en
ENSO	El Niño–Southern Oscillation	
ERA	European Research Area	http://ec.europa.eu/research/era/index_en.htm
ERA4CS	ERA for climate services	http://www.jpi-climate.eu/ERA4CS
ESA	European Space Agency	http://www.esa.int

Table 8.1 Abbreviations and acronyms (except research projects) (cont.)

Acronym or abbreviation	Name	Reference (*)
ESIF	European Structural & Investment Fund	http://ec.europa.eu/contracts_grants/funds_en.htm
ESM	Earth system model	
ESPON	European Observation Network for Territorial Development and Cohesion	https://www.espon.eu/main
ETC-CCA	European Topic Centre on Climate Change impacts, vulnerability and Adaptation	http://cca.eionet.europa.eu
EU-27/28	The 27/28 Member States of the European Union (depending on the period in question)	
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites	http://www.eumetsat.int
EURO-CORDEX	Coordinated Downscaling Experiment — European Domain	http://www.euro-cordex.net
EUROPOP2013	European Population Projections, base year 2013	http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-projections-data
Eurostat	The Statistical Office of the European Union	http://ec.europa.eu/eurostat
FAO	Food and Agriculture Organization of the United Nations	http://www.fao.org
FP(5/6/7)	EU's Framework Programme(s) for Research	http://cordis.europa.eu/fp7/home_en.html
FWI	Canadian Forest Fire Weather Index	http://cwfis.cfs.nrcan.gc.ca/background/dsm/fwi
GCM	General circulation model	
GCOS	Global Climate Observing System	http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS
GDP	Gross domestic product	
GEO BON	Group on Earth Observations Biodiversity Observation Network	http://geobon.org
GFCS	Global Framework for Climate Services	http://www.wmo.int/gfcs
GHCN	Global Historical Climatology Network dataset	https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn
GISS	NASA Goddard Institute for Space Studies	http://www.giss.nasa.gov
GMSL	Global mean sea level	
HadCM3	Hadley Centre Coupled Model version 3	http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3
HadGEM2(-ES)	Hadley Centre Global Environment Model version 2 (Earth System)	http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2
HadISST1	Hadley Centre Sea Ice and Sea Surface Temperature dataset	http://www.metoffice.gov.uk/hadobs/hadisst
HDD	Heating degree day	
HELCOM	Baltic Marine Environment Protection Commission	http://www.helcom.fi
Horizon 2020	The current EU Framework Programme for Research and Innovation	http://ec.europa.eu/research/horizon2020/index_en.cfm
HWMI(d)	Heat Wave Magnitude Index (daily)	https://ec.europa.eu/jrc/en/news/heat-wave-index
IAEA	International Atomic Energy Agency	http://www.iaea.org
IAS	Invasive alien species	http://ec.europa.eu/environment/nature/invasivealien/index_en.htm

Table 8.1 Abbreviations and acronyms (except research projects) (cont.)

Acronym or abbreviation	Name	Reference (*)
IG CCA	Interest Group on 'Climate Change and Adaptation' (of the network of European Nature Conservation Agencies)	http://www.encanetwork.eu/interest-groups/climate-change-adaptation
IMF	International Monetary Fund	http://www.imf.org
INDC	Intended nationally determined contribution	http://unfccc.int/focus/indc_portal/items/8766.php
IPCC	Intergovernmental Panel on Climate Change	http://www.ipcc.ch
IUCN	International Union for Conservation of Nature	https://www.iucn.org
IWD	Irrigation water demand	
JPI Climate	Joint Programming Initiative 'Connecting Climate Knowledge for Europe'	http://www.jpi-climate.eu/home
JRC	The Joint Research Centre of the European Commission	http://ec.europa.eu/dgs/jrc/index.cfm
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)	http://www.knmi.nl
LISFLOOD	GIS-based hydrological rainfall-runoff-routing model (JRC)	https://www.efas.eu/user-information.html
LUCAS	Land Use/Cover Area frame Statistical Survey	http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Land_use/cover_area_frame_survey_(LUCAS)
LWR	Longwave radiation	
MAP	Mediterranean Action Plan (for the Barcelona Convention)	http://www.unepmap.org
MARS/STAT	Monitoring Agriculture with Remote Sensing – Stat Action database	http://mars.jrc.ec.europa.eu/mars/About-us/The-MARS-Unit
MRE	Monitoring, reporting and evaluation	
Mtoe	Million tonnes of oil equivalent	
N_2O	Nitrous oxide (gas)	
NAO	North Atlantic Oscillation	
NAP	National adaptation plan	
NAS	National adaptation strategy	
NatCatSERVICE	Natural catastrophe loss database (Munich RE)	http://www.munichre.com/en/reinsurance/business/non-life/georisks/natcatservice/default.aspx
NCDC	NOAA National Climatic Data Center	http://www.ncdc.noaa.gov
ND-GAIN	Notre Dame Global Adaptation Index	http://index.gain.org
NDVI	Normalized Difference Vegetation Index	
NOAA	National Oceanic and Atmospheric Administration	http://www.noaa.gov
NODUS	GIS-based software model that provides a tool for detailed analysis of freight transportation over extensive multi-modal networks	http://www.ltto.com/en/commercialisation/technological-offers/ict-software-nodus
NUSAP	The Management of Uncertainty and Quality in Quantitative Information	http://www.nusap.net
NUTS(2/3)	Nomenclature of Territorial Units for Statistics; NUTS2, states/provinces; NUTS3, regional areas, counties, districts	http://ec.europa.eu/eurostat/web/nuts/overview
OCTOP	Topsoil Organic Carbon Content for Europe	http://esdac.jrc.ec.europa.eu/content/octop-topsoil-organic-carbon-content-europe
OECD	The Organisation for Economic Co-operation and Development	http://www.oecd.org
OHC	Ocean heat content	

Table 8.1 Abbreviations and acronyms (except research projects) (cont.)

Acronym or abbreviation	Name	Reference (*)
ONERC	Observatoire National sur les Effets du Réchauffement Climatique (the French national observatory about climate change impacts)	http://www.developpement-durable.gouv.fr/-Observatoire-National-sur-les-.html
OPCC	Pyrenees Climate Change Observatory	http://www.opcc-ctp.org/en
OR	EU outermost region	http://ec.europa.eu/regional_policy/en/policy/themes/outermost-regions
OSI SAF	EUMETSAT Satellite Application Facility on Ocean and Sea Ice	http://www.osi-saf.org
OTCs	Overseas countries and territories	http://ec.europa.eu/europeaid/regions/octs_en
PDO	Pacific Decadal Oscillation	
PFRA	Preliminary Flood Risk Assessment	http://rod.eionet.europa.eu/obligations/601
pH	Decimal logarithm of the reciprocal of the hydrogen ion activity (measure of acidity)	
PHI	Potential hail index	
PM	Particulate matter	
PM_{10}	Particles in the atmosphere with a diameter of less than or equal to a nominal 10 micrometres	
POLES	Prospective Outlook on Long-term Energy Systems	http://www.enerdata.net/enerdatauk/solutions/energy-models/poles-model.php
ppm	Parts per million	
PROVIA	Programme of Research on Climate Change Vulnerability, Impacts and Adaptation	http://www.unep.org/provia
PSMSL	Permanent Service for Mean Sea Level	http://www.psmsl.org
RACMO2	Regional Atmospheric Climate Model (KNMI)	https://www.projects.science.uu.nl/iceclimate/models/racmo.php
RCM	Regional climate model	
RCP	Representative concentration pathway	
RDI	Reconnaissance Drought Index	
REDES	Rainfall Erosivity Database at European Scale	https://ec.europa.eu/jrc/en/publication/rainfall-erosivity-database-european-scale-redes-product-high-temporal-resolution-rainfall-data
SAHFOS	Sir Alister Hardy Foundation for Ocean Science	https://www.sahfos.ac.uk
SDDI	Supply–Demand Drought Index	
SOC	Soil organic carbon	
SOER	EEA State of the Environment Report	http://www.eea.europa.eu/soer
SPEI	Standardised Precipitation Evapotranspiration Index	
SPI	Standardised Precipitation Index	
SRES	IPCC Special Report on Emissions Scenarios	http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation	http://www.ipcc-wg2.gov/SREX
SRI	Standardized Runoff Index	
SSP	Shared socio-economic pathway	
SSR	Seasonal Severity Rating (index of forest fire risk)	
SST	Sea surface temperature	
SWR	Shortwave radiation	

Table 8.1 Abbreviations and acronyms (except research projects) (cont.)

Acronym or abbreviation	Name	Reference (*)
TAR	IPCC Third Assessment Report	https://www.ipcc.ch/ipccreports/tar/vol4/english
TBE	Tick-borne encephalitis	
TCI	Tourism climate index	
TED	Total Economy Database	https://www.conference-board.org/data/economydatabase
TEU	Twenty-foot equivalent	
TIMES	The Integrated MARKAL-EFOM System model	http://ledsgp.org/resource/the-integrated-markal-efom-system-model/?loclang=en_gb
Twh	Terawatt-hours	
Tx_x	Annual maximum value of daily maximum temperature	
UHI	Urban heat island	
UNECE	United Nations Economic Commission for Europe	http://www.unece.org
UNEP	United Nations Environment Programme	http://www.unep.org
UNFCCC	United Nations Framework Convention on Climate Change	http://unfccc.int
UNISDR	United Nations Office for Disaster Risk Reduction	http://www.unisdr.org
VBORNET	European Network for Arthropod Vector Surveillance for Human Public Health	http://www.vbornet.eu
W/m^2	Watts per square metre	
WAIS	West Antarctic Ice Sheet	
WCDRR	World Conference on Disaster Risk Reduction	http://www.wcdrr.org
WEF	World Economic Forum	https://www.weforum.org
WEO	World Economic Outlook of the IMF	http://www.imf.org/external/ns/cs.aspx?id=28
WHO	World Health Organization	http://www.who.int
WMO	World Meteorological Organization	http://www.wmo.int
WNV	West Nile virus (disease-causing agent)	

Note: (*) No references are provided for technical terms.

8.2 Acronyms of research projects

Table 8.2 presents those research projects that are explicitly mentioned in the text of this report. Many more projects have contributed to the publications cited in this report and to the data presented therein, but the compilation of a complete overview was not feasible.

Table 8.2 Acronyms of research projects

Project acronym	Project name	Website	Funding
ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling	https://www.pik-potsdam.de/ateam	FP5
BaltAdapt	Baltic Sea Region Climate Change Adaptation Strategy	http://www.baltadapt.eu	ERDF
BASE	Bottom-up Climate Adaptation Strategies Towards a Sustainable Europe	http://base-adaptation.eu	FP7
CAPRESE	CArbon PREservation and SEquestration in agricultural soils	http://publications.jrc.ec.europa.eu/repository/bitstream/JRC88295/caprese_final%20report-v2.pdf	JRC
CARPATCLIM	Climate of the Carpathian Region	http://www.carpatclim-eu.org/pages/home	JRC, NKTH
CarpathCC	Climate Change Framework Project	http://carpathcc.eu	EU
CARPIVIA	Carpathian integrated assessment of vulnerability to climate change and ecosystem-based adaptation measures	http://www.carpivia.eu	DG ENV
cCASHh	Climate change and adaptation strategies for human health in Europe	http://cordis.europa.eu/project/rcn/56944_en.html	FP5
CIRCE	Climate Change and Impact Research: the Mediterranean Environment	http://www.iddri.org/Iddri/Circe-Overview.pdf	FP6
CIRCLE-2	Climate Impact Research & Response Coordination for a Larger Europe	http://www.circle-era.eu	FP7
ClimateCost	The Full cost of climate change	http://www.climatecost.cc	FP7
Climate-TRAP	Training, Adaptation, Preparedness of the Health Care System to Climate Change	http://www.climatetrap.eu	EAHC
CLIMSAVE	Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe	http://www.climsave.eu/climsave/index.html	FP7
ECA&D	European Climate Assessment & Dataset project	http://eca.knmi.nl	KNMI, EC, EUMETNET
ECCONET	Effects of climate change on the inland waterway networks	http://www.ecconet.eu	FP7
ECONADAPT	The Economics of Climate Change Adaptation	http://econadapt.eu	FP7
EDEN	Emerging Diseases in a changing European eNvironment	http://www.eden-fp6project.net	FP6
EDENext	Biology and control of vector-borne infections in Europe	http://www.edenext.eu	FP7
ENHANCE	Enhancing risk management partnerships for catastrophic natural hazards in Europe	http://enhanceproject.eu	FP7
ENSEMBLES	ENSEMBLE-based Predictions of Climate Changes and their Impacts	http://www.ensembles-eu.org	FP6
ESPON Climate	Climate Change and Territorial Effects on Regions and Local Economies	https://www.espon.eu/main/Menu_Projects/Menu_ESPON2013Projects/Menu_AppliedResearch/climate.html	ERDF
Eurosion	European initiative for sustainable coastal erosion management	http://www.eurosion.org	DG ENV

Table 8.2 Acronyms of research projects (cont.)

Project acronym	Project name	Website	Funding
EWENT	Extreme weather impacts on European networks of transport	http://ewent.vtt.fi	FP7
GEMAS	Geochemical Mapping of Agricultural and Grazing Land Soil	http://gemas.geolba.ac.at	EuroGeoSurveys, Eurometaux
IMPACT2C	Quantifying projected impacts under 2 °C warming	http://impact2c.hzg.de	FP7
IMPRESSIONS	Impacts and Risks from High-end Scenarios: Strategies for Innovative Solutions	http://www.impressions-project.eu	FP7
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project	https://www.isimip.org	BMBF
JRA-25	Japanese 25-year Reanalysis Project	http://www.jreap.org/indexe.html	JMA
MOTIVE	Models for Adaptive Forest Management	http://motive-project.net	FP7
MOWE-IT	Management of Weather Events in the Transport System	http://www.mowe-it.eu	FP7
NetBiome-CSA	Strengthening European research cooperation for smart and sustainable management of tropical and subtropical biodiversity in outermost regions and overseas countries and territories	http://www.netbiomecsa.netbiome.eu/np4/home.html	FP7
PESETA II	Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis	http://peseta.jrc.ec.europa.eu	JRC
PIOMAS	Pan Arctic Ice-Ocean Modeling and Assimilation System	http://psc.apl.washington.edu/zhang/IDAO/data_piomas.html	NSF
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects	http://prudence.dmi.dk	FP5
RAMSES	Reconciling, adaptation, mitigation and sustainable development for cities	http://www.ramses-cities.eu	FP7
RESPONSES	European responses to climate change: deep emissions reductions and mainstreaming of mitigation and adaptation	http://www.responsesproject.eu	FP7
SEAMLESS	System for Environmental and Agricultural Modelling: Linking European Science and Society	http://www.seamless-ip.org	FP6
STEP	Status and Trends of European Pollinators	http://www.step-project.net	FP7
ToPDAd	Tool-supported policy development for regional adaptation	http://www.topdad.eu	FP7
WEATHER	Weather Extremes: Impacts on Transport Systems and Hazards for European Regions	http://www.weather-project.eu	FP7

References

Executive summary

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

EC, 2013, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — An EU Strategy on adaptation to climate change, COM(2013) 216 final of 16 April 2013.

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2015a, *National monitoring, reporting and evaluation of climate change adaptation in Europe*, EEA Technical report No 20/2015, European Environment Agency.

EEA, 2015b, *SOER 2015: The European environment — state and outlook 2015*, European Environment Agency.

EEA, 2015c, *The European environment — state and outlook 2015: Assessment of global megatrends*, European Environment Agency.

EEA, 2015d, *Trends and projections in Europe 2015 — Tracking progress towards Europe's climate and energy targets*, EEA Report No 4/2015, European Environment Agency.

EEA, 2016a, *Mapping and assessing the condition of Europe's ecosystems: Progress and challenges*, EEA Report No 3/2016, European Environment Agency.

EEA, 2016b, *Urban adaptation to climate change in Europe 2016 — Transforming cities in a changing climate*, EEA Report No 12/2016, European Environment Agency.

EU, 2013a, Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism, OJ L 347, 20.12.2013, pp. 924–947.

EU, 2013b, Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet', OJ L 354, 28.12.2013, pp. 171–200.

Forzieri, G., Bianchi, A., Marin Herrera, M. A., Batista e Silva, F., Feyen, L., Lavalle, C., European Commission, Joint Research Centre and Institute for the Protection and the Security of the Citizen, 2015, *Resilience of large investments and critical infrastructures in Europe to climate change*, Publications Office, Luxembourg.

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Millennium Ecosystem Assessment, 2005, *Ecosystems and human well-being: Biodiversity synthesis*, World Resources Institute, Washington, DC.

UN, 2015a, Sendai Framework for Disaster Risk Reduction 2015–2030, A/RES/69/283, General Assembly, 69th session.

UN, 2015b, Transforming our world: The 2030 Agenda for Sustainable Development, A/RES/70/1, General Assembly, 70th session.

UNEP, 2015, The emissions gap report 2015, United Nations Environment Programme (UNEP), Nairobi.

UNFCCC, 2015, *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*, Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session, United Nations Framework Convention on Climate Change.

WEF, 2016, *The global risks report 2016*, Insight Report 11th edition, World Economic Forum, Geneva, Switzerland.

Chapter 1: Introduction

Ahmad, Q. K., Warrick, R. A., Downing, T. E., Nishioka, S., Parikh, K. S., Parmesan, C., Schneider, S. H., Toth, F. and Yohe, G., 2007, 'Methods and tools', in: McCarthy, J. J., Canziani, O. F., Leary, N. A., et al. (eds), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp. 105–143.

Barnett, J., Lambert, S. and Fry, I., 2008, 'The Hazards of Indicators: Insights from the Environmental Vulnerability Index', *Annals of the Association of American Geographers* 98(1), 102–119 (doi: 10.1080/00045600701734315).

Birkmann, J. and UNU-EHS Expert Working Group on Measuring Vulnerability (eds), 2013, *Measuring vulnerability to natural hazards: towards disaster resilient societies*, Second edition, United Nations University Press, Tokyo; New York.

Booth, B. B. B., Bernie, D., McNeall, D., Hawkins, E., Caesar, J., Boulton, C., Friedlingstein, P. and Sexton, D. M. H., 2013, 'Scenario and modelling uncertainty in global mean temperature change derived from emission-driven global climate models', *Earth System Dynamics* 4(1), 95–108 (doi: 10.5194/esd-4-95-2013).

Capela Lourenço, T., Rovisco, A., Groot, A., Nilsson, C., Füssel, H.-M., Van Bree, L. and Street, R. B. (eds), 2014, *Adapting to an uncertain climate*, Springer International Publishing, Cham.

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M., 2013, 'Long-term climate change: Projections, commitments and irreversibility', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 029–1 136.

Costa, L. and Kropp, J. P., 2013, 'Linking components of vulnerability in theoretic frameworks and case studies', *Sustainability Science* 8(1), 1–9 (doi: 10.1007/s11625-012-0158-4).

Cuaresma, J. C., 2015, 'Income projections for climate change research: A framework based on human capital dynamics', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.02.012).

Dellink, R., Chateau, J., Lanzi, E. and Magné, B., 2015, 'Long-term economic growth projections in the Shared Socioeconomic Pathways', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.06.004).

Diffenbaugh, N. S., Giorgi, F., Raymond, L. and Bi, X., 2007, 'Indicators of 21st century socioclimatic exposure', *Proceedings of the National Academy of Sciences* 104(51), 20195–20198 (doi: 10.1073/pnas.0706680105).

Downing, T. E., Gawith, M. J., Olsthoorn, A. A., Tol, R. S. J. and Vellinga, P., 1999, 'Introduction', in: Downing, T. E., Olsthoorn, A. A., and Tol, R. S. J. (eds), *Climate, change and risk*, Routledge, London.

Dunford, R., Harrison, P. A., Jäger, J., Rounsevell, M. D. A. and Tinch, R., 2015, 'Exploring climate change vulnerability across sectors and scenarios using indicators of impacts and coping capacity', *Climatic Change* 128(3–4), 339–354 (doi: 10.1007/s10584-014-1162-8).

EC, 2000, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, pp. 1–73.

EC, 2007, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, OJ L 288, 6.11.2007, pp. 27–34.

EC, 2013, *Commission Staff Working Document — Impact Assessment — Accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — An EU Strategy on adaptation to climate change*, SWD(2013) 132 final, European Commission, Brussels.

EEA, 2004, *Impacts of Europe's changing climate*, EEA Report No 2/2004, European Environment Agency.

EEA, 2008, *Impacts of Europe's changing climate — 2008 indicator-based assessment*, Joint EEA–JRC–WHO Report No 4/2008, European Environment Agency.

EEA, 2012a, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2012b, *Water resources in Europe in the context of vulnerability*, EEA Report No 11/2012, European Environment Agency.

EEA, 2013a, *Adaptation in Europe — Addressing risks and opportunities from climate change in the context of socio-economic developments*, EEA Report No 3/2013, European Environment Agency.

EEA, 2013b, *Balancing the future of Europe's coasts: Knowledge base for integrated management*, EEA Report No 12/2013, European Environment Agency.

EEA, 2013c, *Environment and human health*, Joint EEA–JRC Report No 5/2013, European Environment Agency.

EEA, 2014a, *Adaptation of transport to climate change in Europe: Challenges and options across transport modes and stakeholders*, EEA Report No 8/2014, European Environment Agency.

EEA, 2014b, *National adaptation policy processes across European countries- 2014*, EEA Report No 4/2014, European Environment Agency, Copenhagen, Denmark.

EEA, 2015a, *European ecosystem assessment: Concept, data, and implementation*, EEA Technical report No 6/2015, European Environment Agency.

EEA, 2015b, *National monitoring, reporting and evaluation of climate change adaptation in Europe*, EEA Technical report No 20/2015, European Environment Agency.

EEA, 2015c, *Overview of climate change adaptation platforms in Europe*, EEA Technical report No 5/2015, European Environment Agency.

EEA, 2015d, *SOER 2015: The European environment — state and outlook 2015*, European Environment Agency.

EEA, 2015e, *State of Europe's seas*, EEA Report No 2/2015, European Environment Agency.

EEA, 2015f, *State of nature in the EU: Results from reporting under the nature directives 2007–2012*, EEA Technical report No 2/2015, European Environment Agency.

EEA, 2015g, *The European environment — state and outlook 2015: Assessment of global megatrends*, European Environment Agency.

EEA, 2015h, 'Urban vulnerability to climate change in Europe — A map book' (http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction) accessed 8 February 2016.

EEA, 2016, *Urban adaptation to climate change in Europe 2016*, EEA Report No 12/2016, European Environment Agency.

EU, 2013, Regulation (EU) No 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change, OJ L 165, 18.6.2013, pp. 13–40.

Funtowicz, S. O. and Ravetz, J. R., 1990, *Uncertainty and quality in science for policy*, Theory and Decision Library A, Kluwer, Dordrecht.

Füssel, H.-M., 2007, 'Vulnerability: A generally applicable conceptual framework for climate change research', *Global Environmental Change* 17, 155–167 (doi: 10.1016/j.gloenvcha.2006.05.002).

Füssel, H.-M., 2010, 'How inequitable is the global distribution of responsibility, capability, and vulnerability to climate change: A comprehensive indicator-based assessment', *Global Environmental Change* 20(4), 597–611 (doi: 10.1016/j.gloenvcha.2010.07.009).

GIZ, 2013, *Economic approaches for assessing climate change adaptation options under uncertainty*, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Eschborn.

Haasnoot, M., Kwakkel, J. H., Walker, W. E. and ter Maat, J., 2013, 'Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world', *Global Environmental Change* 23(2), 485–498 (doi: 10.1016/j.gloenvcha.2012.12.006).

Hallegatte, S., Shah, A., Lempert, R., Brown, C. and Gill, S., 2012, *Investment decision making under deep uncertainty — application to climate change*, Policy Research Working Papers, The World Bank, Washington, DC.

Hansen, G. and Stone, D., 2015, 'Assessing the observed impact of anthropogenic climate change', *Nature Climate Change* advance online publication (doi: 10.1038/nclimate2896).

Hawkins, E. and Sutton, R., 2009, 'The potential to narrow uncertainty in regional climate predictions', *Bulletin of the American Meteorological Society* 90(8), 1 095–1 107 (doi: 10.1175/2009BAMS2607.1).

Hawkins, E. and Sutton, R., 2011, 'The potential to narrow uncertainty in projections of regional precipitation change', *Climate Dynamics* 37(1), 407–418 (doi: 10.1007/s00382-010-0810-6).

Hildén, M. and Marx, A., 2013, *Technical paper on evaluation of climate change state, impact and vulnerability indicators*, ETC/CCA Technical Paper 2/2013, European Topic Centre on Climate Impacts, Vulnerability and Adaptation, Copenhagen.

Hinkel, J., 2011, 'Indicators of vulnerability and adaptive capacity: Towards a clarification of the science–policy interface', *Global Environmental Change* 21(1), 198–208 (doi: 10.1016/j.gloenvcha.2010.08.002).

Hov, Ø., Cubasch, U., Fischer, E., Höppe, P., Iversen, T., Kvamstø, N. G., Kundzewicz, Z. W., Rezacova, D., Rios, D., Duarte Santos, F., Schädler, B., Veisz, O., Zerefos, C., Benestad, R., Murlis, J., Donat, M., Leckebusch, G. C. and Ulbrich, U., 2013, *Extreme weather events in Europe: preparing for climate change adaptation*, Norwegian Meteorological Institute, Oslo.

IPCC, 2007a, *Climate change 2007: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2007b, *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014a, *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014b, *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jiang, L. and O'Neill, B. C., 2015, 'Global urbanization projections for the Shared Socioeconomic Pathways', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.03.008).

Klein, R. J. T., 2009, 'Identifying countries that are particularly vulnerable to the adverse effects of climate change: An academic or a political challenge?', *Carbon and Climate Law Review* 3, 284–291.

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Leimbach, M., Kriegler, E., Roming, N. and Schwanitz, J., 2015, 'Future growth patterns of world regions — A GDP scenario approach', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.02.005).

van der Linden, P., Dempsey, P., Dunn, R., Caesar, J. and Kurnik, B., 2015, *Extreme weather and climate in Europe*, ETC-CCA Technical Paper No 2/2015, European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation, Bologna.

Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., Held, H., Kriegler, E., Mach, K. J., Matschoss, P. R., Plattner, G.-K., Yohe, G. W. and Zwiers, F. W., 2010, Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, Intergovernmental Panel on Climate Change (IPCC), Geneva.

McCallum, S., Dworak, T., Prutsch, A., Kent, N., Mysiak, J., Bosello, F., Klostermann, J., Dlugolecki, A., Williams, E., König, M., Leitner, M., Miller, K., Harley, M., Smithers, R., Berglund, M., Glas, N., Romanovska, L., van de Sandt, K., Bachschmidt, R. et al., 2013, *Support to the development of the EU Strategy for Adaptation to Climate Change: Background report to the Impact Assessment, Part I — Problem definition, policy context and assessment of policy options*, Environment Agency Austria, Vienna.

McCallum, S., Prutsch, A., Berglund, M., Dworak, T., Kent, N., Leitner, M., Miller, K. and Matauschek, M., 2013, *Support to the development of the EU Strategy for*

Adaptation to Climate Change: Background report to the Impact Assessment, Part II — Stakeholder involvement, Environment Agency Austria, Vienna.

Monier, E., Gao, X., Scott, J. R., Sokolov, A. P. and Schlosser, C. A., 2014, 'A framework for modeling uncertainty in regional climate change', *Climatic Change* 131(1), 51–66 (doi: 10.1007/s10584-014-1112-5).

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. and Wilbanks, T. J., 2010, 'The next generation of scenarios for climate change research and assessment', *Nature* 463(7282), 747–756 (doi: 10.1038/nature08823).

Nakicenovic, N. and Swart, R. (eds), 2000, *Special Report on Emissions Scenarios*, Cambridge University Press, Cambridge, United Kingdom.

O'Brien, K., Eriksen, S., Nygaard, L. P. and Schjolden, A., 2007, 'Why different interpretations of vulnerability matter in climate change discourses', *Climate Policy* 7, 73–88.

OECD, 2015, *Climate change risks and adaptation*, OECD Publishing, Paris.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W., 2015, 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.01.004).

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R. and Vuuren, D. P. van, 2014, 'A new scenario framework for climate change research: The concept of shared socioeconomic pathways', *Climatic Change* 122(3), 387–400 (doi: 10.1007/s10584-013-0905-2).

Preston, B. L., Yuen, E. J. and Westaway, R. M., 2011, 'Putting vulnerability to climate change on the map: A review of approaches, benefits, and risks', *Sustainability Science* 6(2), 177–202 (doi: 10.1007/s11625-011-0129-1).

PROVIA, 2013, *PROVIA guidance on assessing vulnerability, impacts and adaptation to climate change*, Consultation Document, United Nations Environment Programme, Nairobi.

Samir, K. C. and Lutz, W., 2015, 'The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2014.06.004).

Schröter, D., Polsky, C. and Patt, A. G., 2005, 'Assessing vulnerabilities to the effects of global change: An eight step approach', *Mitigation and Adaptation Strategies for Global Change* 10(4), 573–595 (doi: 10.1007/s11027-005-6135-9).

Sense about Science, 2013, *Making sense of uncertainty*, Sense about Science, London.

Sherwood, S. C., Bony, S., Boucher, O., Bretherton, C., Forster, P. M., Gregory, J. M. and Stevens, B., 2015, 'Adjustments in the forcing-feedback framework for understanding climate change', *Bulletin of the American Meteorological Society* 96(2), 217–228 (doi: 10.1175/BAMS-D-13-00167.1).

Tonmoy, F. N., El-Zein, A. and Hinkel, J., 2014, 'Assessment of vulnerability to climate change using indicators: A meta-analysis of the literature', *Wiley Interdisciplinary Reviews: Climate Change* 5(6), 775–792 (doi: 10.1002/wcc.314).

UN, 1992, United Nations Framework Convention on Climate Change, Secretary-General of the United Nations.

UN, 2004, *Living with risk: A global review of disaster reduction initiatives*, United Nations International Strategy for Disaster Reduction, Geneva.

van Vuuren, D. P. and Carter, T. R., 2014, 'Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old', *Climatic Change* 122(3), 415–429 (doi: 10.1007/s10584-013-0974-2).

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K., 2011, 'The representative concentration pathways: an overview', *Climatic Change* 109(1–2), 5–31 (doi: 10.1007/s10584-011-0148-z).

van Vuuren, D. P., Kok, M. T. J., Girod, B., Lucas, P. L. and de Vries, B., 2012, 'Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use', *Global Environmental Change* 22(4), 884–895 (doi: 10.1016/j.gloenvcha.2012.06.001).

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H., 2014, 'A new scenario framework for Climate Change Research: Scenario matrix architecture', *Climatic Change* 122(3), 373–386 (doi: 10.1007/s10584-013-0906-1).

Wilby, R. L. and Dessai, S., 2010, 'Robust adaptation to climate change', *Weather* 65(7), 180–185 (doi: 10.1002/wea.543).

Yip, S., Ferro, C. A. T., Stephenson, D. B. and Hawkins, E., 2011, 'A simple, coherent framework for partitioning uncertainty in climate predictions', *Journal of Climate* 24(17), 4 634–4 643 (doi: 10.1175/2011JCLI4085.1).

Yohe, G. W., Malone, E., Brenkert, A., Schlesinger, M., Meij, H. and Xing, X., 2006, 'Global distributions of vulnerability to climate change', *Integrated Assessment* 6(3), 35–44.

Chapter 2: Policy context

Alpine Convention, 2014a, Guidelines for Climate Change Adaptation at the Local Level in the Alps.

Alpine Convention, 2014b, Guidelines on Local Adaptation to Climate Change for Water Management and Natural Hazards in the Alps.

Barcelona Convention, 1995, Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean.

BEAC, 2013, Action Plan on Climate Change for the Barents Cooperation. Adopted at the 11th meeting of the environmental ministers under the Barents Euro-Arctic Council, Inari, Finland, 5 December 2013.

CBSS, 2014, Decision by the Council of the Baltic Sea States on a review of the CBSS long term priorities, Council of the Baltic Sea States.

CBSS, 2016, 'Expert group on sustainable development — Baltic 21' (http://www.cbss.org/sustainable-prosperous-region/egsd-baltic-21) accessed 15 March 2016.

EC, 2000, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, pp. 1–73.

EC, 2007, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, OJ L 288, 6.11.2007, pp. 27–34.

EC, 2010, Europe 2020: A strategy for smart, sustainable and inclusive growth, COM(2010) 2020 final, Brussels, 3.3.2010.

EC, 2011, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final of 08 March 2011.

EC, 2012, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions concerning the European Union Strategy for the Baltic Sea Region, COM(2012) 128 final of 23 March 2012.

EC, 2013a, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Region — An EU Strategy on adaptation to climate change, COM(2013) 216 final of 16 April 2013, Brussels.

EC, 2013b, *Guidelines on developing adaptation strategies*, SWD(2013) 134 final.

EC, 2015, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Investing in jobs and growth — Maximising the contribution of European Structural and Investment Funds, COM(2015) 639 final of 14 December 2015.

EC, 2016a, 'International climate finance' (http://ec.europa.eu/clima/policies/international/finance/index_en.htm) accessed 21 March 2016.

EC, 2016b, 'Progress made in cutting emissions' (http://ec.europa.eu/clima/policies/strategies/progress/index_en.htm) accessed 15 March 2016.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J. C., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C. and Zwickel, T., 2014, *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

EEA, 2014, *National adaptation policy processes across European countries — 2014*, EEA Report No 4/2014, European Environment Agency.

EEA, 2015a, *National monitoring, reporting and evaluation of climate change adaptation in Europe*, EEA Technical report No 20/2015, European Environment Agency.

EEA, 2015b, *Trends and projections in Europe 2015 — Tracking progress towards Europe's climate and energy targets*, EEA Report No 4/2015, European Environment Agency.

EEAS, 2014, 'EU Arctic Policy' (http://www.eeas.europa.eu/arctic_region) accessed 16 March 2016.

EU, 2009, Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020, OJ L 140, 5.6.2009, pp. 136–148.

EU, 2013a, Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet', OJ L 354, 28.12.2013, pp. 171–200.

EU, 2013b, Regulation (EU) No 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change, OJ L 165, 18.6.2013, pp. 13–40.

EU, 2014, Commission implementing decision of 19 March 2014 on the adoption of the LIFE multiannual work programme for 2014–17, 2014/203/EU, OJ L 116, 17.4.2014, pp. 1–56.

European Parliament, 2014, European Parliament resolution of 12 March 2014 on the EU strategy for the Arctic (2013/2595(RSP)).

Northern Forum, 2016, 'Water & Climate Change Working Group' (http://www.northernforum.org/en/projects/environment/west-climate-change-working-group) accessed 15 March 2016.

OECD, 2015, *Climate finance in 2013-14 and the USD 100 billion goal*, Report by the Organisation for Economic Co-operation and Development (OECD) in collaboration with Climate Policy Initiative (CPI), OECD.

The Nordic Council, 2014, 'The Nordic Council of Ministers' Arctic Co-operation Programme 2015–2017 — Nordic cooperation' (http://www.norden.org/en/nordic-council-of-ministers/ministers-for-co-operation-mr-sam/the-arctic/the-nordic-council-of-ministers-arctic-co-operation-programme-2015-2017) accessed 15 March 2016.

UN, 2015, Sendai Framework for Disaster Risk Reduction 2015–2030, A/RES/69/283, General Assembly, 69th session.

UN, 2016, 'Sustainable Development Goals: Sustainable Development Knowledge Platform' (http://sustainabledevelopment.un.org/index.php?menu=1300) accessed 27 January 2016.

UNEP, 2015, The Emissions Gap Report 2015, United Nations Environment Programme (UNEP), Nairobi.

UNEP, 2016, Regional Climate Change Adaptation Framework for the Mediterranean Marine and Coastal Areas, (DEPI)/MED IG.22/28., Decision IG.22/6, 19th Meeting of the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean.

UNFCCC, 1992, United Nations framework convention on climate change.

UNFCCC, 2005, *Report of the Conference of the Parties on its eleventh session, held at Montreal from 28 November to 10 December 2005. Addendum. Part Two: Action taken by the Conference of the Parties at its eleventh session.*

UNFCCC, 2010, *Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010*, FCCC/CP/2010/7/Add.1, UNFCCC, Cancun.

UNFCCC, 2012, Doha amendment to the Kyoto Protocol.

UNFCCC, 2015, *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Addendum. Part two: Action taken by the Conference of the Parties at its twenty-first session.*

UNFCCC, 2016, 'Annex I national communications (NC6)' (http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/7742.php) accessed 15 March 2016.

WEF, 2016, *The Global Risks Report 2016. 11th Edition*, Insight Report, World Economic Forum, Geneva, Switzerland.

Chapter 3: Changes in the climate system

Section 3.1: Human influence on the climate system

Ban, N., Schmidli, J. and Schär, C., 2015, 'Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster?', *Geophysical Research Letters* 42(4), 1 165–1 172 (doi: 10.1002/2014GL062588).

Bindoff, N. L., Stott, P. A., Allen, M. R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Overland, J., Perlwitz, J., Sebbari, R. and Zhang, X., 2013, 'Detection and attribution of climate change: From global to regional', in: Mokhov, I. I., Stocker, T. F., Qin, D., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 867–952.

Christidis, N., Jones, G. S. and Stott, P. A., 2015, 'Dramatically increasing chance of extremely hot summers since the 2003 European heatwave', *Nature Climate Change* 5(1), 46–50 (doi: 10.1038/nclimate2468).

Cubasch, U., Wuebbles, D., Chen, D., Facchini, M. C., Frame, D., Mahowald, N. and Winther, J.-G., 2013, 'Introduction', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 119–158.

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R. and Caesar, J., 2013, 'Global land-based datasets for monitoring climatic extremes', *Bulletin of the American Meteorological Society* 94(7), 997–1 006 (doi: 10.1175/BAMS-D-12-00109.1).

EURO4M, 2015, *2014: Warmest year on record in Europe*, Climate Indicator Bulletin (19 January 2015), EURO4M.

EURO4M, 2016, *2015: Joint warmest year on record in Europe*, Climate Indicator Bulletin (25 January 2016), EURO4M.

Fischer, E. M. and Knutti, R., 2015, 'Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes', *Nature Climate Change* 5(6), 560–564 (doi: 10.1038/nclimate2617).

Good, P., Caesar, J., Bernie, D., Lowe, J. A., Linden, P. van der, Gosling, S. N., Warren, R., Arnell, N. W., Smith, S., Bamber, J., Payne, T., Laxon, S., Srokosz, M., Sitch, S., Gedney, N., Harris, G., Hewitt, H., Jackson, L., Jones, C. D. et al., 2011, 'A review of recent developments in climate change science. Part I: Understanding of future change in the large-scale climate system', *Progress in Physical Geography* 35(3), 281–296 (doi: 10.1177/0309133311407651).

Good, P., Lowe, J., Ridley, J., Bamber, J., Payne, T., Keen, A., Stroeve, J., Jackson, L., Srokosz, M., Kay, G., Harper, A., Kruijt, B., Burke, E., Abbott, B., O'Connor, F., Minshull, T., Turley, C. and Williamson, P., 2014, *An updated view of tipping points and the relevance for long-term climate goals*, AVOID 2 WPA. 5 Report 1, AVOID 2 Programme.

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M. and Lo, K.-W., 2016, 'Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous', *Atmospheric Chemistry and Physics* 16(6), 3 761–3 812 (doi: 10.5194/acp-16-3761-2016).

Hegerl, G. and Zwiers, F., 2011, 'Use of models in detection and attribution of climate change', *Wiley Interdisciplinary Reviews: Climate Change* 2(4), 570–591 (doi: 10.1002/wcc.121).

Herring, S. C., Hoerling, M. P., Peterson, T. C. and Stott, P. A., 2014, 'Explaining extreme events of 2013 from a climate perspective', *Bulletin Of The American Meteorological Society* 95(9), S1–S96.

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013a, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2013b, 'Summary for policymakers', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S. et al., 2014, 'EURO-CORDEX: New high-resolution climate change projections for European impact research', *Regional Environmental Change* 14(2), 563–578 (doi: 10.1007/s10113-013-0499-2).

Jones, C., Giorgi, F. and Asrar, G. R., 2011, *The Coordinated Regional Downscaling Experiment: CORDEX — An international downscaling link to CMIP5*, CLIVAR Exchanges 56.

Kam, J., Knutson, T. R., Zeng, F. and Wittenberg, A. T., 2015, 'Record annual mean warmth over Europe, the Northeast Pacific, and the Northwest Atlantic during 2014: Assessment of anthropogenic influence', *Bulletin of the American Meteorological Society* 96(12), S61–S65 (doi: 10.1175/BAMS-EEE_2014_ch13.1).

Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C. and Senior, C. A., 2014, 'Heavier summer downpours with climate change revealed by weather forecast resolution model', *Nature Climate Change* 4(7), 570–576 (doi: 10.1038/nclimate2258).

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K. and Wulfmeyer, V., 2014, 'Regional climate modeling on European scales: A joint standard evaluation of the EURO-CORDEX RCM ensemble', *Geoscientific Model Development* 7(4), 1 297–1 333 (doi: 10.5194/gmd-7-1297-2014).

Lehmann, J., Coumou, D. and Frieler, K., 2015, 'Increased record-breaking precipitation events under global warming', *Climatic Change* 132(4), 501–515 (doi: 10.1007/s10584-015-1434-y).

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. and Schellnhuber, H. J., 2008, 'Tipping elements in the Earth's climate system', *Proceedings of the National Academy of Sciences* 105(6), 1 786–1 793 (doi: 10.1073/pnas.0705414105).

Luterbacher, J., Werner, J. P., Smerdon, J. E., Fernández-Donado, L., González-Rouco, F. J., Barriopedro, D., Ljungqvist, F. C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J. H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R. et al., 2016, 'European summer temperatures since Roman times', *Environmental Research Letters* 11(2), 24001 (doi: 10.1088/1748-9326/11/2/024001).

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K. and Stocker, T. F., 2008, 'High-resolution carbon dioxide concentration record 650,000–800,000 years before present', *Nature* 453(7193), 379–382 (doi: 10.1038/nature06949).

Montesarchio, M., Zollo, A. L., Bucchignani, E., Mercogliano, P. and Castellari, S., 2014, 'Performance evaluation of high-resolution regional climate simulations in the Alpine space and analysis of extreme events', *Journal of Geophysical Research: Atmospheres* 119(6), 3 222–3 237 (doi: 10.1002/2013JD021105).

National Academies of Sciences, Engineering, and Medicine, 2016, *Attribution of Extreme Weather Events in the Context of Climate Change*, National Academies Press, Washington, D.C.

Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Hilberts, A. G. J., Lohmann, D. and Allen, M. R., 2011, 'Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000', *Nature* 470(7334), 382–385 (doi: 10.1038/nature09762).

van der Schrier, G., van den Besselaar, E. J. M., Klein Tank, A. M. G. and Verver, G., 2013, 'Monitoring European average temperature based on the E-OBS gridded data set', *Journal of Geophysical Research: Atmospheres* 118(11), 5 120–5 135 (doi: 10.1002/jgrd.50444).

Stott, P. A., Christidis, N., Otto, F. E. L., Sun, Y., Vanderlinden, J.-P., van Oldenborgh, G. J., Vautard, R., von Storch, H., Walton, P., Yiou, P. and Zwiers, F. W., 2016, 'Attribution of extreme weather and climate-related events', *Wiley Interdisciplinary Reviews: Climate Change* 7(1), 23–41 (doi: 10.1002/wcc.380).

Stott, P. A., Stone, D. A. and Allen, M. R., 2004, 'Human contribution to the European heatwave of 2003', *Nature* 432, 610–614.

Trenberth, K. E., Fasullo, J. T. and Shepherd, T. G., 2015, 'Attribution of climate extreme events', *Nature Climate Change* 5(8), 725–730 (doi: 10.1038/nclimate2657).

US EPA Climate Change Division, 2015, 'Atmospheric concentrations of greenhouse gases' (http://www3.epa.gov/climatechange/science/indicators/ghg/ghg-concentrations.html) accessed 18 November 2015.

WMO, 2016, *2015 is hottest year on record*, Press Release No 2, World Meteorological Organization.

Zwiers, F. W., Alexander, L. V., Hegerl, G. C., Knutson, T. R., Kossin, J. P., Naveau, P., Nicholls, N., Schär, C., Seneviratne, S. I. and Zhang, X., 2013, 'Climate extremes: Challenges in estimating and understanding recent changes in the frequency and intensity of extreme climate and weather events', in: Asrar, G. R. and Hurrell, J. W. (eds), *Climate science for serving society*, Springer Netherlands, Dordrecht, pp. 339–389.

Section 3.2: Atmosphere

Baatsen, M., Haarsma, R. J., Van Delden, A. J. and de Vries, H., 2015, 'Severe autumn storms in future western Europe with a warmer Atlantic Ocean', *Climate Dynamics* 45(3–4), 949–964 (doi: 10.1007/s00382-014-2329-8).

Ban, N., Schmidli, J. and Schär, C., 2015, 'Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster?', *Geophysical Research Letters* 42(4), 1 165–1 172 (doi: 10.1002/2014GL062588).

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. and Garcia-Herrera, R., 2011, 'The hot summer of 2010: Redrawing the temperature record map of Europe', *Science* 332(6026), 220–224 (doi: 10.1126/science.1201224).

van den Besselaar, E. J. M., Klein Tank, A. M. G. and Buishand, T. A., 2013, 'Trends in European precipitation extremes over 1951–2010', *International Journal of Climatology* 33(12), 2 682–2 689 (doi: 10.1002/joc.3619).

Blunden, J. and Arndt, D. S., 2015, 'State of the Climate in 2014', *Bulletin of the American Meteorological Society* 96(7), ES1-ES32 (doi: 10.1175/2015BAMSStateoftheClimate.1).

Brönnimann, S., Martius, O., von Waldow, H., Welker, C., Luterbacher, J., Compo, G. P., Sardeshmukh, P. D. and Usbeck, T., 2012, ‚Extreme winds at northern mid-latitudes since 1871', *Meteorologische Zeitschrift* 21(1), 13–27 (doi: 10.1127/0941-2948/2012/0337).

Brooks, H. E., 2013, 'Severe thunderstorms and climate change', *Atmospheric Research* 123, 129–138 (doi: 10.1016/j.atmosres.2012.04.002).

Casanueva, A., Rodríguez-Puebla, C., Frías, M. D. and González-Reviriego, N., 2014, 'Variability of extreme precipitation over Europe and its relationships with teleconnection patterns', *Hydrology and Earth System Sciences* 18(2), 709–725 (doi: 10.5194/hess-18-709-2014).

Chan, S. C., Kendon, E. J., Fowler, H. J., Blenkinsop, S., Roberts, N. M. and Ferro, C. A. T., 2014, 'The value of high-resolution Met Office regional climate models in the simulation of multihourly precipitation extremes', *Journal of Climate* 27(16), 6 155–6 174 (doi: 10.1175/JCLI-D-13-00723.1).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M., 2013, 'Long-term climate change: Projections, commitments and irreversibility', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 029–1 136.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J. et al., 2011, 'The ERA-Interim reanalysis: Configuration and performance of the data assimilation system', *Quarterly Journal of the Royal Meteorological Society* 137(656), 553–597 (doi: 10.1002/qj.828).

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R. and Caesar, J., 2013, 'Global land-based datasets for monitoring climatic extremes', *Bulletin of the American Meteorological Society* 94(7), 997–1 006 (doi: 10.1175/BAMS-D-12-00109.1).

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., Willett, K. M., Aguilar, E., Brunet, M., Caesar, J., Hewitson, B., Jack, C., Klein Tank, A. M. G., Kruger, A. C., Marengo, J., Peterson, T. C., Renom, M., Oria Rojas, C., Rusticucci, M. et al., 2013, 'Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset', *Journal of Geophysical Research: Atmospheres* 118(5), 2 098–2 118 (doi: 10.1002/jgrd.50150).

Donat, M. G., Leckebusch, G. C., Wild, S. and Ulbrich, U., 2011, 'Future changes in European winter storm losses and extreme wind speeds inferred from GCM and RCM multi-model simulations', *Natural Hazards and Earth System Science* 11(5), 1 351–1 370 (doi: 10.5194/nhess-11-1351-2011).

Donat, M. G., Renggli, D., Wild, S., Alexander, L. V., Leckebusch, G. C. and Ulbrich, U., 2011, 'Reanalysis suggests long-term upward trend in European storminess since 1871', *Geophysical Research Letters* 38, L14703 (doi: 10.1029/2011GL047995).

EURO4M, 2015, *2014: Warmest year on record in Europe*, Climate Indicator Bulletin (19 January 2015), EURO4M.

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R. and Xia, L., 2014, 'Storminess over the North Atlantic and northwestern Europe-A review: Storminess over the North Atlantic and Northwestern Europe — A Review', *Quarterly Journal of the Royal Meteorological Society* 141, 350–382 (doi: 10.1002/qj.2364).

Fischer, E. M., Sedláček, J., Hawkins, E. and Knutti, R., 2014, 'Models agree on forced response pattern of precipitation and temperature extremes', *Geophysical Research Letters* 41(23), 8 554–8 562 (doi: 10.1002/2014GL062018).

Fischer, E. and Schär, C., 2010, 'Consistent geographical patterns of changes in high-impact European heatwaves', *Nature Geoscience* 3, 398–403 (doi: 10.1038/ngeo866).

Fleig, A. K., Tallaksen, L. M., James, P., Hisdal, H. and Stahl, K., 2015, 'Attribution of European precipitation and temperature trends to changes in synoptic circulation', *Hydrology and Earth System Sciences* 19(7), 3 093–3 107 (doi: 10.5194/hess-19-3093-2015).

Fyfe, J. C., Meehl, G. A., England, M. H., Mann, M. E., Santer, B. D., Flato, G. M., Hawkins, E., Gillett, N. P., Xie, S.-P., Kosaka, Y. and Swart, N. C., 2016, 'Making sense of the early-2000s warming slowdown', *Nature Climate Change* 6(3), 224–228 (doi: 10.1038/nclimate2938).

Gallant, A. J. E., Karoly, D. J. and Gleason, K. L., 2013, 'Consistent trends in a modified climate extremes index in the United States, Europe, and Australia', *Journal of Climate* 27(4), 1 379–1 394 (doi: 10.1175/JCLI-D-12-00783.1).

García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J. and Fischer, E. M., 2010, 'A review of the European summer heat wave of 2003', *Critical Reviews in Environmental Science and Technology* 40(4), 267–306 (doi: 10.1080/10643380802238137).

Gastineau, G. and Soden, B. J., 2009, 'Model projected changes of extreme wind events in response to global warming', *Geophysical Research Letters* 36, L10810 (doi: 10.1029/2009GL037500).

Giorgi, F., Coppola, E. and Raffaele, F., 2014, 'A consistent picture of the hydroclimatic response to global warming from multiple indices: Models and observations', *Journal of Geophysical Research: Atmospheres* 119(20), 11 695–11 708 (doi: 10.1002/2014JD022238).

Giorgi, F., Coppola, E., Raffaele, F., Diro, G. T., Fuentes-Franco, R., Giuliani, G., Mamgain, A., Llopart, M. P., Mariotti, L. and Torma, C., 2014, 'Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections', *Climatic Change* 125(1), 39–51 (doi: 10.1007/s10584-014-1117-0).

GISTEMP team, 2016, 'GISS Surface Temperature Analysis (GISTEMP)' (http://data.giss.nasa.gov/gistemp) accessed 30 August 2016.

Hansen, J., Ruedy, R. and Sato, M., 2010, 'Global surface temperature change', *Reviews of Geophysics* 48(RG4004), 1–29 (doi: 10.1029/2010RG000345).

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, S., Brönimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M. and Zhai, P. M., 2013, 'Observations: Atmosphere and surface', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 159–254.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D. and New, M., 2008, 'A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006', *Journal of Geophysical Research* 113(D20), D20119 (doi: 10.1029/2008JD010201).

Hofstra, N., Haylock, M., New, M. and Jones, P. D., 2009, 'Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature', *Journal of Geophysical Research* 114(D21), D21101 (doi: 10.1029/2009JD011799).

Hov, Ø., Cubasch, U., Fischer, E., Höppe, P., Iversen, T., Kvamstø, N. G., Kundzewicz, Z. W., Rezacova, D., Rios, D., Duarte Santos, F., Schädler, B., Veisz, O., Zerefos, C., Benestad, R., Murlis, J., Donat, M., Leckebusch, G. C. and Ulbrich, U., 2013, *Extreme weather events in Europe: preparing for climate change adaptation*, Norwegian Meteorological Institute, Oslo.

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S. et al., 2014, 'EURO-CORDEX: New high-resolution climate change projections for European impact research', *Regional Environmental Change* 14(2), 563–578 (doi: 10.1007/s10113-013-0499-2).

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C. et al., 1996, 'The NCEP/NCAR 40-year reanalysis project', *Bulletin of the American Meteorological Society* 77, 437–471 (doi: 10.1175/1520-0477(1996)077).

Kam, J., Knutson, T. R., Zeng, F. and Wittenberg, A. T., 2015, 'Record annual mean warmth over Europe, the Northeast Pacific, and the Northwest Atlantic during 2014: Assessment of anthropogenic influence', *Bulletin of the American Meteorological Society* 96(12), S61–S65 (doi: 10.1175/BAMS-EEE_2014_ch13.1).

Kapsch, M.-L., Kunz, M., Vitolo, R. and Economou, T., 2012, 'Long-term trends of hail-related weather types in an ensemble of regional climate models using a Bayesian approach', *Journal of Geophysical Research: Atmospheres* 117(D15), D15107 (doi: 10.1029/2011JD017185).

Karl, T. R., Arguez, A., Huang, B., Lawrimore, J. H., McMahon, J. R., Menne, M. J., Peterson, T. C., Vose, R. S. and Zhang, H.-M., 2015, 'Possible artifacts of data biases in the recent global surface warming hiatus', *Science* 348(6242), 1 469–1 472 (doi: 10.1126/science.aaa5632).

Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C. and Senior, C. A., 2014, 'Heavier summer downpours with climate change revealed by weather forecast resolution model', *Nature Climate Change* 4(7), 570–576 (doi: 10.1038/nclimate2258).

King, A. D., Black, M. T., Min, S.-K., Fischer, E. M., Mitchell, D. M., Harrington, L. J. and Perkins-Kirkpatrick, S. E., 2016, 'Emergence of heat extremes attributable to anthropogenic influences', *Geophysical Research Letters* 43(7), 3 438–3 443 (doi: 10.1002/2015GL067448).

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K. and Takahashi, K., 2015, 'The JRA-55 reanalysis: General specifications and basic characteristics', *Journal of the Meteorological Society of Japan. Ser. II* 93(1), 5–48 (doi: 10.2151/jmsj.2015-001).

Kopparla, P., Fischer, E. M., Hannay, C. and Knutti, R., 2013, 'Improved simulation of extreme precipitation in a high-resolution atmosphere model', *Geophysical Research Letters* 40(21), 5 803–5 808 (doi: 10.1002/2013GL057866).

Krueger, O., Schenk, F., Feser, F. and Weisse, R., 2013, 'Inconsistencies between long-term trends in storminess derived from the 20CR reanalysis and observations', *Journal of Climate* 26(3), 868–874 (doi: 10.1175/JCLI-D-12-00309.1).

Kunz, M., Sander, J. and Kottmeier, C., 2009, 'Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany', *International Journal of Climatology* 29(15), 2 283–2 297 (doi: 10.1002/joc.1865).

Lehmann, J., Coumou, D. and Frieler, K., 2015, 'Increased record-breaking precipitation events under global warming', *Climatic Change* 132(4), 501–515 (doi: 10.1007/s10584-015-1434-y).

Lehner, F., Deser, C. and Sanderson, B. M., 2016, 'Future risk of record-breaking summer temperatures and its mitigation', *Climatic Change* (doi: 10.1007/s10584-016-1616-2).

Luterbacher, J., Werner, J. P., Smerdon, J. E., Fernández-Donado, L., González-Rouco, F. J., Barriopedro, D., Ljungqvist, F. C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J. H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R. et al., 2016, 'European summer temperatures since Roman times', *Environmental Research Letters* 11(2), 24001 (doi: 10.1088/1748-9326/11/2/024001).

Maraun, D., 2013, 'When will trends in European mean and heavy daily precipitation emerge?', *Environmental Research Letters* 8(1), 14004 (doi: 10.1088/1748-9326/8/1/014004).

Matulla, C., Schoener, W., Alexandersson, H., von Storch, H. and Wang, X. L., 2007, 'European storminess: Late nineteenth century to present', *Climate Dynamics* 31(2–3), 125–130 (doi: 10.1007/s00382-007-0333-y).

McDonald, R., 2011, 'Understanding the impact of climate change on Northern Hemisphere extra-tropical cyclones', *Climate Dynamics* 37, 1 399–1 425 (doi: 10.1007/s00382-010-0916-x).

Meinshausen, M., Smith, S., Calvin, K., Daniel, J., Kainuma, M., Lamarque, J.-F., Matsumoto, K., Montzka, S., Raper, S., Riahi, K., Thomson, A., Velders, G. and van Vuuren, D. P., 2011, 'The RCP greenhouse gas concentrations and their extensions from 1765 to 2300', *Climatic Change* 109(1), 213–241 (doi: 10.1007/s10584-011-0156-z).

Mohr, S. and Kunz, M., 2013, 'Recent trends and variabilities of convective parameters relevant for hail events in Germany and Europe', *Atmospheric Research* 123, 211–228 (doi: 10.1016/j.atmosres.2012.05.016).

Mohr, S., Kunz, M. and Geyer, B., 2015, 'Hail potential in Europe based on a regional climate model hindcast', *Geophysical Research Letters* 42(24), 10 904–10 912 (doi: 10.1002/2015GL067118).

Mohr, S., Kunz, M. and Keuler, K., 2015, 'Development and application of a logistic model to estimate the past and future hail potential in Germany', *Journal of Geophysical Research: Atmospheres* 120(9), 3 939–3 956 (doi: 10.1002/2014JD022959).

Montesarchio, M., Zollo, A. L., Bucchignani, E., Mercogliano, P. and Castellari, S., 2014, 'Performance evaluation of high-resolution regional climate simulations in the Alpine space and analysis of extreme events', *Journal of Geophysical Research: Atmospheres* 119(6), 3 222–3 237 (doi: 10.1002/2013JD021105).

Morice, C. P., Kennedy, J. J., Rayner, N. A. and Jones, P. D., 2012, 'Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set', *Journal of Geophysical Research* 117(D8), D08101 (doi: 10.1029/2011JD017187).

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P. and Wilbanks, T. J., 2010, 'The next generation of scenarios for climate change research and assessment', *Nature* 463(7282), 747–756 (doi: 10.1038/nature08823).

Mueller, B. and Seneviratne, S. I., 2012, 'Hot days induced by precipitation deficits at the global scale', *Proceedings of the National Academy of Sciences* 109(31), 12398–12403 (doi: 10.1073/pnas.1204330109).

Munich RE, 2014, 'Overall picture of natural catastrophes in 2013 dominated by weather extremes in Europe and Supertyphoon Haiyan' (http://www.munichre.com/en/media-relations/publications/press-releases/2014/2014-01-07-press-release/index.html) accessed 13 July 2015.

Munich RE, 2015, 'NatCatSERVICE' (http://www.munichre.com/natcatservice) accessed 5 August 2015.

Nikulin, G., Kjellstrom, E., Hansson, U., Stanberg, G. and Ullestrig, A., 2011, 'Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations', *Tellus Series A* 64, 41–55 (doi: 10.1111/j.1600-0870.2010.00466.x).

Osinski, R., Lorenz, P., Kruschke, T., Voigt, M., Ulbrich, U., Leckebusch, G. C., Faust, E., Hofherr, T. and Majewski, D., 2015, 'An approach to build an event set of European wind storms based on ECMWF EPS', *Natural Hazards and Earth System Sciences Discussions* 3(2), 1 231–1 268 (doi: 10.5194/nhessd-3-1231-2015).

Outten, S. D. and Esau, I., 2013, 'Extreme winds over Europe in the ENSEMBLES regional climate models', *Atmospheric Chemistry and Physics* 13(10), 5 163–5 172 (doi: 10.5194/acp-13-5163-2013).

Pardowitz, T., 2015, *Anthropogenic changes in the frequency and severity of European winter storms*, Dissertation FUDISS_derivate_000000017018, Free University, Berlin.

Pfahl, S., 2014, 'Characterising the relationship between weather extremes in Europe and synoptic circulation features', *Natural Hazards and Earth System Science* 14(6), 1 461–1 475 (doi: 10.5194/nhess-14-1461-2014).

Punge, H. J., Bedka, K. M., Kunz, M. and Werner, A., 2014, 'A new physically based stochastic event catalog for hail in Europe', *Natural Hazards* 73(3), 1 625–1 645 (doi: 10.1007/s11069-014-1161-0).

Punge, H. J. and Kunz, M., 2016, 'Hail observations and hailstorm characteristics in Europe: A review', *Atmospheric Research* 176–177, 159–184 (doi: 10.1016/j.atmosres.2016.02.012).

Rajczak, J., Pall, P. and Schär, C., 2013, 'Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region', *Journal of Geophysical Research: Atmospheres* 118(9), 3 610–3 626 (doi: 10.1002/jgrd.50297).

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P. and Vogt, J. V., 2014, 'Magnitude of extreme heat waves in present climate and their projection in a warming world', *Journal of Geophysical Research: Atmospheres* 119(22), 12 500–12 512 (doi: 10.1002/2014JD022098).

Russo, S., Sillmann, J. and Fischer, E. M., 2015, 'Top ten European heatwaves since 1950 and their occurrence in the coming decades', *Environmental Research Letters* 10(12), 124003 (doi: 10.1088/1748-9326/10/12/124003).

Sanderson, M. G., Hand, W. H., Groenemeijer, P., Boorman, P. M., Webb, J. D. C. and McColl, L. J., 2015, 'Projected changes in hailstorms during the 21st century over the UK', *International Journal of Climatology* 35(1), 15–24 (doi: 10.1002/joc.3958).

Scaife, A. A., Spangehl, T., Fereday, D. R., Cubasch, U., Langematz, U., Akiyoshi, H., Bekki, S., Braesicke, P., Butchart, N., Chipperfield, M. P., Gettelman, A., Hardiman, S. C., Michou, M., Rozanov, E. and Shepherd, T. G., 2011, 'Climate change projections and stratosphere–troposphere interaction', *Climate Dynamics* 38(9–10), 2 089–2 097 (doi: 10.1007/s00382-011-1080-7).

Schoetter, R., Cattiaux, J. and Douville, H., 2014, 'Changes of western European heat wave characteristics projected by the CMIP5 ensemble', *Climate Dynamics* 45(5–6), 1 601–1 616 (doi: 10.1007/s00382-014-2434-8).

van der Schrier, G., van den Besselaar, E. J. M., Klein Tank, A. M. G. and Verver, G., 2013, 'Monitoring European average temperature based on the E-OBS gridded data set', *Journal of Geophysical Research: Atmospheres* 118(11), 5 120–5 135 (doi: 10.1002/jgrd.50444).

Seneviratne, S. I., Donat, M. G., Mueller, B. and Alexander, L. V., 2014, 'No pause in the increase of hot temperature extremes', *Nature Climate Change* 4(3), 161–163 (doi: 10.1038/nclimate2145).

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X. and Bronaugh, D., 2013, 'Climate extremes indices in the CMIP5 multimodel ensemble. Part 2: Future climate projections', *Journal of Geophysical Research: Atmospheres* 118(6), 2 473–2 493 (doi: 10.1002/jgrd.50188).

Stott, P. A., Jones, G. S., Christidis, N., Zwiers, F. W., Hegerl, G. and Shiogama, H., 2011, 'Single-step attribution of increasing frequencies of very warm regional temperatures to human influence', *Atmospheric Science Letters* 12(2), 220–227 (doi: 10.1002/asl.315).

Taylor, C. M., 2015, 'Detecting soil moisture impacts on convective initiation in Europe', *Geophysical Research Letters* 42(11), 4 631–4 638 (doi: 10.1002/2015GL064030).

Ulbrich, U., Leckebusch, G. C. and Pinto, J. G., 2009, 'Extra-tropical cyclones in the present and future climate: A review', *Theoretical and Applied Climatology* 96, 117–131 (doi: 10.1007/s00704-008-0083-8).

UN, 1992, United Nations Framework Convention on Climate Change, Secretary-General of the United Nations.

UNFCCC, 2009, *Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009*, UNFCCC, Copenhagen.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O., Nikulin, G., Teichmann, C. and Jacob, D., 2014, 'The European climate under a 2 °C global warming', *Environmental Research Letters* 9(3), 34006 (doi: 10.1088/1748-9326/9/3/034006).

Wang, X. L., Feng, Y., Compo, G. P., Zwiers, F. W., Allan, R. J., Swail, V. R. and Sardeshmukh, P. D., 2014, 'Is the storminess in the twentieth century reanalysis really inconsistent with observations? A reply to the comment by Krueger et al. (2013b)', *Climate Dynamics* 42(3–4), 1 113–1 125 (doi: 10.1007/s00382-013-1828-3).

Wang, X. L., Wan, H., Zwiers, F. W., Swail, V. R., Compo, G. P., Allan, R. J., Vose, R. S., Jourdain, S. and Yin, X., 2011, 'Trends and low-frequency variability of storminess over western Europe, 1 878–2 007.', *Climate Dynamics* 37(11), 2355–2371 (doi: 10.1007/s00382-011-1107-0).

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G. and Roberts, N. M., 2014, 'Future changes to the intensity and frequency of short-duration extreme rainfall', *Reviews of Geophysics* 52(3), 522–555 (doi: 10.1002/2014RG000464).

WMO, 2016, *2015 is hottest year on record*, Press Release No 2, World Meteorological Organization.

Zappa, G., Shaffrey, L. C., Hodges, K. I., Sansom, P. G. and Stephenson, D. B., 2013, 'A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models', *Journal of Climate* 26(16), 5 846–5 862 (doi: 10.1175/JCLI-D-12-00573.1).

Zolina, O., Simmer, C., Gulev, S. and Kollet, S., 2010, 'Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls', *Geophysical Research Letters* 37, 1–5 (doi: 10.1029/2010GL042468).

Section 3.3: Cryosphere

ACIA, 2005, *Arctic climate impact assessment*, Cambridge University Press, Cambridge.

AMAP, 2011, *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate change and the cryosphere*, Arctic Monitoring and Assessment Programme, Oslo.

Applegate, P. J., Parizek, B. R., Nicholas, R. E., Alley, R. B. and Keller, K., 2015, 'Increasing temperature forcing reduces the Greenland ice sheet's response time scale', *Climate Dynamics* 45, 2 001–2 011 (doi: 10.1007/s00382-014-2451-7).

BAFU, 2012, *Auswirkungen der Klimaänderung auf Wasserressourcen und Gewässer. Synthesebericht zum Projekt 'Klimaänderung und Hydrologie in der Schweiz' (CCHydro)*, Umwelt-Wissen, Bundesamt für Umwelt, Bern.

Barletta, V. R., Sørensen, L. S. and Forsberg, R., 2013, 'Scatter of mass changes estimates at basin scale for Greenland and Antarctica', *The Cryosphere* 7(5), 1 411–1 432 (doi: 10.5194/tc-7-1411-2013).

Barry, R. G. and Gan, T. Y., 2011, *The global cryosphere: Past, present and future*, Cambridge University Press, Cambridge.

Benning, L. G., Anesio, A. M., Lutz, S. and Tranter, M., 2014, 'Biological impact on Greenland's albedo', *Nature Geoscience* 7(10), 691–691 (doi: 10.1038/ngeo2260).

Bevan, S., Luckman, A., Murray, T., Sykes, H. and Kohler, J., 2007, 'Positive mass balance during the late 20th century on Austfonna, Svalbard, revealed using satellite radar interferometry', *Annals of Glaciology* 46(1), 117–122 (doi: 10.3189/172756407782871477).

Biskaborn, B. K., Lanckman, J.-P., Lantuit, H., Elger, K., Streletskiy, D. A., Cable, W. L. and Romanovsky, V. E., 2015, 'The Global Terrestrial Network for Permafrost Database: metadata statistics and prospective analysis on future permafrost temperature and active layer depth monitoring site distribution', *Earth System Science Data Discussions* 8(1), 279–315 (doi: 10.5194/essdd-8-279-2015).

Blaschek, M., Bakker, P. and Renssen, H., 2014, 'The influence of Greenland ice sheet melting on the Atlantic meridional overturning circulation during past and future warm periods: a model study', *Climate Dynamics* 44(7–8), 2 137–2 157 (doi: 10.1007/s00382-014-2279-1).

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K. and Steffen, K., 2012, 'Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers', *The Cryosphere* 6(4), 821–839 (doi: 10.5194/tc-6-821-2012).

Brown, R. D. and Robinson, D. A., 2011, 'Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty', *The Cryosphere* 5(1), 219–229 (doi: 10.5194/tc-5-219-2011).

Brutel-Vuilmet, C., Ménégoz, M. and Krinner, G., 2013, 'An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models', *The Cryosphere* 7(1), 67–80 (doi: 10.5194/tc-7-67-2013).

Choi, G., Robinson, D. A. and Kang, S., 2010, 'Changing Northern Hemisphere snow seasons', *Journal of Climate* 23(19), 5 305–5 310 (doi: 10.1175/2010JCLI3644.1).

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. and Unnikrishnan, A. S., 2013, 'Sea-level change', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 137–1 216.

Clark, P. U., Church, J. A., Gregory, J. M. and Payne, A. J., 2015, 'Recent progress in understanding and projecting regional and global mean sea level change', *Current Climate Change Reports* 1(4), 224–246 (doi: 10.1007/s40641-015-0024-4).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M., 2013, 'Long-term climate change: Projections, commitments and irreversibility', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 029–1 136.

Comiso, J. C., 2012, 'Large decadal decline of the Arctic multiyear ice cover', *Journal of Climate* 25(4), 1 176–1 193 (doi: 10.1175/JCLI-D-11-00113.1).

Comiso, J. C., Parkinson, C. L., Gersten, R. and Stock, L., 2008, 'Accelerated decline in the Arctic sea ice cover', *Geophysical Research Letters* 35, L01703 (doi: 10.1029/2007GL031972).

DeConto, R. M. and Pollard, D., 2016, 'Contribution of Antarctica to past and future sea-level rise', *Nature* 531(7596), 591–597 (doi: 10.1038/nature17145).

DMI, GEUS and DTU Space, 2015, 'Polar Portal. Greenland — Total mass change' (http://polarportal.dk/en/groenlands-indlandsis/nbsp/total-masseaendring) accessed 17 August 2016.

EASAC, 2015, *Facing critical decisions on climate change in 2015*, European Academies' Scientific Advisory Council, Halle (Saale).

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

Engelhardt, M., Schuler, T. V. and Andreassen, L. M., 2013, 'Glacier mass balance of Norway

1961–2010 calculated by a temperature-index model', *Annals of Glaciology* 54(63), 32–40 (doi: 10.3189/2013AoG63A245).

Estilow, T. W., Young, A. H. and Robinson, D. A., 2015, 'A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring', *Earth System Science Data* 7(1), 137–142 (doi: 10.5194/essd-7-137-2015).

FAO, 2010, *Forests and climate change in Eastern Europe and Central Asia*, Forests and Climate Change Working Paper 8, Food and Agriculture Organization (FAO), Rome.

Favier, L., Durand, G., Cornford, S. L., Gudmundsson, G. H., Gagliardini, O., Gillet-Chaulet, F., Zwinger, T., Payne, A. J. and Le Brocq, A. M., 2014, 'Retreat of Pine Island Glacier controlled by marine ice-sheet instability', *Nature Climate Change* 4(2), 117–121 (doi: 10.1038/nclimate2094).

Fettweis, X., Franco, B., Tedesco, M., van Angelen, J. H., Lenaerts, J. T. M., van den Broeke, M. R. and Gallée, H., 2013, 'Estimating Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR', *The Cryosphere* 7, 268–489 (doi: 10.5194/tc-7-469-2013).

Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M. and Gallée, H., 2013, 'Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet', *The Cryosphere* 7(1), 241–248 (doi: 10.5194/tc-7-241-2013).

Fettweis, X., Tedesco, M., van den Broeke, M. and Ettema, J., 2011, 'Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models', *The Cryosphere* 5(2), 359–375 (doi: 10.5194/tc-5-359-2011).

Flanner, M. G., Shell, K. M., Barlage, M., Perovich, D. K. and Tschudi, M. A., 2011, 'Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008', *Nature Geoscience* 4(3), 151–155 (doi: 10.1038/ngeo1062).

Fürst, J. J., Goelzer, H. and Huybrechts, P., 2015, 'Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming', *The Cryosphere* 9(3), 1 039–1 062 (doi: 10.5194/tc-9-1039-2015).

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R. and Paul, F., 2013, 'A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009', *Science* 340(6134), 852–857 (doi: 10.1126/science.1234532).

Goelzer, H., Huybrechts, P., Raper, S. C. B., Loutre, M.-F., Goosse, H. and Fichefet, T., 2012, 'Millennial total sea-level commitments projected with the Earth system model of intermediate complexity LOVECLIM', *Environmental Research Letters* 7(4), 45 401 (doi: 10.1088/1748-9326/7/4/045401).

Golledge, N. R., Kowalewski, D. E., Naish, T. R., Levy, R. H., Fogwill, C. J. and Gasson, E. G. W., 2015, 'The multi-millennial Antarctic commitment to future sea-level rise', *Nature* 526(7573), 421–425 (doi: 10.1038/nature15706).

Gomez, N., Pollard, D. and Holland, D., 2015, 'Sea-level feedback lowers projections of future Antarctic Ice-Sheet mass loss', *Nature Communications* 6, 8 798 (doi: 10.1038/ncomms9798).

Gunter, B. C., Didova, O., Riva, R. E. M., Ligtenberg, S. R. M., Lenaerts, J. T. M., King, M. A., van den Broeke, M. R. and Urban, T., 2014, 'Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change', *The Cryosphere* 8(2), 743–760 (doi: 10.5194/tc-8-743-2014).

Haapala, J. J., Ronkainen, I., Schmelzer, N. and Sztobryn, M., 2015, 'Recent change — Sea ice', in: The BACC II Author Team (ed), *Second assessment of climate change for the Baltic Sea basin*, Springer International Publishing, Cham, pp. 145–153.

Halfar, J., Adey, W. H., Kronz, A., Hetzinger, S., Edinger, E. and Fitzhugh, W. W., 2013, 'Arctic sea-ice decline archived by multicentury annual-resolution record from crustose coralline algal proxy', *Proceedings of the National Academy of Sciences* 110(49), 19 737–19 741 (doi: 10.1073/pnas.1313775110).

Hanna, E., Navarro, F. J., Pattyn, F., Domingues, C. M., Fettweis, X., Ivins, E. R., Nicholls, R. J., Ritz, C., Smith, B., Tulaczyk, S., Whitehouse, P. L. and Zwally, H. J., 2013, 'Ice-sheet mass balance and climate change', *Nature* 498(7452), 51–59 (doi: 10.1038/nature12238).

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M. and Lo, K.-W., 2015, 'Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming is highly dangerous', *Atmospheric Chemistry and Physics*

Discussions 15(14), 20 059–20–179 (doi: 10.5194/acpd-15-20059-2015).

Hanssen-Bauer, I., Førland, E. J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, A. and Ådlandsvik, B. (eds), 2015, *Klima i Norge 2100. Kunnskapsgrunnlag for klimatilpasning oppdatert i 2015 (Climate in Norway 2100. Knowledge basis for climate change adaptation updated in 2015)* [in Norwegian], NCCS report, Norsk klimaservicesenter (NKSS).

Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M. A., Lehning, M., Matsuoka, N., Murton, J. B., Nötzli, J., Phillips, M., Ross, N. et al., 2009, 'Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses', *Earth-Science Reviews* 92(3–4), 117–171 (doi: 10.1016/j.earscirev.2008.12.002).

Helm, V., Humbert, A. and Miller, H., 2014, 'Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2', *The Cryosphere* 8(4), 1 539–1 559 (doi: 10.5194/tc-8-1539-2014).

Hezel, P. J., Fichefet, T. and Massonnet, F., 2014, 'Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs', *The Cryosphere* 8(4), 1 195–1 204 (doi: 10.5194/tc-8-1195-2014).

Holland, P. R., Brisbourne, A., Corr, H. F. J., McGrath, D., Purdon, K., Paden, J., Fricker, H. A., Paolo, F. S. and Fleming, A. H., 2015, 'Oceanic and atmospheric forcing of Larsen C ice-shelf thinning', *The Cryosphere* 9(3), 1 005–1 024 (doi: 10.5194/tc-9-1005-2015).

Hollesen, J., Matthiesen, H., Møller, A. B. and Elberling, B., 2015, 'Permafrost thawing in organic Arctic soils accelerated by ground heat production', *Nature Climate Change* 5(6), 574–578 (doi: 10.1038/nclimate2590).

Howat, I. M., de la Peña, S., van Angelen, J. H., Lenaerts, J. T. M. and van den Broeke, M. R., 2013, 'Brief Communication 'Expansion of meltwater lakes on the Greenland Ice Sheet'', *The Cryosphere* 7(1), 201–204 (doi: 10.5194/tc-7-201-2013).

Hudson, S. R., 2011, 'Estimating the global radiative impact of the sea ice–albedo feedback in the Arctic', *Journal of Geophysical Research: Atmospheres* 116(D16), D16102 (doi: 10.1029/2011JD015804).

Huss, M., 2012, 'Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100', *The Cryosphere* 6(4), 713–727 (doi: 10.5194/tc-6-713-2012).

Huss, M. and Hock, R., 2015, 'A new model for global glacier change and sea-level rise', *Frontiers in Earth Science* 3, 54 (doi: 10.3389/feart.2015.00054).

ICCI, 2015, *Thresholds and closing windows — Risks of irreversible cryosphere climate change*, International Cryosphere Climate Initiative.

IPCC, 2013a, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2013b, 'Summary for policymakers', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jackson, J. M., Williams, W. J. and Carmack, E. C., 2012, 'Winter sea-ice melt in the Canada Basin, Arctic Ocean', *Geophysical Research Letters* 39, L03603 (doi: 10.1029/2011GL050219).

Joughin, I., Smith, B. E. and Medley, B., 2014, 'Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica', *Science* 344(6185), 735–738 (doi: 10.1126/science.1249055).

Key, J., Goodison, B., Schöner, W., Godøy, Ø., Ondráš, M. and Snorrason, Á., 2015, 'A global cryosphere watch', *ARCTIC* 68(5), 11.

Killie, M. A. and Lavergne, T., 2011, Time series of the 1979 to 2010 monthly Arctic sea-ice extent in March (the month of sea-ice extent maximum) and September (the month of sea-ice extent minimum) in km^2, Data produced by the EUMETSAT OSI SAF (http://osisaf.met.no) and the CryoClim (http://www.cryoclim.net) project, delivered through MyOcean.

Konrad, H., Sasgen, I., Pollard, D. and Klemann, V., 2015, 'Potential of the solid-Earth response for limiting long-term West Antarctic Ice Sheet retreat in a warming climate', *Earth and Planetary Science Letters* 432, 254–264 (doi: 10.1016/j.epsl.2015.10.008).

Lang, C., Fettweis, X. and Erpicum, M., 2015, 'Stable climate and surface mass balance in Svalbard over 1979-2013 despite the Arctic warming', *The Cryosphere* 9(1), 83–101 (doi: 10.5194/tc-9-83-2015).

Levermann, A., Winkelmann, R., Nowicki, S., Fastook, J. L., Frieler, K., Greve, R., Hellmer, H. H., Martin, M. A., Meinshausen, M., Mengel, M., Payne, A. J., Pollard, D., Sato, T., Timmermann, R., Wang, W. L. and Bindschadler, R. A., 2014, 'Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models', *Earth System Dynamics* 5(2), 271–293 (doi: 10.5194/esd-5-271-2014).

Lindsay, R. and Schweiger, A., 2015, 'Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations', *The Cryosphere* 9(1), 269–283 (doi: 10.5194/tc-9-269-2015).

Liu, J., Curry, J. A., Wang, H., Song, M. and Horton, R. M., 2012, 'Impact of declining Arctic sea ice on winter snowfall', *Proceedings of the National Academy of Sciences of the United States of America* 109(11), 4 074–4 079 (doi: 10.1073/pnas.1114910109).

López-Moreno, J. I., Goyette, S. and Beniston, M., 2009, 'Impact of climate change on snowpack in the Pyrenees: Horizontal spatial variability and vertical gradients', *Journal of Hydrology* 374(3–4), 384–396 (doi: 10.1016/j.jhydrol.2009.06.049).

Luojus, K., Pulliainen, J., Takala, M., Lemmetyinen, J., Kangwa, M., Sohlberg, R., Nagler, T., Rott, H., Derksen, C., Wiesmann, A., Metsämäki, S. and Bojkov, B., 2011, *GlobSnow Final Report. Deliverable 3.5*, European Space Agency Study Contract Report ESRIN Contract 21703/08/I-EC, GlobSnow.

Luomaranta, A., Ruosteenoja, K., Jylhä, K., Gregow, H., Haapala, J. and Laaksonen, A., 2014, 'Multimodel estimates of the changes in the Baltic Sea ice cover during the present century', *Tellus A* 66(22617) (doi: 10.3402/tellusa.v66.22617).

Marzeion, B., Jarosch, A. H. and Hofer, M., 2012, 'Past and future sea-level change from the surface mass balance of glaciers', *The Cryosphere* 6(6), 1 295–1 322 (doi: 10.5194/tc-6-1295-2012).

Massonnet, F., Fichefet, T., Goosse, H., Bitz, C. M., Philippon-Berthier, G., Holland, M. M. and Barriat, P.-Y., 2012, 'Constraining projections of summer Arctic sea ice', *The Cryosphere* 6(6), 1 383–1 394 (doi: 10.5194/tc-6-1383-2012).

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A. and Wingham, D., 2014, 'Increased ice losses from Antarctica detected by CryoSat-2', *Geophysical Research Letters* 41(11), 2014GL060111 (doi: 10.1002/2014GL060111).

Meier, W. N., Stroeve, J. and Fetterer, F., 2007, 'Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record', *Annals of Glaciology* 46(1), 428–434 (doi: 10.3189/172756407782871170).

Mengel, M. and Levermann, A., 2014, 'Ice plug prevents irreversible discharge from East Antarctica', *Nature Climate Change* 4(6), 451–455 (doi: 10.1038/nclimate2226).

Mioduszewski, J. R., Rennermalm, A. K., Robinson, D. A. and Wang, L., 2015, 'Controls on spatial and temporal variability in Northern Hemisphere terrestrial snow melt timing, 1979–2012', *Journal of Climate* 28(6), 2 136–2 153 (doi: 10.1175/JCLI-D-14-00558.1).

Mouginot, J., Rignot, E. and Scheuchl, B., 2014, 'Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013', *Geophysical Research Letters* 41(5), 1 576–1 584 (doi: 10.1002/2013GL059069).

Nesje, A., Bakke, J., Dahl, S. O., Lie, Ø. and Matthews, J. A., 2008, 'Norwegian mountain glaciers in the past, present and future', *Global and Planetary Change* 60 (1–2), 10–27 (doi: 10.1016/j.gloplacha.2006.08.004).

Nghiem, S. V., Hall, D. K., Mote, T. L., Tedesco, M., Albert, M. R., Keegan, K., Shuman, C. A., DiGirolamo, N. E. and Neumann, G., 2012, 'The extreme melt across the Greenland ice sheet in 2012', *Geophysical Research Letters* 39(20), L20502 (doi: 10.1029/2012GL053611).

Noël, B., Fettweis, X., van de Berg, W. J., van den Broeke, M. R. and Erpicum, M., 2014, 'Sensitivity of Greenland Ice Sheet surface mass balance to perturbations in sea surface temperature and sea ice cover: A study with the regional climate model MAR', *The Cryosphere* 8(5), 1 871–1 883 (doi: 10.5194/tc-8-1871-2014).

Olsen, M. S., Reiersen, L.-O., Callaghan, T. V., Prowse, T. and Johansson, M., 2012, 'Preface', *AMBIO* 40(S1), 1–2 (doi: 10.1007/s13280-011-0209-6).

Overland, J. E. and Wang, M., 2013, 'When will the summer Arctic be nearly sea ice free?', *Geophysical Research Letters* 40(10), 2 097–2 101 (doi: 10.1002/grl.50316).

Özdoğan, M., 2011, 'Climate change impacts on snow water availability in the Euphrates-Tigris basin', *Hydrology and Earth System Sciences* 15(9), 2 789–2 803 (doi: 10.5194/hess-15-2789-2011).

Palm, S. P., Strey, S. T., Spinhirne, J. and Markus, T., 2010, 'Influence of Arctic sea ice extent on polar cloud fraction and vertical structure and implications for regional climate', *Journal of Geophysical Research* 115, D21209 (doi: 10.1029/2010JD013900).

Paolo, F. S., Fricker, H. A. and Padman, L., 2015, 'Volume loss from Antarctic ice shelves is accelerating', *Science* 348(6232), 327–331 (doi: 10.1126/science.aaa0940).

Parkinson, C. L., 2014, 'Global sea ice coverage from satellite data: Annual cycle and 35-yr trends', *Journal of Climate* 27(24), 9 377–9 382 (doi: 10.1175/JCLI-D-14-00605.1).

Parmentier, F.-J. W., Zhang, W., Mi, Y., Zhu, X., van Huissteden, J., Hayes, D. J., Zhuang, Q., Christensen, T. R. and David McGuire, A., 2015, 'Rising methane emissions from northern wetlands associated with sea ice decline', *Geophysical Research Letters* 42, 7 214–7 222, (doi: 10.1002/2015GL065013).

Pistone, K., Eisenman, I. and Ramanathan, V., 2014, 'Observational determination of albedo decrease caused by vanishing Arctic sea ice', *Proceedings of the National Academy of Sciences* 111(9), 3 322–3 326 (doi: 10.1073/pnas.1318201111).

Post, E., Forchhammer, M. C., Bret-Harte, M. S., Callaghan, T. V., Christensen, T. R., Elberling, B., Fox, A. D., Gilg, O., Hik, D. S., Høye, T. T., Ims, R. A., Jeppesen, E., Klein, D. R., Madsen, J., McGuire, A. D., Rysgaard, S., Schindler, D. E., Stirling, I., Tamstorf, M. P. et al., 2009, 'Ecological Dynamics Across the Arctic Associated with Recent Climate Change', *Science* 325(5946), 1 355–1 358 (doi: 10.1126/science.1173113).

Radić, V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E. and Cogley, J. G., 2014, 'Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models', *Climate Dynamics* 42(1–2), 37–58 (doi: 10.1007/s00382-013-1719-7).

Rae, J. G. L., Aðalgeirsdóttir, G., Edwards, T. L., Fettweis, X., Gregory, J. M., Hewitt, H. T., Lowe, J. A., Lucas-Picher, P., Mottram, R. H., Payne, A. J., Ridley, J. K., Shannon, S. R., van de Berg, W. J., van de Wal, R. S. W. and van den Broeke, M. R., 2012, 'Greenland ice sheet surface mass balance: Evaluating simulations and making projections with regional climate models', *The Cryosphere* 6(6), 1 275–1 294 (doi: 10.5194/tc-6-1275-2012).

Räisänen, J., 2016, 'Twenty-first century changes in snowfall climate in Northern Europe in ENSEMBLES regional climate models', *Climate Dynamics* (46), 339–353 (doi: 10.1007/s00382-015-2587-0).

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. and Scheuchl, B., 2014, 'Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011', *Geophysical Research Letters* 41(10), 3 502–3 509 (doi: 10.1002/2014GL060140).

Robinson, A., Calov, R. and Ganopolski, A., 2012, 'Multistability and critical thresholds of the Greenland ice sheet', *Nature Climate Change* 2(6), 429–432 (doi: 10.1038/nclimate1449).

RUGSL, 2011, 'Fall, winter, and spring Northern Hemisphere snow cover extent from the Rutgers University Global Snow Lab' (http://pielkeclimatesci.wordpress.com/2011/05/30/fall-winter-and-spring-northern-hemisphere-snow-cover-extent-from-the-rutgers-university-global-snow-lab) accessed 7 February 2012.

Schmucki, E., Marty, C., Fierz, C. and Lehning, M., 2015, 'Simulations of 21st century snow response to climate change in Switzerland from a set of RCMs: Snow response to climate change in Switzerland', *International Journal of Climatology* 35(11), 3 262–3 273 (doi: 10.1002/joc.4205).

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E., 2015, 'Climate change and the permafrost carbon feedback', *Nature* 520(7546), 171–179 (doi: 10.1038/nature14338).

Schweiger, A., Lindsay, R., Zhang, J., Steele, M., Stern, H. and Kwok, R., 2011, 'Uncertainty in modeled Arctic sea ice volume', *Journal of Geophysical Research* 116, C00D06 (doi: 10.1029/2011JC007084).

Screen, J. A. and Simmonds, I., 2010, 'The central role of diminishing sea ice in recent Arctic temperature amplification', *Nature* 464(7293), 1 334–1 337 (doi: 10.1038/nature09051).

Seinä, A., Grönvall, H., Kalliosaari, S. and Vainio, J., 2001, *Ice seasons 1996–2000 in Finnish sea areas*, MERI Report 43, Finnish Institute of Marine Research, Helsinki.

Seinä, A. and Palosuo, E., 1996, *The classification of the maximum annual extent of ice cover in the Baltic Sea 1720–1995*, MERI Report 27, Finnish Institute of Marine Research, Helsinki.

SGHL and CHy, 2011, *Auswirkungen der Klimaänderung auf die Wasserkraftnutzung — Synthesebericht*, Beiträge zur Hydrologie der Schweiz No 38, Schweizerische Gesellschaft für Hydrologie und Limnologie (SGHL) and Hydrologische Kommission (CHy), Bern.

Shaefer, K., Lantuit, H., Romanovsky, V. and Schuur, E. A. G., 2012, *Policy implications of warming permafrost*, UNEP, Nairobi.

Shepherd, A., Ivins, E. R., A, G., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T. M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B. et al., 2012, 'A reconciled estimate of ice-sheet mass balance', *Science* 338(6111), 1 183–1 189 (doi: 10.1126/science.1228102).

Shepherd, A., Ivins, E. R. and Markus, T., 2015, Tracking ice: The latest efforts to measure the polar ice sheets, Presentation at the AGU Fall Meeting, 14–18 December 2015, San Francisco.

Simmonds, I. and Govekar, P. D., 2014, 'What are the physical links between Arctic sea ice loss and Eurasian winter climate?', *Environmental Research Letters* 9(10), 101003 (doi: 10.1088/1748-9326/9/10/101003).

Soncini, A. and Bocchiola, D., 2011, 'Assessment of future snowfall regimes within the Italian Alps using general circulation models', *Cold Regions Science and Technology* 68(3), 113–123 (doi: 10.1016/j.coldregions.2011.06.011).

Stammerjohn, S., Massom, R., Rind, D. and Martinson, D., 2012, 'Regions of rapid sea ice change: An inter-hemispheric seasonal comparison', *Geophysical Research Letters* 39, L06501 (doi: 10.1029/2012GL050874).

Steger, C., Kotlarski, S., Jonas, T. and Schär, C., 2013, 'Alpine snow cover in a changing climate: A regional climate model perspective', *Climate Dynamics* 41(3–4), 735–754 (doi: 10.1007/s00382-012-1545-3).

Stroeve, J. C., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M. and Meier, W. N., 2012, 'Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations', *Geophysical Research Letters* 39(16), L16502 (doi: 10.1029/2012GL052676).

Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J.-P., Koskinen, J. and Bojkov, B., 2011, 'Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements', *Remote Sensing of Environment* 115(12), 3 517–3 529 (doi: 10.1016/j.rse.2011.08.014).

Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E. and Wouters, B., 2013, 'Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data', *The Cryosphere* 7(2), 615–630 (doi: 10.5194/tc-7-615-2013).

UNEP, 2007, *Global outlook for ice and snow*, United Nations Environment Programme, Arendal.

Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K. and Zhang, T., 2013, 'Observations: Cryosphere', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 317–382.

Vavrus, S. J., 2013, 'Extreme Arctic cyclones in CMIP5 historical simulations', *Geophysical Research Letters* 40(23), 6 208–6 212 (doi: 10.1002/2013GL058161).

Vihma, T., 2014, 'Effects of Arctic sea ice decline on weather and climate: A review', *Surveys in Geophysics* 35(5), 1 175–1 214 (doi: 10.1007/s10712-014-9284-0).

Vizcaino, M., Mikolajewicz, U., Ziemen, F., Rodehacke, C. B., Greve, R. and van den Broeke, M. R., 2015, 'Coupled simulations of Greenland Ice Sheet and climate change up to A.D. 2300: GRIS and climate change up to AD 2300', *Geophysical Research Letters* 42(10), 3 927–3 935 (doi: 10.1002/2014GL061142).

Wang, M. and Overland, J. E., 2012, 'A sea ice free summer Arctic within 30 years: An update from CMIP5 models: Summer Arctic sea ice', *Geophysical Research Letters* 39(18), L18501 (doi: 10.1029/2012GL052868).

Wouters, B., Martin-Español, A., Helm, V., Flament, T., Wessem, J. M. van, Ligtenberg, S. R. M., Broeke, M. R. van den and Bamber, J. L., 2015, 'Dynamic thinning of glaciers on the Southern Antarctic Peninsula', *Science* 348(6237), 899–903 (doi: 10.1126/science.aaa5727).

Yang, Q., Dixon, T. H., Myers, P. G., Bonin, J., Chambers, D. and van den Broeke, M. R., 2016, 'Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation', *Nature Communications* 7, 10525 (doi: 10.1038/ncomms10525).

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Cáceres, B. E., Casassa, G., Cobos, G., Dávila,

L. R., Delgado Granados, H., Demuth, M. N. et al., 2015, 'Historically unprecedented global glacier decline in the early 21st century', *Journal of Glaciology* 61(228), 745–762 (doi: 10.3189/2015JoG15J017).

Zemp, M., Haeberli, W., Hoelzle, M. and Paul, F., 2006, 'Alpine glaciers to disappear within decades?', *Geophysical Research Letters* 33, L13504 (doi: 10.1029/2006GL026319).

Zemp, M., Paul, F., Hoelzle, M. and Haeberli, W., 2008, 'Glacier fluctuations in the European Alps, 1850-2000: An overview and a spatiotemporal analysis of available data', in: Orlove, B. S., Wiegandt, E., and Luckman, B. H. (eds), *Darkening peaks: Glacier retreat, science, and society*, University of California Press, Los Angeles, pp. 152–167.

Zwally, H. J., Li, J., Robbins, J. W., Saba, J. L., Yi, D. and Brenner, A. C., 2015, 'Mass gains of the Antarctic ice sheet exceed losses', *Journal of Glaciology* 61(230), 1 019–1 036 (doi: 10.3189/2015JoG15J071).

Chapter 4: Climate change impacts on environmental systems

Bonn, A., Macgregor, N., Stadler, J., Korn, H., Stiffel, S., Wolf, K. and van Dijk, N., 2014, *Helping ecosystems in Europe to adapt to climate change*, BfN-Skripten 375, Federal Agency for Nature Conservation, Bonn.

EC, 1992, Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, OJ L 206, 22.7.1992, p. 7.

EC, 2000, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, pp. 1–73.

EC, 2008a, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L 152, 11.6.2008, pp. 1–44.

EC, 2008b, Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), OJ L 164, 25.6.2008, pp. 19–40.

EC, 2009, Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds, OJ L 20, 26.1.2010, pp. 7–25.

EC, 2010, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: The CAP towards 2020: Meeting the food, natural resources and territorial challenges of the future, COM(2010) 672 final of 18 November 2010, Brussels.

EC, 2011, Communication from the Commission to the European Parliament and the Council, the Economic and Social Committee and the Committee of the Regions 'Our life insurance, our natural capital: an EU biodiversity strategy to 2020', COM(2011) 0244 final.

EC, 2012, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Blueprint to Safeguard Europe's Water Resources, COM(2012) 673 final of 14 November 2012, Brussels.

EC, 2014, Opinion of the Committee of the Regions — Multilevel governance in promoting the EU Biodiversity Strategy to 2020 and implementing the international Aichi Targets, OJ C 271, 19.8.2014, pp. 45–52.

EC, 2016a, Common Implementation Framework — Orientations Version: After Nature Director Meeting, European Commission.

EC, 2016b, 'Natura 2000' (http://ec.europa.eu/environment/nature/natura2000) accessed 19 April 2016.

EU, 2010, Regulation (EU) No 995/2010 of the European Parliament and of the Council of 20 October 2010 laying down the obligations of operators who place timber and timber products on the market, OJ L 295, 12.11.2010, pp. 23–34.

EU, 2013, Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet', OJ L 354, 28.12.2013, pp. 171–200.

EU, 2014, Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species, OJ L 317, 4.11.2014, pp. 35–55.

Korn, H., Stadler, J., Bonn, A., Bockmühl, K. and Macgregor, N., 2014, *Proceedings of the European Conference 'Climate Change and Nature Conservation in Europe — an ecological, policy and economic* *perspective'*, BfN-Skripten 367, Federal Agency for Nature Conservation, Bonn.

Maes, J., Teller, A., Erhard, M., Liquete, C., Braat, L., Berry, P., Egoh, B., Puydarrieux, P., Fiorina, C., Santos, F., Paracchini, M. L., Keune, H., Wittmer, H., Hauck, J., Fiala, I., Verburg, P. H., Condé, S., Schägner, J. P., San Miguel, J. et al., 2013, *Mapping and assessment of ecosystems and their services: An analytical framework for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020*, Publications Office of the European Union, Luxembourg.

van Teeffelen, A., Meller, L., van Minnen, J., Vermaat, J. and Cabeza, M., 2014, 'How climate proof is the European Union's biodiversity policy?', *Regional Environmental Change* 15(6), 997–1 010 (doi: 10.1007/s10113-014-0647-3).

Section 4.1: Oceans and marine environment

Abraham, J. P., Baringer, M., Bindoff, N. L., Boyer, T., Cheng, L. J., Church, J. A., Conroy, J. L., Domingues, C. M., Fasullo, J. T., Gilson, J., Goni, G., Good, S. A., Gorman, J. M., Gouretski, V., Ishii, M., Johnson, G. C., Kizu, S., Lyman, J. M., Macdonald, A. M. et al., 2013, 'A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change: Review of ocean observations', *Reviews of Geophysics* 51(3), 450–483 (doi: 10.1002/rog.20022).

Archer, D., 2005, 'Fate of fossil fuel CO_2 in geologic time', *Journal of Geophysical Research* 110, C09S05 (doi: 10.1029/2004JC002625).

Archer, D. and Brovkin, V., 2008, 'The millennial atmospheric lifetime of anthropogenic CO_2', *Climatic Change* 90, 283–297 (doi: 10.1007/s10584-008-9413-1).

Beaugrand, G., 2009, 'Decadal changes in climate and ecosystems in the North Atlantic Ocean and adjacent seas', *Deep Sea Research Part II: Topical Studies in Oceanography* 56(8–10), 656–673 (doi: 10.1016/j.dsr2.2008.12.022).

Bopp, L., Resplandy, L., Orr, J. C., Doney, S. C., Dunne, J. P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J. and Vichi, M., 2013, 'Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models', *Biogeosciences Discussions* 10(2), 3 627–3 676 (doi: 10.5194/bgd-10-3627-2013).

Brattegard, T., 2011, *Endringer i norsk marin bunnfauna 1997-2010*, DN-utredning 8-2011, Direktoratet for naturforvaltning, Trondheim.

Burrows, M. T., Schoeman, D. S., Buckley, L. B., Moore, P., Poloczanska, E. S., Brander, K. M., Brown, C., Bruno, J. F., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., Kiessling, W., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F. B., Sydeman, W. J. and Richardson, A. J., 2011, 'The pace of shifting climate in marine and terrestrial ecosystems', *Science* 334(6056), 652–655 (doi: 10.1126/science.1210288).

Byrne, R. H., Mecking, S., Feely, R. A. and Liu, X., 2010, 'Direct observations of basin-wide acidification of the North Pacific Ocean', *Geophysical Research Letters* 37, L02601 (doi: 10.1029/2009GL040999).

Caballero-Alfonso, A. M., Carstensen, J. and Conley, D. J., 2015, 'Biogeochemical and environmental drivers of coastal hypoxia', *Journal of Marine Systems* 141, 190–199 (doi: 10.1016/j.jmarsys.2014.04.008).

Cardinale, B. J., Duffy, J. E., Gonzalez, A., Hooper, D. U., Perrings, C., Venail, P., Narwani, A., Mace, G. M., Tilman, D., Wardle, D. A., Kinzig, A. P., Daily, G. C., Loreau, M., Grace, J. B., Larigauderie, A., Srivastava, D. S. and Naeem, S., 2012, 'Biodiversity loss and its impact on humanity', *Nature* 486(7401), 59–67 (doi: 10.1038/nature11148).

Carstensen, J., Andersen, J. H., Gustafsson, B. G. and Conley, D. J., 2014, 'Deoxygenation of the Baltic Sea during the last century', *Proceedings of the National Academy of Sciences* 111(15), 5 628–5 633 (doi: 10.1073/pnas.1323156111).

Cheung, W. W. L., Lam, V. W. Y., Sarmiento, J. L., Kearney, K., Watson, R. and Pauly, D., 2009, 'Projecting global marine biodiversity impacts under climate change scenarios', *Fish and Fisheries* 10(3), 235–251 (doi: 10.1111/j.1467-2979.2008.00315.x).

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. and Unnikrishnan, A. S., 2013, 'Sea-level change', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 137–1 216.

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J. and Velicogna, I., 2011, 'Revisiting the Earth's sea-level and energy budgets from 1961 to 2008: Sea-level and energy budgets', *Geophysical Research Letters* 38, L18601 (doi: 10.1029/2011GL048794).

Chust, G., Allen, J. I., Bopp, L., Schrum, C., Holt, J., Tsiaras, K., Zavatarelli, M., Chifflet, M., Cannaby, H., Dadou, I., Daewel, U., Wakelin, S. L., Machu, E., Pushpadas, D., Butenschon, M., Artioli, Y., Petihakis, G., Smith, C., Garçon, V. et al., 2014, 'Biomass changes and trophic amplification of plankton in a warmer ocean', *Global Change Biology* 20(7), 2 124–2 139 (doi: 10.1111/gcb.12562).

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabre, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S. and Thornton, P., 2013, 'Carbon and other biogeochemical cycles', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 465–570.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M., 2013, 'Long-term climate change: Projections, commitments and irreversibility', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 029–1 136.

Conversi, A., Dakos, V., Gardmark, A., Ling, S., Folke, C., Mumby, P. J., Greene, C., Edwards, M., Blenckner, T., Casini, M., Pershing, A. and Mollmann, C., 2015, 'A holistic view of marine regime shifts', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1659), 20130279 (doi: 10.1098/rstb.2013.0279).

Conversi, A., Fonda Umani, S., Peluso, T., Molinero, J. C., Santojanni, A. and Edwards, M., 2010, 'The Mediterranean Sea regime shift at the end of the 1980s, and intriguing parallelisms with other European basins 'Humphries, S. (ed)', *PLoS ONE* 5(5), e10633 (doi: 10.1371/journal.pone.0010633).

Deutsch, C., Ferrel, A., Seibel, B., Portner, H.-O. and Huey, R. B., 2015, 'Climate change tightens a metabolic constraint on marine habitats', *Science* 348(6239), 1 132–1 135 (doi: 10.1126/science.aaa1605).

Diaz, R. J. and Rosenberg, R., 2008, 'Spreading dead zones and consequences for marine ecosystems', *Science* 321(5891), 926–929 (doi: 10.1126/science.1156401).

Djakovac, T., Supić, N., Bernardi Aubry, F., Degobbis, D. and Giani, M., 2015, 'Mechanisms of hypoxia frequency changes in the northern Adriatic Sea during the period 1972–2012', *Journal of Marine Systems* 141, 179–189 (doi: 10.1016/j.jmarsys.2014.08.001).

Dore, J. E., 2012, *Hawaii Ocean time-series surface CO_2 system data product, 1988-2008*, SOEST, University of Hawaii, Honolulu.

Dore, J. E., Lukas, R., Sadler, D. W., Church, M. J. and Karl, D. M., 2009, 'Physical and biogeochemical modulation of ocean acidification in the central North Pacific', *Proceedings of the National Academy of Sciences* 106, 12 235–12 240 (doi: 10.1073/pnas.0906044106).

Dulvy, N. K., Rogers, S. I., Jennings, S., Stelzenmller, V., Dye, S. R. and Skjoldal, H. R., 2008, 'Climate change and deepening of the North Sea fish assemblage: A biotic indicator of warming seas', *Journal of Applied Ecology* 45(4), 1 029–1 039 (doi: 10.1111/j.1365-2664.2008.01488.x).

Dupont, S., Dorey, N. and Thorndyke, M., 2010, 'What meta-analysis can tell us about vulnerability of marine biodiversity to ocean acidification?', *Estuarine, Coastal and Shelf Science* 89(2), 182–185 (doi: 10.1016/j.ecss.2010.06.013).

Durack, P. J., Gleckler, P. J., Landerer, F. W. and Taylor, K. E., 2014, 'Quantifying underestimates of long-term upper-ocean warming', *Nature Climate Change* 4(11), 999–1005 (doi: 10.1038/nclimate2389).

Edwards, M., Helaouet, P., Alhaija, R. A., Batten, S., Beaugrand, G., Chiba, S., Horaeb, R. R., Hosie, G., Mcquatters-Gollop, A., Ostle, C., Richardson, A. J., Rochester, W., Skinner, J., Stern, R., Takahashi, K., Taylor, C., Verheye, H. M. and Wootton, M., 2016, *Global Marine Ecological Status Report: results from the global CPR Survey 2014/2015*, SAHFOS Technical Report 11, SAHFOS Technical Report, Plymouth, United Kingdom.

Edwards, M. and Richardson, A. J., 2004, 'Impact of climate change on marine pelagic phenology and trophic mismatch', *Nature* 430(7002), 881–884 (doi: 10.1038/nature02808).

EEA, 2015, *State of Europe's seas*, EEA Report No 2/2015, European Environment Agency.

Enochs, I. C., Manzello, D. P., Donham, E. M., Kolodziej, G., Okano, R., Johnston, L., Young, C., Iguel, J., Edwards, C. B., Fox, M. D., Valentino, L., Johnson, S., Benavente, D., Clark, S. J., Carlton, R., Burton, T., Eynaud, Y. and Price, N. N., 2015, 'Shift from coral to macroalgae dominance on a volcanically acidified reef', *Nature Climate Change* 5, 1 083–1 089 (doi: 10.1038/nclimate2758).

Fabry, V. J., Seibel, B. A., Feely, R. A. and Orr, J. C., 2008, 'Impacts of ocean acidification on marine fauna and ecosystem processes', *ICES Journal of Marine Science* 65(3), 414–432 (doi: 10.1093/icesjms/fsn048).

Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., Dale, A. W., Etiope, G., Erdem, Z., Geraga, M., Gilli, A., Gomoiu, M. T., Hall, P. O. J., Hansson, D., He, Y., Holtappels, M., Kirf, M. K., Kononets, M., Konovalov, S. et al., 2014, 'Investigating hypoxia in aquatic environments: Diverse approaches to addressing a complex phenomenon', *Biogeosciences* 11(4), 1 215–1 259 (doi: 10.5194/bg-11-1215-2014).

Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W. W. L., Howes, E. L., Joos, F., Allemand, D., Bopp, L., Cooley, S. R., Eakin, C. M., Hoegh-Guldberg, O., Kelly, R. P., Portner, H.-O., Rogers, A. D., Baxter, J. M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J. et al., 2015, 'Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios', *Science* 349(6243), 4 722 (doi: 10.1126/science.aac4722).

Gleckler, P. J., Durack, P. J., Stouffer, R. J., Johnson, G. C. and Forest, C. E., 2016, 'Industrial-era global ocean heat uptake doubles in recent decades', *Nature Climate Change* 6(4), 394–398 (doi: 10.1038/nclimate2915).

Glibert, P. M., Icarus Allen, J., Artioli, Y., Beusen, A., Bouwman, L., Harle, J., Holmes, R. and Holt, J., 2014, 'Vulnerability of coastal ecosystems to changes in harmful algal bloom distribution in response to climate change: Projections based on model analysis', *Global Change Biology* 20(12), 3 845–3 858 (doi: 10.1111/gcb.12662).

Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M., Rowley, S. J., Tedesco, D. and Buia, M.-C., 2008, 'Volcanic carbon dioxide vents show ecosystem effects of ocean acidification', *Nature* 454(7200), 96–99 (doi: 10.1038/nature07051).

Hansen, J., Sato, M., Kharecha, P. and von Schuckmann, K., 2011, 'Earth's energy imbalance and implications', *Atmospheric Chemistry and Physics* 11(24), 13 421–13 449 (doi: 10.5194/acp-11-13421-2011).

Hartman, J. and Waibel, M., 2014, 'Mackerel war called off?' *Blog of the European Journal of International Law* (http://www.ejiltalk.org/mackerel-war-called-off) accessed 17 November 2015.

Hartmann, D. L., Klein Tank, A. M. G., Rusticucci, M., Alexander, S., Brönimann, S., Charabi, Y., Dentener, F. J., Dlugokencky, E. J., Easterling, D. R., Kaplan, A., Soden, B. J., Thorne, P. W., Wild, M. and Zhai, P. M., 2013, 'Observations: Atmosphere and surface', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 159–254.

HELCOM, 2009, *Eutrophication in the Baltic Sea — An integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region: Executive summary*, Baltic Sea Environment Proceedings No 115A, Helsinki Commission, Helsinki.

HELCOM, 2013, *Climate change in the Baltic Sea Area: HELCOM thematic assessment in 2013*, Baltic Sea Environment Proceedings No 137, Helsinki Commission, Helsinki.

Hendriks, I. E. and Duarte, C. M., 2010, 'Ocean acidification: Separating evidence from judgment — A reply to Dupont et al.', *Estuarine, Coastal and Shelf Science* 89(2), 186–190 (doi: 10.1016/j.ecss.2010.06.007).

Hendriks, I. E., Duarte, C. M. and Álvarez, M., 2010, 'Vulnerability of marine biodiversity to ocean acidification: A meta-analysis', *Estuarine, Coastal and Shelf Science* 86(2), 157–164 (doi: 10.1016/j.ecss.2009.11.022).

Hendriks, I. E., Olsen, Y. S., Ramajo, L., Basso, L., Steckbauer, A., Moore, T. S., Howard, J. and Duarte, C. M., 2014, 'Photosynthetic activity buffers ocean acidification in seagrass meadows', *Biogeosciences* 11(2), 333–346 (doi: 10.5194/bg-11-333-2014).

Hiddink, J. G., Burrows, M. T. and García Molinos, J., 2015, 'Temperature tracking by North Sea benthic invertebrates in response to climate change', *Global Change Biology* 21(1), 117–129 (doi: 10.1111/gcb.12726).

Hordoir, R. and Meier, H. E. M., 2012, 'Effect of climate change on the thermal stratification of the Baltic Sea: A sensitivity experiment', *Climate Dynamics* 38(9–10), 1 703–1 713 (doi: 10.1007/s00382-011-1036-y).

Howes, E. L., Joos, F., Eakin, M. and Gattuso, J.-P., 2015, *The Oceans 2015 Initiative, Part I. An updated synthesis of the observed impacts of climate change on the physical and biological processes in the oceans*, IDDRI, Paris.

IGBP, IOC and SCOR, 2013, *Ocean acidification summary for policymakers — Third Symposium on the Ocean in a High-CO_2 World*, International Geosphere-Biosphere Programme, Stockholm.

Ingunn, S., Emil, J., Melissa, C., Abdirahman, O., Are, O., Siv, L. and Truls, J., 2014, *Havforsuring og opptak av* *antropogent karbon i de Nordiske hav, 1981–2013 (Ocean acidification and uptake of anthropogenic carbon in the Nordic Seas, 1981–2013)*, M244-2014, Uni Research, Havforskningsinstituttet og Universitetet i Bergen, Bergen.

IPCC, 2013, 'Summary for policymakers', in: *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K. A., Botsford, L. W., Bourque, B. J., Bradbury, R. H., Cooke, R., Erlandson, J., Estes, J. A., Hughes, T. P., Kidwell, S., Lange, C. B., Lenihan, H. S., Pandolfi, J. M., Peterson, C. H., Steneck, R. S., Tegner, M. J. and Warner, R. R., 2001, 'Historical overfishing and the recent collapse of coastal ecosystems', *Science* 293(5530), 629–637 (doi: 10.1126/science.1059199).

Jansen, T., Post, S., Kristiansen, T., Óskarsson, G. J., Boje, J., MacKenzie, B. R., Broberg, M. and Siegstad, H., 2016, 'Ocean warming expands habitat of a rich natural resource and benefits a national economy', *Ecological Applications*, 26(7), 2 021–2 032 (doi: 10.1002/eap.1384).

Jones, M. C. and Cheung, W. W. L., 2015, 'Multi-model ensemble projections of climate change effects on global marine biodiversity', *ICES Journal of Marine Science: Journal du Conseil* 72(3), 741–752 (doi: 10.1093/icesjms/fsu172).

Joos, F., Frölicher, T. L., Steinacher, M. and Plattner, G.-K., 2011, 'Impact of climate change mitigation on ocean acidification projections', in: Gathuso, J.-P. and Hansson, L. (eds.), *Ocean acidification*, Oxford University Press, Oxford, pp. 272–290.

Karlson, K., Rosenberg, R. and Bonsdorff, E., 2002, 'Temporal and spatial large-scale effects of eutrophication and oxygen deficiency on benthic fauna in Scandinavia and Baltic Waters — A review', *Oceanography and Marine Biology: An Annual Review* 40, 427–489.

Keeling, R. F., Körtzinger, A. and Gruber, N., 2010, 'Ocean deoxygenation in a warming world', *Annual Review of Marine Science* 2(1), 199–229 (doi: 10.1146/annurev.marine.010908.163855).

Kirtman, B., Power, S., Adedoyin, J. A., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F. J., Fiore, A. M., Kimoto, M., Meehl, G. A., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenbourgh, G. J., Vecchi, G. and Wang, H. J., 2013, 'Near-term climate change: Projections and predictability', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 953–1 028.

Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M. and Gattuso, J.-P., 2013, 'Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming', *Global Change Biology* 19(6), 1 884–1 896 (doi: 10.1111/gcb.12179).

Lambert, E., Pierce, G. J., Hall, K., Brereton, T., Dunn, T. E., Wall, D., Jepson, P. D., Deaville, R. and MacLeod, C. D., 2014, 'Cetacean range and climate in the eastern North Atlantic: Future predictions and implications for conservation', *Global Change Biology* 20(6), 1 782–1 793 (doi: 10.1111/gcb.12560).

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., Mishonov, A. V., Reagan, J. R., Seidov, D., Yarosh, E. S. and Zweng, M. M., 2012, 'World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010', *Geophysical Research Letters* 39, L10603 (doi: 10.1029/2012GL051106).

Lotze, H. K., Lenihan, H. S., Bourque, B. J., Bradbury, R. H., Cooke, R. G., Kay, M. C., Kidwell, S. M., Kirby, M. X., Peterson, C. H. and Jackson, J. B. C., 2006, 'Depletion, degradation, and recovery potential of estuaries and coastal seas', *Science* 312(5781), 1 806–1 809 (doi: 10.1126/science.1128035).

Luczak, C., Beaugrand, G., Lindley, J. A., Dewarumez, J.-M., Dubois, P. J. and Kirby, R. R., 2012, 'North Sea ecosystem change from swimming crabs to seagulls', *Biology Letters* 8, 821–824 (doi: 10.1098/rsbl.2012.0474).

Lyngsgaard, M., Richardson, K., Markager, S., Nielsen, M., Olesen, M. and Christensen, J., 2014, 'Deep primary production in coastal pelagic systems: Importance for ecosystem functioning', *Marine Ecology Progress Series* 517, 15–33 (doi: 10.3354/meps11015).

Macias, D., Garcia-Gorriz, E. and Stips, A., 2013, 'Understanding the Causes of Recent Warming of Mediterranean Waters. How Much Could Be Attributed to Climate Change?', *PLOS ONE* 8(11), e81591 (doi: 10.1371/journal.pone.0081591).

MCCIP, 2013, *Marine climate change impacts report card 2013*, Summary Report, MCCIP, Lovestoft.

McNeil, B. I. and Matear, R. J., 2008, 'Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO_2', *Proceedings of the National Academy of Sciences* 105(48), 18 860–18 864 (doi: 10.1073/pnas.0806318105).

Mollmann, C., Folke, C., Edwards, M. and Conversi, A., 2014, 'Marine regime shifts around the globe: Theory, drivers and impacts', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1659), 20130260–20130260 (doi: 10.1098/rstb.2013.0260).

Montero-Serra, I., Edwards, M. and Genner, M. J., 2015, 'Warming shelf seas drive the subtropicalization of European pelagic fish communities', *Global Change Biology* 21(1), 144–153 (doi: 10.1111/gcb.12747).

Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R. M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G.-K., Rodgers, K. B. et al., 2005, 'Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms', *Nature* 437(7059), 681–686 (doi: 10.1038/nature04095).

Perry, A. L., 2005, 'Climate change and distribution shifts in marine fishes', *Science* 308(5730), 1 912–1 915 (doi: 10.1126/science.1111322).

Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. and Levin, S. A., 2013, 'Marine taxa track local climate velocities', *Science* 341(6151), 1 239–1 242 (doi: 10.1126/science.1239352).

Poloczanska, E. S., Brown, C. J., Sydeman, W. J., Kiessling, W., Schoeman, D. S., Moore, P. J., Brander, K., Bruno, J. F., Buckley, L. B., Burrows, M. T., Duarte, C. M., Halpern, B. S., Holding, J., Kappel, C. V., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Schwing, F., Thompson, S. A. et al., 2013, 'Global imprint of climate change on marine life', *Nature Climate Change* 3(10), 919–925 (doi: 10.1038/nclimate1958).

Pörtner, H. O., Karl, D. M., Boyd, P. W., Cheung, W. W. L., Lluch-Cota, S. E., Nojiri, Y., Schimdt, D. N. and Zavialov, P. O., 2014, 'Ocean systems', in: *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 411–484.

Pörtner, H.-O., 2010, 'Oxygen- and capacity-limitation of thermal tolerance: A matrix for integrating climate-related stressor effects in marine ecosystems', *Journal of Experimental Biology* 213(6), 881–893 (doi: 10.1242/jeb.037523).

Purkey, S. G. and Johnson, G. C., 2010, 'Warming of global abyssal and deep southern ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets', *Journal of Climate* 23(23), 6 336–6 351 (doi: 10.1175/2010JCLI3682.1).

Pyhälä, M., Fleming-Lehtinen, V., Laamanen, M., Łysiak-Pastuszak, E., Carstens, M., Leppänen, J.-M., Leujak, W., Nausch, G. and Carstensen, J., 2014, 'Oxygen debt — HELCOM Core Indicator' (http://helcom.fi/baltic-sea-trends/indicators/oxygen) accessed 5 February 2016.

Raitsos, D. E., Beaugrand, G., Georgopoulos, D., Zenetos, A., Pancucci-Papadopoulou, A. M., Theocharis, A. and Papathanassiou, E., 2010, 'Global climate change amplifies the entry of tropical species into the eastern Mediterranean Sea', *Limnology and Oceanography* 55(4), 1 478–1 484 (doi: 10.4319/lo.2010.55.4.1478).

Rayner, N. A., Brohan, P., Parker, D. E., Folland, C. K., Kennedy, J. J., Vanicek, M., Ansell, T. J. and Tett, S. F. B., 2006, 'Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: The HadSST2 dataset', *Journal of Climate* 19(3), 446–469 (doi: 10.1175/JCLI3637.1).

Reid, P. C., Fischer, A. C., Lewis-Brown, E., Meredith, M. P., Sparrow, M., Andersson, A. J., Antia, A., Bates, N. R., Bathmann, U., Beaugrand, G., Brix, H., Dye, S., Edwards, M., Furevik, T., Gangstø, R., Hátún, H., Hopcroft, R. R., Kendall, M., Kasten, S. et al., 2009, 'Impacts of the oceans on climate change', in: *Advances in Marine Biology*, Advances in Marine Biology, Academic Press, pp. 1–150.

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., Gulev, S., Johnson, G. C., Josey, S. A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L. D. and Wang, F., 2013, 'Observations: Ocean', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 255–316.

Rocha, J., Yletyinen, J., Biggs, R., Blenckner, T. and Peterson, G., 2014, 'Marine regime shifts: Drivers and impacts on ecosystems services', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1659), 20130273 (doi: 10.1098/rstb.2013.0273).

Ruckelshaus, M., Doney, S. C., Galindo, H. M., Barry, J. P., Chan, F., Duffy, J. E., English, C. A., Gaines, S. D., Grebmeier, J. M., Hollowed, A. B., Knowlton, N., Polovina, J., Rabalais, N. N., Sydeman, W. J. and Talley, L. D., 2013, 'Securing ocean benefits for society in the face of climate change', *Marine Policy* 40, 154–159 (doi: 10.1016/j.marpol.2013.01.009).

Rutterford, L. A., Simpson, S. D., Jennings, S., Johnson, M. P., Blanchard, J. L., Schön, P.-J., Sims, D. W., Tinker, J. and Genner, M. J., 2015, 'Future fish distributions constrained by depth in warming seas', *Nature Climate Change* 5(6), 569–573 (doi: 10.1038/nclimate2607).

Secretariat of the Convention on Biological Diversity, 2014, *An updated synthesis of the impacts of ocean acidification on marine biodiversity*, CBD Technical Series No 75, Secretariat of the Convention on Biological Diversity, Montreal.

Simpson, S. D., Jennings, S., Johnson, M. P., Blanchard, J. L., Schön, P.-J., Sims, D. W. and Genner, M. J., 2011, 'Continental shelf-wide response of a fish assemblage to rapid warming of the sea', *Current Biology* 21(18), 1 565–1 570 (doi: 10.1016/j.cub.2011.08.016).

Steinacher, M., Joos, F., Frölicher, T. L., Plattner, G.-K. and Doney, S. C., 2009, 'Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model', *Biogeosciences* 6(4), 515–533 (doi: 10.5194/bg-6-515-2009).

Sunday, J. M., Bates, A. E. and Dulvy, N. K., 2012, 'Thermal tolerance and the global redistribution of animals', *Nature Climate Change* 2(9), 686–690 (doi: 10.1038/nclimate1539).

Taylor, K. E., Stouffer, R. J. and Meehl, G. A., 2012, 'An overview of CMIP5 and the experiment design', *Bulletin of the American Meteorological Society* 93(4), 485–498 (doi: 10.1175/BAMS-D-11-00094.1).

Thackeray, S. J., Sparks, T. H., Frederiksen, M., Burthe, S., Bacon, P. J., Bell, J. R., Botham, M. S., Brereton, T. M., Bright, P. W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Elliott, J. M., Harrington, R., Johns, D., Jones, I. D., Jones, J. T., Leech, D. I. et al., 2010, 'Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments', *Global Change Biology* 16(12), 3 304–3 313 (doi: 10.1111/j.1365-2486.2010.02165.x).

Topcu, H. D. and Brockmann, U. H., 2015, 'Seasonal oxygen depletion in the North Sea, a review', *Marine Pollution Bulletin* (doi: 10.1016/j.marpolbul.2015.06.021).

Tyrrell, T., Shepherd, J. G. and Castle, S., 2007, 'The long-term legacy of fossil fuels', *Tellus B* 59(4), 664–672 (doi: 10.1111/j.1600-0889.2007.00290.x).

UNEP/MAP, 2013, *State of the Mediterranean marine and coastal environment*, UNEP/MAP — Barcelona Convention, Athens.

Veron, J. E. N., 2008, *A reef in time: The Great Barrier Reef from beginning to end*, Belknap Press of Harvard University Press, Cambridge, MA.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J.-M., Hoegh-Guldberg, O. and Bairlein, F., 2002, 'Ecological responses to recent climate change', *Nature* 416(6879), 389–395 (doi: 10.1038/416389a).

Weijerman, M., Lindeboom, H. and Zuur, A., 2005, 'Regime shifts in marine ecosystems of the North Sea and Wadden Sea', *Marine Ecology Progress Series* 298, 21–39 (doi: 10.3354/meps298021).

Welch, M. J., Watson, S.-A., Welsh, J. Q., McCormick, M. I. and Munday, P. L., 2014, 'Effects of elevated CO_2 on fish behaviour undiminished by transgenerational acclimation', *Nature Climate Change* 4(12), 1 086–1 089 (doi: 10.1038/nclimate2400).

Section 4.2: Coastal zones

Araújo, I. B. and Pugh, D. T., 2008, 'Sea levels at Newlyn 1915–2005: Analysis of trends for future flooding risks', *Journal of Coastal Research* 24, 203–212 (doi: 10.2112/06-0785.1).

Baxter, P. J., 2005, 'The east coast Big Flood, 31 January–1 February 1953: A summary of the human disaster', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 363(1831), 1 293–1 312 (doi: 10.1098/rsta.2005.1569).

Bellard, C., Leclerc, C. and Courchamp, F., 2013, 'Potential impact of sea level rise on French islands worldwide', *Nature Conservation* 5, 75–86 (doi: 10.3897/natureconservation.5.5533).

Bellard, C., Leclerc, C. and Courchamp, F., 2014, 'Impact of sea level rise on the 10 insular biodiversity hotspots', *Global Ecology and Biogeography* 23(2), 203–212 (doi: 10.1111/geb.12093).

Blunden, J. and Arndt, D. S., 2016, 'State of the Climate in 2015', *Bulletin of the American Meteorological Society* 97(8), Si-S275 (doi: 10.1175/2016BAMSStateoftheClimate.1).

Brown, S., Nicholls, R., Vafeidis, A., Hinkel, J. and Watkiss, P., 2011, *The impacts and economic costs of sea-level rise in Europe and the costs and benefits of adaptation. Summary of results from the EC RTD ClimateCost Project*, The ClimateCost Project, Technical Policy Briefing Note 2, Stockholm Environment Institute, Stockholm.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D. and Unnikrishnan, A. S., 2013, 'Sea-level change', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 137–1 216.

Church, J. A. and White, N. J., 2011, 'Sea-level rise from the late 19th to the early 21st century', *Surveys in Geophysics* 32(4–5), 585–602 (doi: 10.1007/s10712-011-9119-1).

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J. and Velicogna, I., 2011, 'Revisiting the Earth's sea-level and energy budgets from 1961 to 2008', *Geophysical Research Letters* 38(18), L18601 (doi: 10.1029/2011GL048794).

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

Clark, P. U., Church, J. A., Gregory, J. M. and Payne, A. J., 2015, 'Recent progress in understanding and projecting regional and global mean sea level change', *Current Climate Change Reports* 1(4), 224–246 (doi: 10.1007/s40641-015-0024-4).

Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., Levermann, A., Milne, G. A., Pfister, P. L., Santer, B. D., Schrag, D. P., Solomon, S., Stocker, T. F., Strauss, B. H., Weaver, A. J., Winkelmann, R., Archer, D., Bard, E., Goldner, A. et al., 2016, 'Consequences of twenty-first-century policy for multi-millennial climate and sea-level change', *Nature Climate Change* 6(4), 360–369 (doi: 10.1038/nclimate2923).

Collet, I. and Engelbert, A., 2013, *Coastal regions: People living along the coastline, integration of NUTS 2010 and latest population grid*, Statistics in focus 30/2013, Eurostat, Luxembourg.

Dangendorf, S., Müller-Navarra, S., Jensen, J., Schenk, F., Wahl, T. and Weisse, R., 2014, 'North Sea storminess from a novel storm surge record since AD 1843', *Journal of Climate* 27(10), 3 582–3 595 (doi: 10.1175/JCLI-D-13-00427.1).

DeConto, R. M. and Pollard, D., 2016, 'Contribution of Antarctica to past and future sea-level rise', *Nature* 531(7596), 591–597 (doi: 10.1038/nature17145).

EC, 2007, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, OJ L 288, 6.11.2007, pp. 27–34.

EC, 2013, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Region — An EU Strategy on adaptation to climate change, COM(2013) 216 final of 16 April 2013, Brussels.

EEA, 2013, *Balancing the future of Europe's coasts: Knowledge base for integrated management*, EEA Report No 12/2013, European Environment Agency.

EU, 2014a, Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning, OJ L 257, 28.8.2014, pp. 135–145.

EU, 2014b, Regulation (EU) No 508/2014 of the European Parliament and of the Council of 15 May 2014 on the European Maritime and Fisheries Fund and repealing Council Regulations (EC) No 2328/2003, (EC) No 861/2006, (EC) No 1198/2006 and (EC) No 791/2007 and Regulation (EU) No 1255/2011 of the European Parliament and of the Council, OJ L 149, 20.5.2014, pp. 1–66.

Eurosion, 2004, *Living with coastal erosion in Europe: Sediment and Space for Sustainability. Part I — Major findings and policy recommendations of the Eurosion project*, Maps and Statistics, European Commission, Directorate General for the Environment, Brussels.

Foster, G. L. and Rohling, E. J., 2013, 'Relationship between sea level and climate forcing by CO_2 on geological timescales', *Proceedings of the National Academy of Sciences* 110(4), 1 209–1 214 (doi: 10.1073/pnas.1216073110).

Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M. and Gagliardini, O., 2016, 'The safety band of Antarctic ice shelves', *Nature Climate Change* 6, 479–482 (doi: 10.1038/nclimate2912).

Gerritsen, H., 2005, 'What happened in 1953? The Big Flood in the Netherlands in retrospect', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 363(1831), 1 271–1 291 (doi: 10.1098/rsta.2005.1568).

Haigh, I., Nicholls, R. and Wells, N., 2010, 'Assessing changes in extreme sea levels: Application to the English Channel, 1900–2006', *Continental Shelf Research* 30(9), 1 042–1 055 (doi: 10.1016/j.csr.2010.02.002).

Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C. and Wood, R. M., 2011, 'Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen', *Climatic Change* 104(1), 113–137 (doi: 10.1007/s10584-010-9978-3).

Hamlington, B. D. and Thompson, P. R., 2015, 'Considerations for estimating the 20th century trend in global mean sea level', *Geophysical Research Letters* 42(10), 4 102–4 109 (doi: 10.1002/2015GL064177).

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M. and Lo, K.-W., 2016, 'Ice melt, sea level rise and superstorms: Evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous', *Atmospheric Chemistry and Physics* 16(6), 3 761–3 812 (doi: 10.5194/acp-16-3761-2016).

Hansen, L., 2013, *Vandstandsmåling i Danmark. Månedsmidler og -ekstremer fra 14 vandstandsstationer for 2012*, DMI Teknisk Rapport 13–12 [in Danish], Danmarks Meteorologiske Institut, Copenhagen.

Hay, C. C., Morrow, E., Kopp, R. E. and Mitrovica, J. X., 2015, 'Probabilistic reanalysis of twentieth-century sea-level rise', *Nature* 517(7535), 481–484 (doi: 10.1038/nature14093).

HELCOM, 2013, *Climate change in the Baltic Sea Area — HELCOM thematic assessment in 2013*, Baltic Sea Environment Proceedings 137, HELCOM, Helsinki.

Hemer, M. A., Fan, Y., Mori, N., Semedo, A. and Wang, X. L., 2013, 'Projected changes in wave climate from a multi-model ensemble', *Nature Climate Change* 3(5), 471–476 (doi: 10.1038/nclimate1791).

Hinkel, J., Jaeger, C., Nicholls, R. J., Lowe, J., Renn, O. and Peijun, S., 2015, 'Sea-level rise scenarios and coastal risk management', *Nature Climate Change* 5(3), 188–190 (doi: 10.1038/nclimate2505).

Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., Foden, P. R., Gordon, K. M., Jevrejeva, S. and Pugh, J., 2012, 'New data systems and products at the permanent service for mean sea level', *Journal of Coastal Research* 29(3), 493–504 (doi: 10.2112/JCOASTRES-D-12-00175.1).

Horton, B. P., Rahmstorf, S., Engelhart, S. E. and Kemp, A. C., 2014, 'Expert assessment of sea-level rise by AD 2100 and AD 2300', *Quaternary Science Reviews* 84, 1–6 (doi: 10.1016/j.quascirev.2013.11.002).

Hov, Ø., Cubasch, U., Fischer, E., Höppe, P., Iversen, T., Kvamstø, N. G., Kundzewicz, Z. W., Rezacova, D., Rios, D., Duarte Santos, F., Schädler, B., Veisz, O., Zerefos, C., Benestad, R., Murlis, J., Donat, M., Leckebusch, G. C. and Ulbrich, U., 2013, *Extreme weather events in Europe: Preparing for climate change adaptation*, Norwegian Meteorological Institute, Oslo.

Howard, T., Pardaens, A. K., Bamber, J. L., Ridley, J., Spada, G., Hurkmans, R. T. W. L., Lowe, J. A. and Vaughan, D., 2014, 'Sources of 21st century regional sea-level rise along the coast of northwest Europe', *Ocean Science* 10(3), 473–483 (doi: 10.5194/os-10-473-2014).

Hunter, J., 2012, 'A simple technique for estimating an allowance for uncertain sea-level rise', *Climatic Change* 113(2), 239–252 (doi: 10.1007/s10584-011-0332-1).

Hunter, J. R., Church, J. A., White, N. J. and Zhang, X., 2013, 'Towards a global regionally varying allowance for sea-level rise', *Ocean Engineering* 71, 17–27 (doi: 10.1016/j.oceaneng.2012.12.041).

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014, *Climate change 2014: Impacts, adaptation, and vulnerability*, Cambridge University Press, Cambridge; New York.

Jevrejeva, S., Grinsted, A. and Moore, J. C., 2014, 'Upper limit for sea level projections by 2100', *Environmental Research Letters* 9(10), 104008 (doi: 10.1088/1748-9326/9/10/104008).

Jevrejeva, S., Moore, J. C. and Grinsted, A., 2012, 'Sea level projections to AD2500 with a new generation of climate change scenarios', *Global and Planetary Change* 80–81, 14–20 (doi: 10.1016/j.gloplacha.2011.09.006).

Jevrejeva, S., Moore, J. C., Grinsted, A., Matthews, A. P. and Spada, G., 2014, 'Trends and acceleration in global and regional sea levels since 1807', *Global and Planetary Change* 113, 11–22 (doi: 10.1016/j.gloplacha.2013.12.004).

Johansson, J. M., Davis, J. L., Scherneck, H.-G., Milne, G. A., Vermeer, M., Mitrovica, J. X., Bennett, R. A., Jonsson, B., Elgered, G., Elósegui, P., Koivula, H., Poutanen, M., Rönnäng, B. O. and Shapiro, I. I., 2002, 'Continuous GPS measurements of postglacial adjustment in Fennoscandia 1. Geodetic results', *Journal of Geophysical Research* 107(B8), 2 157 (doi: 10.1029/2001JB000400).

Johansson, M. M., Pellikka, H., Kahma, K. K. and Ruosteenoja, K., 2014, 'Global sea level rise scenarios adapted to the Finnish coast', *Journal of Marine Systems* 129, 35–46 (doi: 10.1016/j.jmarsys.2012.08.007).

Jordà, G., 2014, 'Detection time for global and regional sea level trends and accelerations', *Journal of Geophysical Research: Oceans* 119(10), 7 164–7 174 (doi: 10.1002/2014JC010005).

Khan, S. A., Kjær, K. H., Bevis, M., Bamber, J. L., Wahr, J., Kjeldsen, K. K., Bjørk, A. A., Korsgaard, N. J., Stearns, L. A., van den Broeke, M. R., Liu, L., Larsen, N. K. and Muresan, I. S., 2014, 'Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming', *Nature Climate Change* 4(4), 292–299 (doi: 10.1038/nclimate2161).

KNMI, 2014, *KNMI'14: Climate change scenarios for the 21st century — A Netherlands perspective*, Scientific Report WR2014-01, KNMI, De Bilt.

Konrad, H., Thoma, M., Sasgen, I., Klemann, V., Grosfeld, K., Barbi, D. and Martinec, Z., 2013, 'The deformational response of a viscoelastic solid Earth model coupled to a thermomechanical ice sheet model', *Surveys in Geophysics* 35(6), 1 441–1 458 (doi: 10.1007/s10712-013-9257-8).

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C., 2014, 'Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites', *Earth's Future* 2(8), 383–406 (doi: 10.1002/2014EF000239).

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D. and Rahmstorf, S., 2016, 'Temperature-driven global sea-level variability in the Common Era', *Proceedings of the National Academy of Sciences* 113(11), E1434–E1441 (doi: 10.1073/pnas.1517056113).

Levermann, A., Clark, P. U., Marzeion, B., Milne, G. A., Pollard, D., Radic, V. and Robinson, A., 2013, 'The multimillennial sea-level commitment of global warming', *Proceedings of the National Academy of Sciences* 110(34), 13 745–13 750 (doi: 10.1073/pnas.1219414110).

Lowe, J. A., Woodworth, P. L., Knutson, T., McDonald, R. E., McInnes, K. L., Woth, K., von Storch, H., Wolf, J., Swail, V., Bernier, N. B., Gulev, S., Horsburgh, K. J., Unnikrishnan, A. S., Hunter, J. R. and Weisse, R., 2010, 'Past and future changes in extreme sea levels and waves', in: Church, J. A., Woodworth, P. L., Aarup, T., et al. (eds), *Understanding sea-level rise and variability*, Wiley-Blackwell, Oxford, pp. 326–375.

Madsen, K. S. and Schmith, T., 2014, Regional sea level rise in the 20th and 21st century — The example of Denmark. Presentation at REKLIM international conference 'Our Climate — Our Future Regional perspectives on a global challenge', Forschungsverbund REKLIM.

Marchand, M., 2010, *Concepts and science for coastal erosion management. Concise report for policy makers*, Deltares, Delft.

Marcos, M., Jordà, G., Gomis, D. and Pérez, B., 2011, 'Changes in storm surges in southern Europe from a regional model under climate change scenarios', *Global and Planetary Change* 77(3–4), 116–128 (doi: 10.1016/j.gloplacha.2011.04.002).

Masters, D., Nerem, R. S., Choe, C., Leuliette, E., Beckley, B., White, N. and Ablain, M., 2012, 'Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2', *Marine Geodesy* 35(Suppl. 1), 20–41 (doi: 10.1080/01490419.2012.717862).

Menéndez, M. and Woodworth, P. L., 2010, 'Changes in extreme high water levels based on a quasi-global tide-gauge data set', *Journal of Geophysical Research* 115(C10), C10011 (doi: 10.1029/2009JC005997).

Mengel, M., Levermann, A., Frieler, K., Robinson, A., Marzeion, B. and Winkelmann, R., 2016, 'Future sea level rise constrained by observations and long-term commitment', *Proceedings of the National Academy of Sciences* 113(10), 2 597–2 602 (doi: 10.1073/pnas.1500515113).

Mokrech, M., Kebede, A. S., Nicholls, R. J., Wimmer, F. and Feyen, L., 2014, 'An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe', *Climatic Change* 128(3–4), 245–260 (doi: 10.1007/s10584-014-1298-6).

Olesen, M., Madsen, K. S., Ludwigsen, C. A., Boberg, F., Christensen, T., Cappelen, J., Christensen, O. B., Andersen, K. K. and Christensen, J. H., 2014, *Fremtidige klimaforandringer i Danmark*, Danmarks Klimacenter rapport 6 2014, Danmarks Meteorologiske Institut, Copenhagen.

Pickering, M. D., Wells, N. C., Horsburgh, K. J. and Green, J. A. M., 2012, 'The impact of future sea-level rise on the European Shelf tides', *Continental Shelf Research* 35, 1–15 (doi: 10.1016/j.csr.2011.11.011).

PSMSL, 2016, 'Tide gauge data' (http://www.psmsl.org/data/obtaining) accessed 23 February 2016.

Reager, J. T., Gardner, A. S., Famiglietti, J. S., Wiese, D. N., Eicker, A. and Lo, M.-H., 2016, 'A decade of sea level rise slowed by climate-driven hydrology', *Science* 351(6274), 699–703 (doi: 10.1126/science.aad8386).

Rhein, M., Rintoul, S. R., Aoki, S., Campos, E., Chambers, D., Feely, R. A., Gulev, S., Johnson, G. C., Josey, S. A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L. D. and Wang, F., 2013, 'Observations: Ocean', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 255–316.

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., Eade, R., Fereday, D., Folland, C. K., Gordon, M., Hermanson, L., Knight, J. R., Lea, D. J., MacLachlan, C., Maidens, A., Martin, M., Peterson, A. K., Smith, D., Vellinga, M. et al., 2014, 'Skillful long-range prediction of European and North American winters', *Geophysical Research Letters* 41(7), 2 514–2 519 (doi: 10.1002/2014GL059637).

Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M., 2012, 'Long-term sea-level rise implied by 1.5 °C and 2 °C warming levels', *Nature Climate Change* 2(12), 867–870 (doi: 10.1038/nclimate1584).

Slangen, A. B. A., Carson, M., Katsman, C. A., Wal, R. S. W. van de, Köhl, A., Vermeersen, L. L. A. and Stammer, D., 2014, 'Projecting twenty-first century regional sea-level changes', *Climatic Change* 124(1–2), 317–332 (doi: 10.1007/s10584-014-1080-9).

Slangen, A. B. A., Church, J. A., Zhang, X. and Monselesan, D., 2014, 'Detection and attribution of global mean thermosteric sea level change', *Geophysical Research Letters* 41(16), 5 951–5 959 (doi: 10.1002/2014GL061356).

Sørensen, C., Madsen, H. T. and Knudsen, S. B., 2013, *Højvandsstatistikker 2012*, Kystdirektoratet, Lemvig.

Suursaar, Ü., Kullas, T. and Szava-Kovats, R., 2009, 'Wind and wave storms, storm surges and sea level rise along the Estonian coast of the Baltic Sea', *WIT Transactions on Ecology and Environment* 127, 149–160 (doi: 10.2495/RAV090131).

The BACC II Author Team, 2015, *Second assessment of climate change for the Baltic Sea basin*, Springer International Publishing, Cham, Heidelberg, New York, Dordrecht, London.

Visser, H., Dangendorf, S. and Petersen, A. C., 2015, 'A review of trend models applied to sea level data with reference to the "acceleration-deceleration debate"', *Journal of Geophysical Research: Oceans* 120(6), 3 873–3 895 (doi: 10.1002/2015JC010716).

Vousdoukas, M. I., Voukouvalas, E., Annunziato, A., Giardino, A. and Feyen, L., 2016, 'Projections of extreme storm surge levels along Europe', *Climate Dynamics* (doi: 10.1007/s00382-016-3019-5).

Watson, C. S., White, N. J., Church, J. A., King, M. A., Burgette, R. J. and Legresy, B., 2015, 'Unabated global mean sea-level rise over the satellite altimeter era', *Nature Climate Change* 5(6), 565–568 (doi: 10.1038/nclimate2635).

Weisse, R., Bellafiore, D., Menéndez, M., Méndez, F., Nicholls, R. J., Umgiesser, G. and Willems, P., 2014, 'Changing extreme sea levels along European coasts', *Coastal Engineering* 87, 4–14 (doi: 10.1016/j.coastaleng.2013.10.017).

Wenzel, M. and Schröter, J., 2014, 'Global and regional sea level change during the 20th century', *Journal of Geophysical Research: Oceans* 119(11), 7 493–7 508 (doi: 10.1002/2014JC009900).

Section 4.3: Freshwater systems

Alfieri, L., Burek, P., Feyen, L. and Forzieri, G., 2015, 'Global warming increases the frequency of river floods in Europe', *Hydrology and Earth System Sciences* 19(5), 2 247–2 260 (doi: 10.5194/hess-19-2247-2015).

Alfieri, L., Feyen, L., Dottori, F. and Bianchi, A., 2015, 'Ensemble flood risk assessment in Europe under high end climate scenarios', *Global Environmental Change* 35, 199–212 (doi: 10.1016/j.gloenvcha.2015.09.004).

Alfieri, L., Salamon, P., Bianchi, A., Neal, J., Bates, P. and Feyen, L., 2014, 'Advances in pan-European flood hazard mapping', *Hydrological Processes* 28(13), 4 067–4 077 (doi: 10.1002/hyp.9947).

Antunes, J. T., Leão, P. N. and Vasconcelos, V. M., 2015, 'Cylindrospermopsis raciborskii: Review of the distribution, phylogeography, and ecophysiology of a global invasive species', *Frontiers in Microbiology* 6, 473 (doi: 10.3389/fmicb.2015.00473).

Arnell, N. W., Halliday, S. J., Battarbee, R. W., Skeffington, R. A. and Wade, A. J., 2015, 'The implications of climate change for the water environment in England', *Progress in Physical Geography* 39(1), 93–120 (doi: 10.1177/0309133314560369).

Barredo, J. I., 2009, 'Normalised flood losses in Europe: 1970–2006', *Natural Hazards and Earth System Sciences* 9, 97–104 (doi: 10.5194/nhess-9-97-2009).

Battarbee, R. W., Kernan, M., Livingstone, D. M., Nickus, U., Verdonschot, P., Hering, D., Moss, B., Wright, R. F., Evans, C. D., Grimalt, J. O., Johnson, R. K., Maltby, E., Linstead, C. and Skeffington, R. A., 2008, 'Freshwater ecosystem responses to climate change: the Euro-limpacs project', in: *The Water Framework Directive — Ecological and chemical status monitoring*, John Wiley & Sons Ltd, Chichester, pp. 313–354.

Benson, B. J., Magnuson, J. J., Jensen, O. P., Card, V. M., Hodgkins, G., Korhonen, J., Livingstone, D. M., Stewart, K. M., Weyhenmeyer, G. A. and Granin, N. G., 2011, 'Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005)', *Climatic Change* 112(2), 299–323 (doi: 10.1007/s10584-011-0212-8).

Blauhut, V., Gudmundsson, L. and Stahl, K., 2015, 'Towards pan-European drought risk maps: Quantifying the link between drought indices and reported drought impacts', *Environmental Research Letters* 10(1), 14008 (doi: 10.1088/1748-9326/10/1/014008).

CBS, PBL and Wageningen UR, 2014, 'Temperatuur oppervlaktewater' (http://www.clo.nl/nl0566) accessed 20 July 2015.

Chorynski, A., Pinskwar, I., Kron, W., Brakenridge, G. R. and Kundzewicz, Z. W., 2012, 'Catalogue of large floods in Europe in the 20th century', in: Kundzewicz, Z. W. (ed), *Changes in flood risk in Europe*, IAHS special publication, IAHS Press, Wallingford, Oxfordshire.

Ciscar, J.-C., Iglesias, A., Feyen, L., Szabo, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O. B., Dankers, R., Garrote, L., Goodess, C. M., Hunt, A., Moreno, A., Richards, J. and Soria, A., 2011, 'Physical and economic consequences of climate change in Europe', *Proceedings of the National Academy of Sciences* 108(7), 2 678–2 683 (doi: 10.1073/pnas.1011612108).

Dankers, R. and Feyen, L., 2009, 'Flood hazard in Europe in an ensemble of regional climate scenarios', *Journal of Geophysical Research* 114(D16), D16108 (doi: 10.1029/2008JD011523).

De Groeve, T., Poljansek, K., Ehrlich, D. and Corbane, C., 2014, *Current status and best practices for disaster loss data recording in EU Member States*, European Commission — Joint Research Centre: Institute for the Protection and the Security of the Citizen, Ispra.

Dibike, Y., Prowse, T., Saloranta, T. and Ahmed, R., 2011, 'Response of Northern Hemisphere lake-ice cover and lake-water thermal structure patterns to a changing climate', *Hydrological Processes* 25, 2 942–2 953 (doi: 10.1002/hyp.8068).

Dokulil, M., 2013, 'Impact of climate warming on European inland waters', *Inland Waters* 4(1), 27–40.

EC, 2000, Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, OJ L 327, 22.12.2000, pp. 1–73.

EC, 2007a, Communication from the Commission to the European Parliament and the Council Addressing the challenge of water scarcity and droughts in the European Union, COM(2007) 414 final of 18 July 2007, Brussels.

EC, 2007b, Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks, OJ L 288, 6.11.2007, pp. 27–34.

EC, 2012, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Blueprint to Safeguard Europe's Water Resources, COM(2012) 673 final of 14 November 2012, Brussels.

EC, 2013, *A compilation of reporting sheets adopted by water directors common implementation strategy for the Water Framework Directive (2000/60/EC)*, Guidance Document, European Commission, Brussels.

EEA, 2009, *Regional climate change and adaptation — The Alps facing the challenge of changing water resources*, EEA Report No 8/2009, European Environment Agency.

EEA, 2012a, *Europe's water resources: Current status and future challenges — Synthesis*, EEA Report No 9/2012, European Environment Agency.

EEA, 2012b, *Towards efficient use of water resources in Europe*, EEA Report No 1/2012, European Environment Agency.

EEA, 2012c, *Water resources in Europe in the context of vulnerability: EEA 2012 state of water assessment*, EEA Report No 11/2012, European Environment Agency.

EEA, 2015, *State of nature in the EU: Results from reporting under the nature directives 2007–2012*, EEA Technical report No 2/2015, European Environment Agency.

EEA, 2016a, *Flood risks and environmental vulnerability — Exploring the synergies between floodplain restoration, water policies and thematic policies*, EEA Report No 1/2016, European Environment Agency.

EEA, 2016b, 'Use of freshwater resources' (http://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-1) accessed 15 March 2016.

ETC/ICM, 2015, *Flood phenomena database — Structure and assessment*, European Topic Centre on Inland, Coastal and Marine Water, Magdeburg.

Feyen, L., Dankers, R., Bódis, K., Salamon, P. and Barredo, J. I., 2012, 'Fluvial flood risk in Europe in present and future climates', *Climatic Change* 112(1), 47–62 (doi: 10.1007/s10584-011-0339-7).

FOEN, 2015, 'Indicator Water temperature of surface waters' (http://www.bafu.admin.ch/umwelt/indikatoren/08605/08609/index.html?lang=en) accessed 20 July 2015.

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F. and Bianchi, A., 2014, 'Ensemble projections of future streamflow droughts in Europe', *Hydrology and Earth System Sciences* 18(1), 85–108 (doi: 10.5194/hess-18-85-2014).

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R. and Cid, A., 2016, 'Multi-hazard assessment in Europe under climate change', *Climatic Change* 137, 105–119 (doi: 10.1007/s10584-016-1661-x).

Fraser, A. I., Harrod, T. R. and Haygarth, P. M., 1999, 'The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils', *Water Science and Technology* 39, 41–45 (doi: 10.1016/s0273-1223(99)00316-9).

Giorgi, F., Coppola, E. and Raffaele, F., 2014, 'A consistent picture of the hydroclimatic response to global warming from multiple indices: Models and observations', *Journal of Geophysical Research: Atmospheres* 119(20), 11 695–11 708 (doi: 10.1002/2014JD022238).

Gudmundsson, L. and Seneviratne, S. I., 2015, 'A comprehensive drought climatology for Europe (1950-2013)', in: Andreu Alvarez, J., Solera, A., Paredes-Arquiola, J., et al. (eds), *Drought: Research and science-policy interfacing*, CRC Press, London, pp. 31–37.

Haande, S., Rohrlack, T., Ballot, A., Røberg, K., Skulberg, R., Beck, M. and Wiedner, C., 2008, 'Genetic characterisation of Cylindrospermopsis raciborskii (Nostocales, Cyanobacteria) isolates from Africa and Europe', *Harmful Algae* 7(5), 692–701 (doi: 10.1016/j.hal.2008.02.010).

Hari, R. E., Livingstone, D. M., Siber, R., Burkhardt-Holm, P. and Guttinger, H., 2006, 'Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams', *Global Change Biology* 12, 10–26 (doi: 10.1111/j.1365-2486.2005.001051.x).

Hassall, C., Thompson, D. J., French, G. C. and Harvey, I. F., 2007, 'Historical changes in the phenology of British Odonata are related to climate', *Global Change Biology* 13(5), 933–941 (doi: 10.1111/j.1365-2486.2007.01318.x).

Henrich, G. and Gobiet, A., 2011, 'The future of dry and wet spells in Europe: A comprehensive study based on the ENSEMBLES regional climate model', *International Journal of Climatology* 1, 101–123 (doi: 10.1002/joc.2421).

Hickling, R., Roy, D. B., Hill, J. K. and Thomas, C. D., 2005, 'A northward shift of range margins in British Odonata', *Global Change Biology* 11, 502–506 (doi: 10.1111/j.1365-2486.2005.00904.x).

ICPR, 2014, *Estimation of the effects of climate change scenarios on future Rhine water temperature development. Extensive version*, ICPR Report No 214 EN.

INBO, 2015, 'Trend Zuid-Europese libellensoorten' (https://www.inbo.be/nl/natuurindicator/trend-zuid-europese-libellensoorten) accessed 21 July 2015.

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Jeppesen, E., Kronvang, B., Olesen, J. E., Audet, J., Søndergaard, M., Hoffmann, C. C., Andersen, H. E., Lauridsen, T. L., Liboriussen, L., Larsen, S. E., Beklioglu, M., Meerhoff, M., Özen, A. and Özkan, K., 2010, 'Climate change effects on nitrogen loading from cultivated catchments in Europe: Implications for nitrogen retention, ecological state of lakes and adaptation', *Hydrobiologia* 663(1), 1–21 (doi: 10.1007/s10750-010-0547-6).

Jeppesen, E., Meerhoff, M., Davidson, T. A., Trolle, D., Søndergaard, M., Lauridsen, T. L., Beklioglu, M., Brucet, S., Volta, P., González-Bergonzoni, I. and Nielsen, A., 2014, 'Climate change impacts on lakes: An integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes', *Journal of Limnology* 73(s1), 88–111 (doi: 10.4081/jlimnol.2014.844).

Jeppesen, E., Moss, B., Bennion, H., Carvalho, L., DeMeester, L., Feuchtmayr, H., Friberg, N., Gessner, M. O., Hefting, M., Lauridsen, T. L., Liboriussen, L., Malmquist, H. J., May, L., Meerhoff, M., Olafsson, J. S., Soons, M. B. and Verhoeven, J. T. A., 2010, 'Interaction of climate change and eutrophication', in: Kernan, M., Battarbee, R. W., and Moss, B. (eds), *Climate change impacts on freshwater ecosystems*, Wiley-Blackwell, Oxford, pp. 119–151.

Jöhnk, K. D., Huisman, J., Sharples, J., Sommeijer, B., Visser, P. M. and Stroom, J. M., 2008, 'Summer heatwaves promote blooms of harmful cyanobacteria', *Global Change Biology* 14, 495–512 (doi: 10.1111/j.1365-2486.2007.01510.x).

Jongman, B., Hochrainer-Stigler, S., Feyen, L., Aerts, J. C. J. H., Mechler, R., Botzen, W. J. W., Bouwer, L. M., Pflug, G., Rojas, R. and Ward, P. J., 2014, 'Increasing stress on disaster-risk finance due to large floods', *Nature Climate Change* 4(4), 264–268 (doi: 10.1038/nclimate2124).

JRC, 2015, *Guidance for recording and sharing disaster damage and loss data: Towards the development of operational indicators to translate the Sendai Framework into action*, JRC Science and Policy Reports, Joint Research Centre, Institute for the Protection and Security of the Citizen and the EU expert working group on disaster damage and loss data, Ispra.

Kernan, M., Battarbee, R. W. and Moss, B. R., 2011, *Climate change impacts on freshwater ecosystems*, John Wiley & Sons, Hoboken, NJ.

Kosten, S., Huszar, V. L. M., Bécares, E., Costa, L. S., van Donk, E., Hansson, L.-A., Jeppesen, E., Kruk, C., Lacerot, G., Mazzeo, N., De Meester, L., Moss, B., Lürling, M., Nõges, T., Romo, S. and Scheffer, M., 2012, 'Warmer climates boost cyanobacterial dominance in shallow lakes', *Global Change Biology* 18(1), 118–126 (doi: 10.1111/j.1365-2486.2011.02488.x).

Kundzewicz, Z. W., Pińskwar, I. and Brakenridge, G. R., 2013, 'Large floods in Europe, 1985–2009', *Hydrological Sciences Journal* 58(1), 1–7 (doi: 10.1080/02626667.2012.745082).

van der Linden, P. and Mitchell, J. F. B., 2009, *ENSEMBLES: Climate change and its impacts: Summary of research and results from the ENSEMBLES project*, Met Office Hadley Centre, Exeter.

Lugeri, N., Kundzewicz, Z. W., Genovese, E., Hochrainer, S. and Radziejewski, M., 2010, 'River flood risk and adaptation in Europe—assessment of the present status', *Mitigation and Adaptation Strategies for Global Change* 15(7), 621–639 (doi: 10.1007/s11027-009-9211-8).

Markovic, D., Carrizo, S., Freyhof, J., Cid, N., Lengyel, S., Scholz, M., Kasperdius, H. and Darwall, W., 2014, 'Europe's freshwater biodiversity under climate change: Distribution shifts and conservation needs', *Diversity and Distributions* 20(9), 1 097–1 107 (doi: 10.1111/ddi.12232).

Merz, B., Vorogushyn, S., Uhlemann, S., Delgado, J. and Hundecha, Y., 2012, 'HESS Opinions 'More efforts and scientific rigour are needed to attribute trends in flood time series'', *Hydrology and Earth System Sciences* 16(5), 1 379–1 387 (doi: 10.5194/hess-16-1379-2012).

Miller, J. D., Kjeldsen, T. R., Hannaford, J. and Morris, D. G., 2013, 'A hydrological assessment of the November 2009 floods in Cumbria, UK', *Hydrology Research* 44(1), 180 (doi: 10.2166/nh.2012.076).

Mokrech, M., Kebede, A. S., Nicholls, R. J., Wimmer, F. and Feyen, L., 2014, 'An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe', *Climatic Change* 128(3–4), 245–260 (doi: 10.1007/s10584-014-1298-6).

Mooij, W. M., Hulsmann, S., Domis, L. N. D., Nolet, B. A., Bodelier, P. L. E., Boers, P. C. M., Pires, L. M. D., Gons, H. J., Ibelings, B. W., Noordhuis, R., Portielje, R., Wolfstein, K. and Lammens, E., 2005, 'The impact of climate change on lakes in the Netherlands: A review', *Aquatic Ecology* 39, 381–400 (doi: 10.1007/s10452-005-9008-0).

Moss, B., Hering, D., Green, A. J., Aidoud, A., Becares, E., Beklioglu, M., Bennion, H., Boix, D., Brucet, S., Carvalho, L., Clement, B., Davidson, T., Declerck, S., Dobson, M., van Donk, E., Dudley, B., Feuchtmayr, H., Friberg, N., Grenouillet, G. et al., 2009, 'Climate change and the future of freshwater biodiversity in Europe: A primer for policy-makers', *Freshwater Reviews* 2(2), 103–130 (doi: 10.1608/FRJ-2.2.1).

Naturwissenschaften Schweiz, 2016, ‚Eisaufbruchdaten des St. Moritzersees von 1832 bis 2015' (http://www.naturwissenschaften.ch/topics/seasons/science_of_seasons/long_series_of_data?_ga=1.246971015.2076977398.1461595392) accessed 23 May 2016.

Nõges, P. and Nõges, T., 2013, 'Weak trends in ice phenology of Estonian large lakes despite significant warming trends', *Hydrobiologia* 731(1), 5–18 (doi: 10.1007/s10750-013-1572-z).

OECD, 2013, *Water and climate change adaptation*, OECD Studies on Water, OECD Publishing, Paris.

Orlowsky, B. and Seneviratne, S. I., 2013, 'Elusive drought: Uncertainty in observed trends and short- and long-term CMIP5 projections', *Hydrology and Earth System Sciences* 17(5), 1 765–1 781 (doi: 10.5194/hess-17-1765-2013).

Orr, H. G., Simpson, G. L., des Clers, S., Watts, G., Hughes, M., Hannaford, J., Dunbar, M. J., Laizé, C. L. R., Wilby, R. L., Battarbee, R. W. and Evans, R., 2015, 'Detecting changing river temperatures in England and Wales', *Hydrological Processes* 29(5), 752–766 (doi: 10.1002/hyp.10181).

Paerl, H. W. and Huisman, J., 2008, 'Climate — Blooms like it hot', *Science* 320, 57–58 (doi: 10.1126/science.1155398).

Rojas, R., Feyen, L., Bianchi, A. and Dosio, A., 2012, 'Assessment of future flood hazard in Europe using a large ensemble of bias corrected regional climate simulations', *Journal of Geophysical Research* 117, D17109 (doi: 10.1029/2012JD017461).

Rojas, R., Feyen, L. and Watkiss, P., 2013, 'Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation', *Global Environmental Change* 23(6), 1 737–1 751 (doi: 10.1016/j.gloenvcha.2013.08.006).

Schaller, N., Kay, A. L., Lamb, R., Massey, N. R., van Oldenborgh, G. J., Otto, F. E. L., Sparrow, S. N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S. M., Haustein, K., Huntingford, C., Ingram, W. J., Jones, R. G., Legg, T., Miller, J., Skeggs, J. et al., 2016, 'Human influence on climate in the 2014 southern England winter floods and their impacts', *Nature Climate Change* 6, 627–634 (doi: 10.1038/nclimate2927).

Schindler, D. W., 2001, 'The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium', *Canadian Journal of Fisheries and Aquatic Sciences* 58, 18–29 (doi: 10.1139/cjfas-58-1-18).

Sepulcre-Canto, G., Horion, S., Singleton, A., Carrao, H. and Vogt, J., 2012, 'Development of a combined drought indicator to detect agricultural drought in Europe', *Natural Hazards and Earth System Sciences* 12(11), 3 519–3 531 (doi: 10.5194/nhess-12-3519-2012).

Sharma, S., Gray, D. K., Read, J. S., O'Reilly, C. M., Schneider, P., Qudrat, A., Gries, C., Stefanoff, S., Hampton, S. E., Hook, S., Lenters, J. D., Livingstone, D. M., McIntyre, P. B., Adrian, R., Allan, M. G., Anneville, O., Arvola, L., Austin, J., Bailey, J. et al., 2015, 'A global database of lake surface temperatures collected by in situ and satellite methods from 1985–2009', *Scientific Data* 2, 150008 (doi: 10.1038/sdata.2015.8).

Spinoni, J., Naumann, G., Vogt, J. and Barbosa, P., 2015, 'European drought climatologies and trends based on a multi-indicator approach', *Global and Planetary Change* 127, 50–57 (doi: 10.1016/j.gloplacha.2015.01.012).

Spinoni, J., Naumann, G. and Vogt, J. V., 2015, 'Spatial patterns of European droughts under a moderate emission scenario', *Advances in Science and Research* 12 (doi: 10.5194/asr-12-179-2015).

Spinoni, J., Vogt, J., Naumann, G., Barbosa, P., European Commission and Joint Research Centre, 2016, *Meteorological droughts in Europe: events and impacts, past trends and future projections*, Publications Office, Luxembourg.

Stagge, J. H., Rizzi, J., Tallaksen, L. M. and Stahl, K., 2015, *Future meteorological drought: Projections of regional climate models for Europe*, Drought R&SPI Technical Report No 25, Oslo.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Demuth, S., Fendekova, M. and Jódar, J., 2010, 'Streamflow trends in Europe: Evidence from a dataset of near-natural catchments', *Hydrology and Earth System Sciences* 14(12), 2 367–2 382 (doi: 10.5194/hess-14-2367-2010).

Stahl, K., Tallaksen, L. M., Hannaford, J. and van Lanen, H. A. J., 2012, 'Filling the white space on maps of European runoff trends: Estimates from a multi-model ensemble', *Hydrology and Earth System Sciences* 16(7), 2 035–2 047 (doi: 10.5194/hess-16-2035-2012).

SYKE, 2011, 'Lake ice in Finland — Observed trends and future outlooks' (http://www.environment.fi/default.asp?contentid=373875&lan=EN) accessed 22 October 2012.

Takács, K., 2011, Changes in river ice regime of the River Danube, Eötvös Loránd University, Budapest.

Thieken, A. H., Kienzler, S., Kreibich, H., Kuhlicke, C., Kunz, M., Mühr, B., Müller, M., Otto, A., Petrow, T., Pisi, S. and Schröter, K., 2016, 'Review of the flood risk management system in Germany after the major flood in 2013', *Ecology and Society* 21(2), 51 (doi: 10.5751/ES-08547-210251).

Touma, D., Ashfaq, M., Nayak, M. A., Kao, S.-C. and Diffenbaugh, N. S., 2015, 'A multi-model and multi-index evaluation of drought characteristics in the 21st century', *Journal of Hydrology* 526, 196–207 (doi: 10.1016/j.jhydrol.2014.12.011).

UN, 2015a, Sendai Framework for Disaster Risk Reduction 2015–2030, A/RES/69/283, General Assembly, 69th session.

UN, 2015b, Sendai Framework for Disaster Risk Reduction 2015–2030, United Nations International Strategy for Disaster Reduction.

Vadadi-Fülöp, C., Sipkay, C., Mészáros, G. and Hufnagel, L., 2012, 'Climate change and freshwater zooplankton: What does it boil down to?', *Aquatic Ecology* 46(4), 501–519 (doi: 10.1007/s10452-012-9418-8).

Van Loon, A. F., 2015, 'Hydrological drought explained', *Wiley Interdisciplinary Reviews: Water* 2(4), 359–392 (doi: 10.1002/wat2.1085).

Vaughan, I. P. and Ormerod, S. J., 2014, 'Linking interdecadal changes in British river ecosystems to water quality and climate dynamics', *Global Change Biology* 20(9), 2 725–2 740 (doi: 10.1111/gcb.12616).

van Vliet, M. T. H., Franssen, W. H. P., Yearsley, J. R., Ludwig, F., Haddeland, I., Lettenmaier, D. P. and Kabat, P., 2013, 'Global river discharge and water temperature under climate change', *Global Environmental Change* 23(2), 450–464 (doi: 10.1016/j.gloenvcha.2012.11.002).

Vormoor, K., Lawrence, D., Schlichting, L., Wilson, D. and Wong, W. K., 2016, 'Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway', *Journal of Hydrology* 538, 33–48 (doi: 10.1016/j.jhydrol.2016.03.066).

Webb, B. W. and Nobilis, F., 1994, 'Water temperature behaviour in the River Danube during the twentieth century', *Hydrobiologia* 291(2), 105–113 (doi: 10.1007/BF00044439).

Weyhenmeyer, G. A., Livingstone, D. M., Meili, M., Jensen, O., Benson, B. and Magnuson, J. J., 2011, 'Large geographical differences in the sensitivity of ice-covered lakes and rivers in the Northern Hemisphere to temperature changes', *Global Change Biology* 17, 268–275 (doi: 10.1111/j.1365-2486.2010.02249.x).

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M. and Wade, A. J., 2009, 'A review of the potential impacts of climate change on surface water quality', *Hydrological Sciences Journal* 54, 101–123 (doi: 10.1623/hysj.54.1.101).

Wilhelm, S. and Adrian, R., 2008, 'Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen, nutrients and phytoplankton', *Freshwater Biology* 53, 226–237 (doi: 10.1111/j.1365-2427.2007.01887.x).

Wong, W. K., Beldring, S., Engen-Skaugen, T., Haddeland, I. and Hisdal, H., 2011, 'Climate change effects on spatiotemporal patterns of hydroclimatological summer droughts in Norway', *Journal of Hydrometeorology* 12(6), 1 205–1 220 (doi: 10.1175/2011JHM1357.1).

Section 4.4: Terrestrial ecosystems, soil and forests

Alkemade, R., Bakkenes, M. and Eickhout, B., 2011, 'Towards a general relationship between climate change and biodiversity: An example for plant species in Europe', *Regional Environmental Change* 11, 143–150 (doi: 10.1007/s10113-010-0161-1).

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A. et al., 2010, 'A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests', *Forest Ecology and Management* 259(4), 660–684 (doi: 10.1016/j.foreco.2009.09.001).

Allison, S. D. and Treseder, K. K., 2011, 'Climate change feedbacks to microbial decomposition in boreal soils', *Fungal Ecology* 4(6), 362–374 (doi: 10.1016/j.funeco.2011.01.003).

Amano, T., Smithers, R. J., Sparks, T. H. and Sutherland, W. J., 2010, 'A 250-year index of first flowering dates and its response to temperature changes', *Proceedings of the Royal Society B: Biological Sciences* 277(1693), 2 451–2 457 (doi: 10.1098/rspb.2010.0291).

Araújo, M. B., Alagador, D., Cabeza, M., Nogués-Bravo, D. and Thuiller, W., 2011, 'Climate change threatens European conservation areas', *Ecology Letters* 14(5), 484–492 (doi: 10.1111/j.1461-0248.2011.01610.x).

Araújo, M. B., Thuiller, W. and Pearson, R. G., 2006, 'Climate warming and the decline of amphibians and reptiles in Europe', *Journal of Biogeography* 33(10), 1712–1728 (doi: 10.1111/j.1365-2699.2006.01482.x).

Arneth, A., Harrison, S. P., Zaehle, S., Tsigaridis, K., Menon, S., Bartlein, P. J., Feichter, J., Korhola, A., Kulmala, M., O'Donnell, D., Schurgers, G., Sorvari, S. and Vesala, T., 2010, 'Terrestrial biogeochemical feedbacks in the climate system', *Nature Geoscience* 3(8), 525–532 (doi: 10.1038/ngeo905).

van Asch, M., van Tienderen, P. H., Holleman, L. J. M. and Visser, M. E., 2007, 'Predicting adaptation of phenology in response to climate change, an insect herbivore example', *Global Change Biology* 13(8), 1 596–1 604 (doi: 10.1111/j.1365-2486.2007.01400.x).

Baier, P., Pennerstorfer, J. and Schopf, A., 2007, 'PHENIPS—A comprehensive phenology model of Ips typographus (L.) (Col., Scolytinae) as a tool for hazard rating of bark beetle infestation', *Forest Ecology and Management* 249(3), 171–186 (doi: 10.1016/j.foreco.2007.05.020).

Balci, Y. and Halmschlager, E., 2003, 'Incidence of Phytophthora species in oak forests in Austria and their possible involvement in oak decline', *Forest Pathology* 33(3), 157–174 (doi: 10.1046/j.1439-0329.2003.00318.x).

Baritz, R., Ernstsen, V. and Zirlewagen, D., 2014, '6 carbon concentrations in European agricultural and grazing land soil', in: Reimann, C., Birke, M., Demetriades, A., et al. (eds), *General background information and further analysis of the GEMAS data set*, Chemistry of Europe's Agricultural Soils, Part B, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, pp. 117–144.

Barredo, J. I., Strona, G., de Rigo, D., Caudullo, G., Stancanelli, G. and San-Miguel-Ayanz, J., 2015, 'Assessing the potential distribution of insect pests: Case studies on large pine weevil (*Hylobius abietis* L) and horse-chestnut leaf miner (*Cameraria ohridella*) under present and future climate conditions in European forests', *EPPO Bulletin* 45(2), 273–281 (doi: 10.1111/epp.12208).

Battisti, A., 2008, 'Forests and climate change — Lessons from insects', *iForest: Biogeosciences and Forestry* 1(1), 1–5 (doi: 10.3832/ifor0210-0010001).

Battisti, A., Benvegnu, I., Colombari, F. and Haack, R. A., 2014, 'Invasion by the chestnut gall wasp in Italy causes significant yield loss in Castanea sativa nut production', *Agricultural and Forest Entomology* 16(1), 75–79.

Bebber, D. P., Holmes, T. and Gurr, S. J., 2014, 'The global spread of crop pests and pathogens', *Global Ecology and Biogeography* 23(12), 1 398–1 407.

Bedia, J., Herrera, S., Camia, A., Moreno, J. M. and Gutiérrez, J. M., 2013, 'Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios', *Climatic Change* 122(1–2), 185–199 (doi: 10.1007/s10584-013-1005-z).

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W. and Courchamp, F., 2012, 'Impacts of climate change on the future of biodiversity', *Ecology Letters* 15(4), 365–377 (doi: 10.1111/j.1461-0248.2011.01736.x).

Bellard, C., Thuiller, W., Leroy, B., Genovesi, P., Bakkenes, M. and Courchamp, F., 2013, 'Will climate change promote future invasions?', *Global Change Biology* 19(12), 3 740–3 748 (doi: 10.1111/gcb.12344).

Benadi, G., Hovestadt, T., Poethke, H.-J. and Blüthgen, N., 2014, 'Specialization and phenological synchrony of plant-pollinator interactions along an altitudinal gradient', *Journal of Animal Ecology* 83(3), 639–650 (doi: 10.1111/1365-2656.12158).

Berger, S., Sohlke, G., Walther, G. R. and Pott, R., 2007, 'Bioclimatic limits and range shifts of cold-hardy evergreen broad-leaved species at their northern distributional limit in Europe', *Phytocoenologia* 37(3–4), 523–539 (doi: 10.1127/0340-269X/2007/0037-0523).

Bertin, R. I., 2008, 'Plant phenology and distribution in relation to recent climate change', *The Journal of the Torrey Botanical Society* 135(1), 126–146 (doi: 10.3159/07-RP-035R.1).

Betts, R. A., Golding, N., Gonzalez, P., Gornall, J., Kahana, R., Kay, G., Mitchell, L. and Wiltshire, A., 2015, 'Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways', *Biogeosciences* 12(5), 1 317–1 338 (doi: 10.5194/bg-12-1317-2015).

Blackburn, T. M., Essl, F., Evans, T., Hulme, P. E., Jeschke, J. M., Kühn, I., Kumschick, S., Marková, Z., Mrugała, A., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D. M., Sendek, A., Vilà, M., Wilson, J. R. U., Winter, M. et al., 2014, 'A unified classification of alien species based on the magnitude of their environmental impacts', *PLoS Biology* 12(5), e1001850 (doi: 10.1371/journal.pbio.1001850).

Bolte, A., Hilbrig, L., Grundmann, B., Kampf, F., Brunet, J. and Roloff, A., 2010, 'Climate change impacts on stand structure and competitive interactions in a southern Swedish spruce–beech forest', *European Journal of Forest Research* 129(3), 261–276 (doi: 10.1007/s10342-009-0323-1).

Borrelli, P., Ballabio, C., Panagos, P. and Montanarella, L., 2014, 'Wind erosion susceptibility of European soils', *Geoderma* 232–234, 471–478 (doi: 10.1016/j.geoderma.2014.06.008).

Both, C. and Marvelde, L., 2007, 'Climate change and timing of avian breeding and migration throughout Europe', *Climate Research* 35, 93–105 (doi: 10.3354/cr00716).

Both, C., Van Asch, M., Bijlsma, R. G., Van Den Burg, A. B. and Visser, M. E., 2009, 'Climate change and unequal phenological changes across four trophic levels: Constraints or adaptations?', *Journal of Animal Ecology* 78(1), 73–83 (doi: 10.1111/j.1365-2656.2008.01458.x).

Both, C., Van Turnhout, C. A. M., Bijlsma, R. G., Siepel, H., Van Strien, A. J. and Foppen, R. P. B., 2010, 'Avian population consequences of climate change are most severe for long-distance migrants in seasonal habitats', *Proceedings of the Royal Society B: Biological Sciences* 277(1685), 1 259–1 266 (doi: 10.1098/rspb.2009.1525).

Bowler, D. E., Haase, P., Kröncke, I., Tackenberg, O., Bauer, H. G., Brendel, C., Brooker, R. W., Gerisch, M., Henle, K., Hickler, T., Hof, C., Klotz, S., Kühn, I., Matesanz, S., O'Hara, R., Russell, D., Schweiger, O., Valladares, F., Welk, E. et al., 2015, 'A cross-taxon analysis of the impact of climate change on abundance trends in central Europe', *Biological Conservation* 187, 41–50 (doi: 10.1016/j.biocon.2015.03.034).

de Brogniez, D., Ballabio, C., Stevens, A., Jones, R. J. A., Montanarella, L. and van Wesemael, B., 2015, 'A map of the topsoil organic carbon content of Europe generated by a generalized additive model: Soil organic carbon content at pan-European level', *European Journal of Soil Science* 66(1), 121–134 (doi: 10.1111/ejss.12193).

Burkle, L. A., Marlin, J. C. and Knight, T. M., 2013, 'Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function', *Science* 339(6127), 1 611–1 615 (doi: 10.1126/science.1232728).

Calanca, P., Roesch, A., Jasper, K. and Wild, M., 2006, 'Global warming and the summertime evapotranspiration regime of the Alpine region', *Climatic Change* 79, 65–78 (doi: 10.1007/s10584-006-9103-9).

Camia, A. and Amatulli, G., 2009, 'Weather factors and fire danger in the Mediterranean', in: Chuvieco, E. (ed), *Earth observation of wildland fires in Mediterranean ecosystems*, Springer, Heidelberg, pp. 71–82.

Camia, A., Amatulli, G. and San-Miguel-Ayanz, J., 2008, *Past and future trends of fire danger in Europe*, EUR 23427 EN, JRC 46533, JRC, Ispra.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sánchez, G. and Peñuelas, J., 2011, 'Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought', *Proceedings of the National Academy of Sciences* 108(4), 1 474–1 478 (doi: 10.1073/pnas.1010070108).

Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B. and Thomas, C. D., 2011, 'Rapid range shifts of species associated with high levels of climate warming', *Science* 333(6045), 1 024–1 026 (doi: 10.1126/science.1206432).

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre, Institute for Prospective Technological Studies, Institute for Environment and Sustainability.

Cook, B. I., Wolkovich, E. M. and Parmesan, C., 2012, 'Divergent responses to spring and winter warming drive community level flowering trends', *Proceedings of the National Academy of Sciences* 109(23), 9 000–9 005 (doi: 10.1073/pnas.1118364109).

Copp, G. H. and Fox, M. G., 2007, 'Growth and life history traits of introduced pumpkinseed (Lepomis gibbosus) in Europe, and the relevance to its potential invasiveness', in: Gherardi, F. (ed), *Biological invaders in inland waters: Profiles, distribution, and threats*, Invading Nature — Springer Series in Invasion Ecology, Springer Netherlands, pp. 289–306.

Davey, C. M., Chamberlain, D. E., Newson, S. E., Noble, D. G. and Johnston, A., 2012, 'Rise of the generalists: Evidence for climate driven homogenization in avian communities — Avian diversity, homogenization and warming climate', *Global Ecology and Biogeography* 21(5), 568–578 (doi: 10.1111/j.1466-8238.2011.00693.x).

De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E. and Carnicelli, S., 2015, 'Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey', *Geoderma* 251–252, 33–46 (doi: 10.1016/j.geoderma.2015.03.008).

Delzon, S., Urli, M., Samalens, J.-C., Lamy, J.-B., Lischke, H., Sin, F., Zimmermann, N. E. and Porté, A. J., 2013, 'Field evidence of colonisation by holm oak, at the northern margin of its distribution range, during the Anthropocene period', *PLOS ONE* 8(11), e80443 (doi: 10.1371/journal.pone.0080443).

Devictor, V., van Swaay, C., Brereton, T., Brotons, L., Chamberlain, D., Heliola, J., Herrando, S., Julliard, R., Kuussaari, M., Lindstrom, A., Reif, J., Roy, D. B., Schweiger, O., Settele, J., Stefanescu, C., Van Strien, A., Van Turnhout, C., Vermouzek, Z., WallisDeVries, M. et al., 2012, 'Differences in the climatic debts of birds and butterflies at a continental scale', *Nature Climate Change* 2(2), 121–124 (doi: 10.1038/nclimate1347).

Diamond, S. E., Frame, A. M., Martin, R. A. and Buckley, L. B., 2011, 'Species' traits predict phenological responses to climate change in butterflies', *Ecology* 92(5), 1 005–1 012 (doi: 10.1890/10-1594.1).

Dirnböck, T., Essl, F. and Rabitsch, W., 2011, 'Disproportional risk for habitat loss of high-altitude endemic species under climate change', *Global Change Biology* 17(2), 990–996 (doi: 10.1111/j.1365-2486.2010.02266.x).

Drenkhan, R., Kurkela, T. and Hanso, M., 2006, 'The relationship between the needle age and the growth rate in Scots pine (Pinus sylvestris): A retrospective analysis by needle trace method (NTM)', *European Journal of Forest Research* 125(4), 397–405 (doi: 10.1007/s10342-006-0131-9).

Dullinger, S., Gattringer, A., Thuiller, W., Moser, D., Zimmermann, N. E., Guisan, A., Willner, W., Plutzar, C., Leitner, M., Mang, T., Caccianiga, M., Dirnböck, T., Ertl, S., Fischer, A., Lenoir, J., Svenning, J.-C., Psomas, A., Schmatz, D. R., Silc, U. et al., 2012, 'Extinction debt of high-mountain plants under twenty-first-century climate change', *Nature Climate Change* 2(8), 619–622 (doi: 10.1038/nclimate1514).

Dunn, P. O. and Møller, A. P., 2014, 'Changes in breeding phenology and population size of birds', *Journal of Animal Ecology* 83(3), 729–739 (doi: 10.1111/1365-2656.12162).

EC, 1992, Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora, OJ L 206, 22.7.1992, p. 7.

EC, 2011, Communication from the Commission to the European Parliament and the Council, the Economic and Social Committee and the Committee of the Regions 'Our life insurance, our natural capital: an EU biodiversity strategy to 2020', COM(2011) 0244 final.

EC, 2013a, Communication from the Commission to the European Parliament and the Council, the Economic and Social Committee and the Committee of the Regions 'A new EU Forest Strategy: for forests and the forest-based sector', COM(2013) 659 final.

EC, 2013b, *Guidelines on climate change and Natura 2000 — Dealing with the impact of climate change on the management of the Natura 2000 Network of areas of high biodiversity value*, Technical Report No 2013-68, European Commission, Luxembourg.

EC, 2014a, *LIFE and invasive alien species*, European Commission (DG ENV), LIFE Nature, Luxembourg.

EC, 2014b, 'Severe forest fire in Sweden' (https://ec.europa.eu/jrc/en/news/severe-forest-fire-sweden) accessed 15 March 2016.

EEA, 2010, 'Invasive alien species in Europe (SEBI 010)' (http://www.eea.europa.eu/data-and-maps/indicators/invasive-alien-species-in-europe/invasive-alien-species-in-europe) accessed 15 July 2015.

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2016, *European forest ecosystems — State and trends*, EEA Report No 05/2016, European Environment Agency.

Ellwanger, G., Ssymank, A. and Paulsch, C., 2012, *Natura 2000 and climate change — A challenge*, Federal Agency for Nature Conservation, Bonn.

Engler, R., Randin, C. F., Thuiller, W., Dullinger, S., Zimmermann, N. E., Araújo, M. B., Pearman, P. B., Le Lay, G., Piedallu, C., Albert, C. H., Choler, P., Coldea, G., De LAMO, X., Dirnböck, T., Gégout, J., Gómez-García, D., Grytnes, J., Heegaard, E., Høistad, F. et al., 2011, '21st century climate change threatens mountain flora unequally across Europe', *Global Change Biology* 17(7), 2 330–2 341 (doi: 10.1111/j.1365-2486.2010.02393.x).

Essl, F. and Kobler, J., 2009, 'Spiny invaders — Patterns and determinants of cacti invasion in Europe', *Flora* 204(7), 485–494 (doi: 10.1016/j.flora.2008.06.002).

Estrella, N., Sparks, T. H. and Menzel, A., 2009, 'Effects of temperature, phase type and timing, location, and human density on plant phenological responses in Europe', *Climate Research* 39(3), 235–248 (doi: 10.3354/cr00818).

ETC/BD, 2015, 'State of nature in the EU' (http://www.eea.europa.eu/publications/state-of-nature-in-the-eu) accessed 4 August 2015.

EU, 2013, Regulation (EU) No 1307/2013 of the European Parliament and of the Council of

17 December 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009, OJ L 347, 20.12.2013, pp. 608–670.

EU, 2014, Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species, OJ L 317, 4.11.2014, pp. 35–55.

Evangelista, P. H., Kumar, S., Stohlgren, T. J. and Young, N. E., 2011, 'Assessing forest vulnerability and the potential distribution of pine beetles under current and future climate scenarios in the Interior West of the US', *Forest Ecology and Management* 262(3), 307–316 (doi: 10.1016/j.foreco.2011.03.036).

Fares, S., Mugnozza, G. S., Corona, P. and Palahí, M., 2015, 'Sustainability: Five steps for managing Europe's forests', *Nature* 519(7544), 407–409 (doi: 10.1038/519407a).

Ficetola, G. F., Thuiller, W. and Padoa-Schioppa, E., 2009, 'From introduction to the establishment of alien species: Bioclimatic differences between presence and reproduction localities in the slider turtle', *Diversity and Distributions* 15(1), 108–116 (doi: 10.1111/j.1472-4642.2008.00516.x).

Filz, K. J., Engler, J. O., Stoffels, J., Weitzel, M. and Schmitt, T., 2013, 'Missing the target? A critical view on butterfly conservation efforts on calcareous grasslands in south-western Germany', *Biodiversity and Conservation* 22(10), 2 223–2 241 (doi: 10.1007/s10531-012-0413-0).

Fitzgerald, J. and Lindner, M., 2013, *Adapting to climate change in European forests — Results of the MOTIVE project*, Pensoft Publishers, Sofia.

Forestry Commission, 2012, 'Status of Dothistroma needle blight in Britain' (http://www.forestry.gov.uk/fr/INFD-6ZFDBT) accessed 24 May 2016.

Framstad, E., 2012, *The terrestrial ecosystems monitoring programme in 2011: Ground vegetation, epiphytes, small mammals and birds*, NINA Rapport 840, Norsk institutt for naturforskning, Oslo.

Fu, Y. H., Piao, S., Op de Beeck, M., Cong, N., Zhao, H., Zhang, Y., Menzel, A. and Janssens, I. A., 2014, 'Recent spring phenology shifts in western Central Europe based on multiscale observations: Multiscale observation of spring phenology', *Global Ecology and Biogeography* 23(11), 1 255–1 263 (doi: 10.1111/geb.12210).

Gange, A. C., Gange, E. G., Sparks, T. H. and Boddy, L., 2007, 'Rapid and recent changes in fungal fruiting patterns', *Science* 316(5821), 71 (doi: 10.1126/science.1137489).

Gillingham, P. K., Alison, J., Roy, D. B., Fox, R. and Thomas, C. D., 2015, 'High abundances of species in protected areas in parts of their geographic distributions colonized during a recent period of climatic change: Species show higher abundance inside PAs', *Conservation Letters* 8(2), 97–106 (doi: 10.1111/conl.12118).

Gordo, O. and Sanz, J. J., 2006a, 'Climate change and bird phenology: a long-term study in the Iberian Peninsula', *Global Change Biology* 12(10), 1 993–2 004 (doi: 10.1111/j.1365-2486.2006.01178.x).

Gordo, O. and Sanz, J. J., 2006b, 'Temporal trends in phenology of the honey bee Apis mellifera (L.) and the small white Pieris rapae (L.) in the Iberian Peninsula (1952–2004)', *Ecological Entomology* 31(3), 261–268 (doi: 10.1111/j.1365-2311.2006.00787.x).

Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barancok, P., Benito Alonso, J. L., Coldea, G., Dick, J., Erschbamer, B., Fernandez Calzado, M. R., Kazakis, G., Krajci, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D., Moiseev, P., Molau, U., Merzouki, A. et al., 2012, 'Continent-wide response of mountain vegetation to climate change', *Nature Climate Change* 2(2), 111–115 (doi: 10.1038/nclimate1329).

Guillemain, M., Pöysä, H., Fox, A. D., Arzel, C., Dessborn, L., Ekroos, J., Gunnarsson, G., Holm, T. E., Christensen, T. K., Lehikoinen, A., Mitchell, C., Rintala, J. and Møller, A. P., 2013, 'Effects of climate change on European ducks: What do we know and what do we need to know?', *Wildlife Biology* 19(4), 404–419 (doi: 10.2981/12-118).

Hamunyela, E., Verbesselt, J., Roerink, G. and Herold, M., 2013, 'Trends in Spring Phenology of Western European Deciduous Forests', *Remote Sensing* 5(12), 6 159–6 179 (doi: 10.3390/rs5126159).

Hanewinkel, M., Cullmann, D. A., Schelhaas, M.-J., Nabuurs, G.-J. and Zimmermann, N. E., 2012, 'Climate change may cause severe loss in the economic value of European forest land', *Nature Climate Change* 3(3), 203–207 (doi: 10.1038/nclimate1687).

Hanso, M. and Drenkhan, R., 2007, 'Retrospective analysis of Lophodermium seditiosum epidemics in Estonia', *Acta Silvatica & Lignaria Hungarica* 2007, 31–45.

Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A. L. and Totland, U., 2009, 'How does climate warming affect plant-pollinator interactions?', *Ecology Letters* 12(2), 184–195 (doi: 10.1111/j.1461-0248.2008.01269.x).

Heinrich, G. and Gobiet, A., 2012, 'The future of dry and wet spells in Europe: a comprehensive study based on the ENSEMBLES regional climate models', *International Journal of Climatology* 32(13), 1 951–1 970 (doi: 10.1002/joc.2421).

Hellmann, J. J., Byers, J. E., Bierwagen, B. G. and Dukes, J. S., 2008, 'Five potential consequences of climate change for invasive species', *Conservation Biology* 22(3), 534–543 (doi: 10.1111/j.1523-1739.2008.00951.x).

Hickler, T., Vohland, K., Feehan, J., Miller, P. A., Smith, B., Costa, L., Giesecke, T., Fronzek, S., Carter, T. R., Cramer, W., Kühn, I. and Sykes, M. T., 2012, 'Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model', *Global Ecology and Biogeography* 21(1), 50–63 (doi: 10.1111/j.1466-8238.2010.00613.x).

Hickling, R., Roy, D. B., Hill, J. K., Fox, R. and Thomas, C. D., 2006, 'The distributions of a wide range of taxonomic groups are expanding polewards', *Global Change Biology* 12(3), 450–455 (doi: 10.1111/j.1365-2486.2006.01116.x).

Hiederer, R. and Durrant, T., 2010, *Evaluation of BioSoil Demonstration Project: Preliminary data analysis*, EUR 24258 EN, JRC, Ispra.

Hlásny, T. and Turčáni, M., 2009, 'Insect pests as climate change driven disturbances in forest ecosystems', in: Střelcová, K., Mátyás, C., Kleidon, A., et al. (eds), *Bioclimatology and natural hazards*, Springer Netherlands, Dordrecht, pp. 165–177.

Hódar, J. A., Castro, J. and Zamora, R., 2003, 'Pine processionary caterpillar Thaumetopoea pityocampa as a new threat for relict Mediterranean Scots pine forests under climatic warming', *Biological Conservation* 110(1), 123–129 (doi: 10.1016/S0006-3207(02)00183-0).

Hodgson, J. A., Thomas, C. D., Oliver, T. H., Anderson, B. J., Brereton, T. M. and Crone, E. E., 2011, 'Predicting insect phenology across space and time', *Global Change Biology* 17(3), 1 289–1 300 (doi: 10.1111/j.1365-2486.2010.02308.x).

Hof, A. R., Jansson, R. and Nilsson, C., 2012, 'Future climate change will favour non-specialist mammals in the (sub)Arctics', *PLOS ONE* 7(12), e52574 (doi: 10.1371/journal.pone.0052574).

Hulme, P. E., 2012, 'Invasive species unchecked by climate', *Science* 335(6068), 537–538 (doi: 10.1126/science.335.6068.537-b).

Huntley, B., Collingham, Y. C., Willis, S. G. and Green, R. E., 2008, 'Potential Impacts of Climatic Change on European Breeding Birds', *PLoS ONE* 3(1), e1439 (doi: 10.1371/journal.pone.0001439).

Isbell, F., Craven, D., Connolly, J., Loreau, M., Schmid, B., Beierkuhnlein, C., Bezemer, T. M., Bonin, C., Bruelheide, H., de Luca, E., Ebeling, A., Griffin, J. N., Guo, Q., Hautier, Y., Hector, A., Jentsch, A., Kreyling, J., Lanta, V., Manning, P. et al., 2015, 'Biodiversity increases the resistance of ecosystem productivity to climate extremes', *Nature* 526(7574), 574–577 (doi: 10.1038/nature15374).

ISSG, 2011, 'Global Invasive Species Database (GISD)' (http://www.issg.org/database).

IUCN, 2009, *Guidelines on biofuels and invasive species*, International Union for Conservation of Nature and Natural Resources, Gland.

IUCN, 2012, *IUCN Red List Categories and Criteria: Version 3.1. Second edition*, International Union for Conservation of Nature and Natural Resources, Gland, Switzerland, and Cambridge, United Kingdom.

Ivits, E., Cherlet, M., Tóth, G., Sommer, S., Mehl, W., Vogt, J. and Micale, F., 2012, 'Combining satellite derived phenology with climate data for climate change impact assessment', *Global and Planetary Change* 88–89, 85–97 (doi: 10.1016/j.gloplacha.2012.03.010).

Jactel, H., Petit, J., Desprez-Loustau, M.-L., Delzon, S., Piou, D., Battisti, A. and Koricheva, J., 2012, 'Drought effects on damage by forest insects and pathogens: a meta-analysis', *Global Change Biology* 18(1), 267–276 (doi: 10.1111/j.1365-2486.2011.02512.x).

Jiguet, F., Gregory, R. D., Devictor, V., Green, R. E., Vorisek, P., van Strien, A. and Couvet, D., 2010, 'Population trends of European common birds are predicted by characteristics of their climatic niche', *Global Change Biology* 16(2), 497–505 (doi: 10.1111/j.1365-2486.2009.01963.x).

Jochner, S. C., Sparks, T. H., Estrella, N. and Menzel, A., 2012, 'The influence of altitude and urbanisation on trends and mean dates in phenology (1980–2009)', *International Journal of Biometeorology* 56(2), 387–394 (doi: 10.1007/s00484-011-0444-3).

Johnston, A., Ausden, M., Dodd, A. M., Bradbury, R. B., Chamberlain, D. E., Jiguet, F., Thomas, C. D., Cook, A. S. C. P., Newson, S. E., Ockendon, N., Rehfisch, M. M., Roos, S., Thaxter, C. B., Brown, A., Crick, H. Q. P., Douse, A., McCall, R. A., Pontier, H., Stroud, D. A. et al., 2013, 'Observed and predicted effects of climate change on species abundance in protected areas', *Nature Climate Change* 3(12), 1 055–1 061 (doi: 10.1038/nclimate2035).

Jones, A., Panagos, P., Barcelo, S., Bouraoui, F., Bosco, C., Dewitte, O., Gardi, C., Erhard, M., Hervás, J., Hiederer, R., Jeffery, S., Lükewille, A., Marmo, L., Montanarella, L., Olazábal, C., Petersen, J. E., Penizek, V., Strassburger, T., Tóth, G. et al., 2012, *The state of soil in Europe*, Joint Research Centre Reference Report EUR 25186 EN, Publications Office of the European Union, Luxembourg.

Jones, R. J. A., Hiederer, R., Rusco, E. and Montanarella, L., 2005, 'Estimating organic carbon in the soils of Europe for policy support', *European Journal of Soil Science* 56, 655–671 (doi: 10.1111/j.1365-2389.2005.00728.x).

Jonzén, N., Lindén, A., Ergon, T., Knudsen, E., Vik, J. O., Rubolini, D., Piacentini, D., Brinch, C., Spina, F., Karlsson, L. and others, 2006, 'Rapid advance of spring arrival dates in long-distance migratory birds', *Science* 312(5782), 1 959–1 961 (doi: 10.1126/science.1126119).

Karlsson, B., 2014, 'Extended season for northern butterflies', *International Journal of Biometeorology* 58(5), 691–701 (doi: 10.1007/s00484-013-0649-8).

Katsanevakis, S., Deriu, I., D'Amico, F., Nunes, A. L., Sanchez, S. P., Crocetta, F., Arianoutsou, M., Bazos, I., Christopoulou, A., Curto, G., Delipetrou, P., Kokkoris, Y., Panov, V. E., Rabitsch, W., Roques, A., Scalera, R., Shirley, S. M., Tricarico, E., Vannini, A. et al., 2015, 'European Alien Species Information Network (EASIN): Supporting European policies and scientific research', *Management of Biological Invasions* 6(2), 147–157 (doi: 10.3391/mbi.2015.6.2.05).

Keller, R. P., Geist, J., Jeschke, J. M. and Kühn, I., 2011, 'Invasive species in Europe: Ecology, status, and policy', *Environmental Sciences Europe* 23(1), 23 (doi: 10.1186/2190-4715-23-23).

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K. T. and Strandman, H., 2008, 'Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management', *Philosophical Transactions of the Royal Society B: Biological Sciences* 363(1501), 2 341 (doi: 10.1098/rstb.2007.2204).

Kerr, J. T., Pindar, A., Galpern, P., Packer, L., Potts, S. G., Roberts, S. M., Rasmont, P., Schweiger, O., Colla, S. R., Richardson, L. L., Wagner, D. L., Gall, L. F., Sikes, D. S. and Pantoja, A., 2015, 'Climate change impacts on bumblebees converge across continents', *Science* 349(6244), 177–180 (doi: 10.1126/science.aaa7031).

Khabarov, N., Krasovskii, A., Obersteiner, M., Swart, R., Dosio, A., San-Miguel-Ayanz, J., Durrant, T., Camia, A. and Migliavacca, M., 2014, 'Forest fires and adaptation options in Europe', *Regional Environmental Change* 16(1), 21–30 (doi: 10.1007/s10113-014-0621-0).

Kjær, E. D., Lobo, A. and Myking, T., 2014, 'The role of exotic tree species in Nordic forestry', *Scandinavian Journal of Forest Research* 29(4), 323–332 (doi: 10.1080/02827581.2014.926098).

Kleinbauer, I., Dullinger, S., Peterseil, J. and Essl, F., 2010a, 'Climate change might drive the invasive tree Robinia pseudacacia into nature reserves and endangered habitats', *Biological Conservation* 143(2), 382–390 (doi: 10.1016/j.biocon.2009.10.024).

Kleinbauer, I., Dullinger, S., Peterseil, J. and Essl, F., 2010b, 'Climate change might drive the invasive tree Robinia pseudacacia into nature reserves and endangered habitats', *Biological Conservation* 143(2), 382–390 (doi: 10.1016/j.biocon.2009.10.024).

Knudsen, E., Lindén, A., Both, C., Jonzén, N., Pulido, F., Saino, N., Sutherland, W. J., Bach, L. A., Coppack, T., Ergon, T., Gienapp, P., Gill, J. A., Gordo, O., Hedenström, A., Lehikoinen, E., Marra, P. P., Møller, A. P., Nilsson, A. L. K., Péron, G. et al., 2011, 'Challenging claims in the study of migratory birds and climate change', *Biological Reviews* 86(4), 928–946 (doi: 10.1111/j.1469-185X.2011.00179.x).

Koch, E., Dittmann, E., Lipa, W., Menzel, A., Nekovar, J., Sparks, T. H. and van Vliet, A. J. H., 2009, 'COST725 – establishing a European phenological data platform for climatological applications: Major results', *Advances in Science and Research* 3, 119–122 (doi: 10.5194/asr-3-119-2009).

Kollberg, I., Bylund, H., Schmidt, A., Gershenzon, J. and BjöRkman, C., 2013, 'Multiple effects of temperature, photoperiod and food quality on the performance of a pine sawfly: Multiple effects on sawfly performance', *Ecological Entomology* 38(2), 201–208 (doi: 10.1111/een.12005).

Kolström, M., Lindner, M., Vilén, T., Maroschek, M., Seidl, R., Lexer, M. J., Netherer, S., Kremer, A., Delzon, S., Barbati, A., Marchetti, M. and Corona, P., 2011, 'Reviewing the science and implementation of climate change adaptation measures in European forestry', *Forests* 2(4), 961–982 (doi: 10.3390/f2040961).

Koutsias, N., Arianoutsou, M., Kallimanis, A. S., Mallinis, G., Halley, J. M. and Dimopoulos, P., 2012, 'Where did the fires burn in Peloponnisos, Greece the summer of 2007? Evidence for a synergy of fuel and weather', *Agricultural and Forest Meteorology* 156, 41–53 (doi: 10.1016/j.agrformet.2011.12.006).

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Kurnik, B., Kajfež-Bogataj, L. and Horion, S., 2015, 'An assessment of actual evapotranspiration and soil water deficit in agricultural regions in Europe', *International Journal of Climatology* 35(9), 2 451–2 471 (doi: 10.1002/joc.4154).

Kurnik, B., Louwagie, G., Erhard, M., Ceglar, A. and Kajfež, L. B., 2014, 'Analysing seasonal differences between a soil water balance model and in situ soil moisture measurements at nine locations across Europe', *Environmental Modeling & Assessment* 19, 19–34 (doi: 10.1007/s10666-013-9377-z).

Lenoir, J., Gégout, J. C., Guisan, A., Vittoz, P., Wohlgemuth, T., Zimmermann, N. E., Dullinger, S., Pauli, H., Willner, W. and Svenning, J. C., 2010, 'Going against the flow: Potential mechanisms for unexpected downslope range shifts in a warming climate', *Ecography* 33(2), 295–303 (doi: 10.1111/j.1600-0587.2010.06279.x).

Lenoir, J., Gegout, J., Marquet, P., De Ruffray, P. and Brisse, H., 2008, 'A significant upward shift in plant species optimum elevation during the 20th century', *Science* 320(5884), 1 768 (doi: 10.1126/science.1156831).

Lenoir, J. and Svenning, J.-C., 2015, 'Climate-related range shifts — A global multidimensional synthesis and new research directions', *Ecography* 38(1), 15–28 (doi: 10.1111/ecog.00967).

Levinsky, I., Skov, F., Svenning, J.-C. and Rahbek, C., 2007, 'Potential impacts of climate change on the distributions and diversity patterns of European mammals', *Biodiversity and Conservation* 16(13), 3 803–3 816 (doi: 10.1007/s10531-007-9181-7).

Liebhold, A. M., Brockerhoff, E. G., Garrett, L. J., Parke, J. L. and Britton, K. O., 2012, 'Live plant imports: The major pathway for forest insect and pathogen invasions of the US', *Frontiers in Ecology and the Environment* 10(3), 135–143 (doi: 10.1890/110198).

Lindner, M., Fitzgerald, J. B., Zimmermann, N. E., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M.-J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B. and Hanewinkel, M., 2014, 'Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management?', *Journal of Environmental Management* 146, 69–83 (doi: 10.1016/j.jenvman.2014.07.030).

Ljungström, G., Wapstra, E. and Olsson, M., 2015, 'Sand lizard (Lacerta agilis) phenology in a warming world', *BMC Evolutionary Biology* 15, 206 (doi: 10.1186/s12862-015-0476-0).

López-Moreno, J. I., Goyette, S. and Beniston, M., 2009, 'Impact of climate change on snowpack in the Pyrenees: Horizontal spatial variability and vertical gradients', *Journal of Hydrology* 374(3–4), 384–396 (doi: 10.1016/j.jhydrol.2009.06.049).

Lugato, E., Bampa, F., Panagos, P., Montanarella, L. and Jones, A., 2014, 'Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices', *Global Change Biology* 20(11), 3 557–3 567 (doi: 10.1111/gcb.12551).

Lugato, E. and Jones, A., 2015, 'Modelling soil organic carbon changes under different maize cropping scenarios for cellulosic ethanol in Europe', *BioEnergy Research* 8(2), 537–545 (doi: 10.1007/s12155-014-9529-2).

Lugato, E., Panagos, P., Bampa, F., Jones, A. and Montanarella, L., 2014, 'A new baseline of organic carbon stock in European agricultural soils using a modelling approach', *Global Change Biology* 20(1), 313–326 (doi: 10.1111/gcb.12292).

Maclean, I. M. D. and Wilson, R. J., 2011, 'Recent ecological responses to climate change support predictions of high extinction risk', *Proceedings of the National Academy of Sciences* 108(30), 12 337–12 342 (doi: 10.1073/pnas.1017352108).

Maiorano, L., Amori, G., Capula, M., Falcucci, A., Masi, M., Montemaggiori, A., Pottier, J., Psomas, A., Rondinini, C., Russo, D., Zimmermann, N. E., Boitani, L. and Guisan, A., 2013, 'Threats from climate change to terrestrial vertebrate hotspots in Europe', *PLoS ONE* 8(9), e74989 (doi: 10.1371/journal.pone.0074989).

Maiorano, L., Falcucci, A., Zimmermann, N. E., Psomas, A., Pottier, J., Baisero, D., Rondinini, C., Guisan, A. and Boitani, L., 2011, 'The future of terrestrial mammals in the Mediterranean basin under climate change', *Philosophical Transactions of the Royal Society B: Biological Sciences* 366(1578), 2 681–2 692 (doi: 10.1098/rstb.2011.0121).

Malmström, C. M. and Raffa, K. F., 2000, 'Biotic disturbance agents in the boreal forest: Considerations for vegetation change models', *Global Change Biology* 6(S1), 35–48 (doi: 10.1046/j.1365-2486.2000.06012.x).

Mantyka-Pringle, C. S., Martin, T. G. and Rhodes, J. R., 2012, 'Interactions between climate and habitat loss effects on biodiversity: A systematic review and meta-analysis', *Global Change Biology* 18(4), 1 239–1 252 (doi: 10.1111/j.1365-2486.2011.02593.x).

Marcais, B. and Desprez-Loustau, M., 2007, 'Le réchauffement climatique a-t-il un impact sur les maladies forestières?', in: *Forêts et milieux naturels face aux changements climatiques*, Rendez-vous techniques de l'ONF, hors-série No 3, French Government Office National des Forêts (ONF), Paris, pp. 47–52.

Marini, L., Ayres, M. P., Battisti, A. and Faccoli, M., 2012, 'Climate affects severity and altitudinal distribution of outbreaks in an eruptive bark beetle', *Climatic Change* 115(2), 327–341.

Märker, M., Angeli, L., Bottai, L., Costantini, R., Ferrari, R., Innocenti, L. and Siciliano, G., 2008, 'Assessment of land degradation susceptibility by scenario analysis: A case study in Southern Tuscany, Italy', *Geomorphology* 93 (1–2), 120–129 (doi: 10.1016/j.geomorph.2006.12.020).

McRae, L., Zöckler, C., Gill, M., Loh, J., Latham, J., Harrison, N., J., M. and Collen, B., 2010, *Arctic Species Trend Index 2010: Tracking trends in Arctic wildlife*, CAFF CBMP Report 20, CAFF International Secretariat, Akureyri.

Meier, E. S., Lischke, H., Schmatz, D. R. and Zimmermann, N. E., 2012, 'Climate, competition and connectivity affect future migration and ranges of European trees', *Global Ecology and Biogeography* 21(2), 164–178 (doi: 10.1111/j.1466-8238.2011.00669.x).

Memmott, J., Craze, P. G., Waser, N. M. and Price, M. V., 2007, 'Global warming and the disruption of plant-pollinator interactions', *Ecology Letters* 10(8), 710–717.

Menzel, A., Seifert, H. and Estrella, N., 2011, 'Effects of recent warm and cold spells on European plant phenology', *International Journal of Biometeorology* 55(6), 921–932 (doi: 10.1007/s00484-011-0466-x).

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavska, O., Briede, A. and others, 2006, 'European phenological response to climate change matches the warming pattern', *Global Change Biology* 12(10), 1 969–1 976 (doi: 10.1111/j.1365-2486.2006.01193.x).

Millennium Ecosystem Assessment, 2005, *Ecosystems and human well-being: Biodiversity synthesis*, World Resources Institute, Washington, DC.

Moore, B. and Allard, G., 2008, *Climate change impacts on forest health*, Forest Health & Biosecurity Working Papers FBS/34E, Food and Agriculture Organization of the United Nations, Rome.

Moreno, J. M. (ed), 2014, Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world, FUME project.

Nabuurs, G.-J., Lindner, M., Verkerk, P. J., Gunia, K., Deda, P., Michalak, R. and Grassi, G., 2013, 'First signs of carbon sink saturation in European forest biomass', *Nature Climate Change* 3(9), 792–796 (doi: 10.1038/nclimate1853).

Navarro-Cano, J. A., Karlsson, B., Posledovich, D., Toftegaard, T., Wiklund, C., Ehrlén, J. and Gotthard, K., 2015, 'Climate change, phenology, and butterfly host plant utilization', *AMBIO* 44(S1), 78–88 (doi: 10.1007/s13280-014-0602-z).

Netherer, S. and Schopf, A., 2010, 'Potential effects of climate change on insect herbivores in European forests—General aspects and the pine processionary moth as specific example', *Forest Ecology and Management* 259(4), 831–838 (doi: 10.1016/j.foreco.2009.07.034).

Orlowsky, B. and Seneviratne, S. I., 2013, 'Elusive drought: Uncertainty in observed trends and short- and long-term CMIP5 projections', *Hydrology and Earth System Sciences* 17(5), 1 765–1 781 (doi: 10.5194/hess-17-1765-2013).

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S. and Hayes, D., 2011, 'A large and persistent carbon sink in the world's forests', *Science* 333(6045), 988–993 (doi: 10.1126/science.1201609).

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M. P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S. and Alewell, C., 2015, 'Rainfall erosivity in Europe', *Science of The Total Environment* 511, 801–814 (doi: 10.1016/j.scitotenv.2015.01.008).

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L. and Alewell, C., 2015, 'The new assessment of soil loss by water erosion in Europe', *Environmental Science & Policy* 54, 438–447 (doi: 10.1016/j.envsci.2015.08.012).

Panagos, P., Hiederer, R., Van Liedekerke, M. and Bampa, F., 2013, 'Estimating soil organic carbon in Europe based on data collected through an European network', *Ecological Indicators* 24, 439–450 (doi: 10.1016/j.ecolind.2012.07.020).

Parmesan, C., 2006, 'Ecological and evolutionary responses to recent climate change', *Annual Review of Ecology, Evolution, and Systematics* 37, 637–669 (doi: 10.1146/annurev.ecolsys.37.091305.110100).

Paterson, J. S., AraúJo, M. B., Berry, P. M., Piper, J. M. and Rounsevell, M. D. A., 2008, 'Mitigation, adaptation, and the threat to biodiversity', *Conservation Biology* 22(5), 1 352–1 355 (doi: 10.1111/j.1523-1739.2008.01042.x).

Pauchard, A., Kueffer, C., Dietz, H., Daehler, C. C., Alexander, J., Edwards, P. J., Arévalo, J. R., Cavieres, L. A., Guisan, A., Haider, S., Jakobs, G., McDougall, K., Millar, C. I., Naylor, B. J., Parks, C. G., Rew, L. J. and Seipel, T., 2009, 'Ain't no mountain high enough: Plant invasions reaching new elevations', *Frontiers in Ecology and the Environment* 7(9), 479–486 (doi: 10.1890/080072).

Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Alonso, J. L. B., Coldea, G., Dick, J., Erschbamer, B., Calzado, R. F., Ghosn, D., Holten, J. I., Kanka, R., Kazakis, G., Kollár, J., Larsson, P., Moiseev, P., Moiseev, D., Molau, U. et al., 2012, 'Recent plant diversity changes on Europe's mountain summits', *Science* 336(6079), 353–355 (doi: 10.1126/science.1219033).

Pearce-Higgins, J. W., Ausden, M. A., Beale, C. M., Oliver, T. H. and Crick, H. Q. P., 2015, *Research on the assessment of risks & opportunities for species in England as a result of climate change*, Natural England Commissioned Reports No 175, Natural England, London.

Penuelas, J. and Boada, M., 2003, 'A global change-induced biome shift in the Montseny mountains (NE Spain)', *Global Change Biology* 9(2), 131–140 (doi: 10.1046/j.1365-2486.2003.00566.x).

Peñuelas, J., Sardans, J., Estiarte, M., Ogaya, R., Carnicer, J., Coll, M., Barbeta, A., Rivas-Ubach, A., Llusià, J., Garbulsky, M., Filella, I. and Jump, A. S., 2013, 'Evidence of current impact of climate change on life: A walk from genes to the biosphere', *Global Change Biology* 19(8), 2303–2338 (doi: 10.1111/gcb.12143).

Petrucco-Toffolo, E. and Battisti, B., 2008, 'Performances of an expanding insect under elevated CO_2 and snow cover in the Alps', *iForest: Biogeosciences and Forestry* 1(1), 126–131 (doi: 10.3832/ifor0466-0010126).

Pielke, R. A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K. K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P. and de Noblet, N., 2011, 'Land use/land cover changes and climate: Modeling analysis and observational evidence', *Wiley Interdisciplinary Reviews: Climate Change* 2(6), 828–850 (doi: 10.1002/wcc.144).

Pompe, S., Berger, S., Bergmann, J., Badeck, F., Lübbert, J., Klotz, S., Rehse, A. K., Söhlke, G., Sattler, S., Walther, G. R. and Kühn, I., 2011, *Modellierung der Auswirkungen des Klimawandels auf die Flora und Vegetation in Deutschland*, BfN-Skripten 304, Federal Agency for Nature Conservation, Bonn.

Rabasa, S. G., Granda, E., Benavides, R., Kunstler, G., Espelta, J. M., Ogaya, R., Peñuelas, J., Scherer-Lorenzen, M., Gil, W., Grodzki, W., Ambrozy, S., Bergh, J., Hódar, J. A., Zamora, R. and Valladares, F., 2013, 'Disparity in elevational shifts of European trees in response to recent climate warming', *Global Change Biology* 19(8), 2 490–2 499 (doi: 10.1111/gcb.12220).

Rabitsch, W., Genovesi, P., Scalera, R., Biała, K., Josefsson, M. and Essl, F., 2016, 'Developing and testing alien species indicators for Europe', *Journal for Nature Conservation* 29, 89–96 (doi: 10.1016/j.jnc.2015.12.001).

Rasmont, P., Franzen, M., Lecocq, T., Harpke, A., Roberts, S., Biesmeijer, K., Castro, L., Cederberg, B., Dvorak, L., Fitzpatrick, U., Gonseth, Y., Haubruge, E., Mahe, G., Manino, A., Michez, D., Neumayer, J., Odegaard, F., Paukkunen, J., Pawlikowski, T. et al., 2015, 'Climatic Risk and Distribution Atlas of European Bumblebees', *BioRisk* 10, 1–236 (doi: 10.3897/biorisk.10.4749).

Renwick, K. M. and Rocca, M. E., 2015, 'Temporal context affects the observed rate of climate-driven range shifts in tree species: Importance of temporal context in tree range shifts', *Global Ecology and Biogeography* 24(1), 44–51 (doi: 10.1111/geb.12240).

Resco de Dios, V., Fischer, C. and Colinas, C., 2006, 'Climate change effects on Mediterranean forests and preventive measures', *New Forests* 33(1), 29–40 (doi: 10.1007/s11056-006-9011-x).

Roberts, S., Potts, S., Biesmeijer, K., Kuhlmann, M., Kunin, B. and Ohlemüller, R., 2011, 'Assessing continental-scale risks for generalist and specialist pollinating bee species under climate change', *BioRisk* 6, 1–18 (doi: 10.3897/biorisk.6.1325).

Robinet, C. and Roques, A., 2010, 'Direct impacts of recent climate warming on insect populations', *Integrative Zoology* 5(2), 132–142 (doi: 10.1111/j.1749-4877.2010.00196.x).

Rocchini, D., Hortal, J., Lengyel, S., Lobo, J. M., Jiménez-Valverde, A., Ricotta, C., Bacaro, G. and Chiarucci, A., 2011, 'Accounting for uncertainty when mapping species distributions: The need for maps of ignorance', *Progress in Physical Geography* 35(2), 211–226 (doi: 10.1177/0309133311399491).

Root, T. L., Price, J. T., Hall, K. R., Schneider, S. H., Rosenzweig, C. and Pounds, J. A., 2003, 'Fingerprints of global warming on wild animals and plants', *Nature* 421(6918), 57–60 (doi: 10.1038/nature01333).

Roth, T., Plattner, M. and Amrhein, V., 2014, 'Plants, birds and butterflies: Short-term responses of species communities to climate warming vary by taxon and with altitude', *PLoS ONE* 9(1), e82490 (doi: 10.1371/journal.pone.0082490).

Rubolini, D., Moller, A. P., Rainio, K. and Lehikoinen, E., 2007, 'Intraspecific consistency and geographic variability in temporal trends of spring migration phenology among European bird species', *Climate Research* 35(1/2), 135 (doi: 10.3354/cr00720).

Rusco, E., Jones, R. and Bidoglio, G., 2001, *Organic Matter in the soils of Europe: Present status and future trends*, EUR 20556 EN, JRC, Ispra.

Samaniego, L., Kumar, R. and Zink, M., 2013, 'Implications of parameter uncertainty on soil moisture drought analysis in Germany', *Journal of Hydrometeorology* 14, 47–68 (doi: 10.1175/JHM-D-12-075.1).

San-Miguel-Ayanz, J., Moreno, J. M. and Camia, A., 2013, 'Analysis of large fires in European Mediterranean landscapes: Lessons learned and perspectives', *Forest Ecology and Management* 294, 11–22 (doi: 10.1016/j.foreco.2012.10.050).

Santini, A., Ghelardini, L., De Pace, C., Desprez-Loustau, M. L., Capretti, P., Chandelier, A., Cech, T., Chira, D., Diamandis, S., Gaitniekis, T., Hantula, J., Holdenrieder, O., Jankovsky, L., Jung, T., Jurc, D., Kirisits, T., Kunca, A., Lygis, V., Malecka, M. et al., 2013, 'Biogeographical patterns and determinants of invasion by forest pathogens in Europe', *New Phytologist* 197(1), 238–250 (doi: 10.1111/j.1469-8137.2012.04364.x).

Scherrer, D. and Körner, C., 2011, 'Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming', *Journal of Biogeography* 38(2), 406–416 (doi: 10.1111/j.1365-2699.2010.02407.x).

Schils, R., Kuikman, P., Liski, J., van Oijen, M., Smith, P., Webb, J., Alm, J., Somogyi, Z., van den Akker, J., Billett, M., Emmett, B., Evans, C., Lindner, M., Palosuo, T., Bellamy, P., Jandl, R. and Hiederer, R., 2008, *Final report on review of existing information on the interrelations between soil and climate change (Climsoil)*, Final Report for the European Commission's Directorate-General for the Environment, European Commission, Brussels.

Schlüter, M. H., Merico, A., Reginatto, M., Boersma, M., Wiltshire, K. H. and Greve, W., 2010, 'Phenological shifts of three interacting zooplankton groups in relation to climate change', *Global Change Biology* 16(11), 3 144–3 153 (doi: 10.1111/j.1365-2486.2010.02246.x).

Schmuck, G., San-Miguel-Ayanz, J., Durrant, T., Boca, R., Liberta', G., Petroliagkis, T., Di Leo, M., Boccacci, F. and Rodriguez Aseretto Roque, D., 2015, *Forest fires in Europe, Middle East and North Africa 2014*, EUR — Scientific and Technical Research Reports, Publications Office of the European Union, Luxembourg.

Scholz, G., Quinton, J. N. and Strauss, P., 2008, 'Soil erosion from sugar beet in Central Europe in response to climate change induced seasonal precipitation variations', *CATENA* 72(1), 91–105 (doi: 10.1016/j.catena.2007.04.005).

Schulze, E. D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens et al., I. A., Schulze, E. D., Soussana, J. F., Smith, P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A. J., Valentini, R., Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G. et al., 2009, 'Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance', *Nature Geoscience* 2(12), 842–850 (doi: 10.1038/ngeo686).

Schweiger, O., Biesmeijer, J. C., Bommarco, R., Hickler, T., Hulme, P. E., Klotz, S., Kühn, I., Moora, M., Nielsen, A., Ohlemüller, R. and others, 2010, 'Multiple stressors on biotic interactions: How climate change and alien species interact to affect pollination', *Biological Reviews* 85(4), 777–795 (doi: 10.1111/j.1469-185X.2010.00125.x).

Schweiger, O., Heikkinen, R. K., Harpke, A., Hickler, T., Klotz, S., Kudrna, O., Kühn, I., Pöyry, J. and Settele, J., 2012, 'Increasing range mismatching of interacting species under global change is related to their ecological characteristics', *Global Ecology and Biogeography* 21(1), 88–99 (doi: 10.1111/j.1466-8238.2010.00607.x).

Schweiger, O., Settele, J., Kudrna, O., Klotz, S. and Kühn, I., 2008, 'Climate change can cause spatial mismatch of trophically interacting species', *Ecology* 89(12), 3 472–3 479 (doi: 10.1890/07-1748.1).

Seidl, R., Schelhaas, M.-J., Rammer, W. and Verkerk, P. J., 2014, 'Increasing forest disturbances in Europe and their impact on carbon storage', *Nature Climate Change* 4(9), 806–810 (doi: 10.1038/nclimate2318).

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. and Teuling, A. J., 2010, 'Investigating soil moisture–climate interactions in a changing climate: A review', *Earth-Science Reviews* 99(3–4), 125–161 (doi: 10.1016/j.earscirev.2010.02.004).

Settele, J., Kudrna, O., Harpke, A., Kühn, I., Van Swaay, C., Verovnik, R., Warren, M. S., Wiemers, M., Hanspach, J., Hickler, T., Kühn, E., van Halder, I., Veling, K., Vliegenthart, A., Wynhoff, I. and Schweiger, O., 2008, *Climatic risk atlas of European butterflies*, Biorisk 1 — Special Issue, Pensoft, Sofia.

Settele, J., Scholes, R., Betts, R., Bunn, S. E., Leadley, P., Nepstad, D., Overpeck, J. T. and Taboada, M. A., 2014, 'Terrestrial and inland water systems', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 271–359.

Sheffield, J., Wood, E. F. and Roderick, M. L., 2012, 'Little change in global drought over the past 60 years', *Nature* 491(7424), 435–438 (doi: 10.1038/nature11575).

Singer, M. C. and Parmesan, C., 2010, 'Phenological asynchrony between herbivorous insects and their hosts: Signal of climate change or pre-existing adaptive strategy?', *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1555), 3 161–3 176 (doi: 10.1098/rstb.2010.0144).

Spathelf, P., van der Maaten, E., van der Maaten-Theunissen, M., Campioli, M. and Dobrowolska, D., 2014, 'Climate change impacts in European forests: The expert views of local observers', *Annals of Forest Science* 71(2), 131–137 (doi: 10.1007/s13595-013-0280-1).

van Swaay, C. A. M., Nowicki, P., Settele, J. and van Strien, A. J., 2008, 'Butterfly monitoring in Europe: Methods, applications and perspectives', *Biodiversity and Conservation* 17(14), 3 455–3 469 (doi: 10.1007/s10531-008-9491-4).

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and Zimov, S., 2009, 'Soil organic carbon pools in the northern circumpolar permafrost region', *Global Biogeochemical Cycles* 23(2), GB2023 (doi: 10.1029/2008GB003327).

Thackeray, S. J., Sparks, T. H., Frederiksen, M., Burthe, S., Bacon, P. J., Bell, J. R., Botham, M. S., Brereton, T. M., Bright, P. W., Carvalho, L., Clutton-Brock, T., Dawson, A., Edwards, M., Elliott, J. M., Harrington, R., Johns, D., Jones, I. D., Jones, J. T., Leech, D. I. et al., 2010, 'Trophic level asynchrony in rates of phenological change for marine, freshwater and terrestrial environments', *Global Change Biology* 16(12), 3 304–3 313 (doi: 10.1111/j.1365-2486.2010.02165.x).

Thodsen, H., Hasholt, B. and Kjærsgaard, J. H., 2008, 'The influence of climate change on suspended sediment transport in Danish rivers', *Hydrological Processes* 22(6), 764–774 (doi: 10.1002/hyp.6652).

Thompson, I., Mackey, B., McNulty, S. and Mosseler, A., 2009, *Forest resilience, biodiversity, and climate change. A synthesis of the biodiversity/resilience/stability relationship in forest ecosystems*, Technical Series No 43, Secretariat of the Convention on Biological Diversity, Montreal.

Thuiller, W., Lavergne, S., Roquet, C., Boulangeat, I., Lafourcade, B. and Araujo, M. B., 2011, 'Consequences of climate change on the tree of life in Europe', *Nature* 470(7335), 531–534 (doi: 10.1038/nature09705).

Trumbore, S., Brando, P. and Hartmann, H., 2015, 'Forest health and global change', *Science* 349(6250), 814–818 (doi: 10.1126/science.aac6759).

Tryjanowski, P., Pawlikowski, T., Pawlikowski, K., Banaszak-Cibicka, W. and Sparks, T. H., 2010, 'Does climate influence phenological trends in social wasps (Hymenoptera: Vespinae) in Poland?', *European Journal of Entomology* 107(2), 203–208.

Turner, W. R., Bradley, B. A., Estes, L. D., Hole, D. G., Oppenheimer, M. and Wilcove, D. S., 2010, 'Climate change: Helping nature survive the human response: Indirect impacts of climate change', *Conservation Letters* 3(5), 304–312 (doi: 10.1111/j.1755-263X.2010.00128.x).

UNECE and FAO, 2015, 'Forests in the ECE region: Trends and challenges in achieving the global objectives on forests' (http://www.unece.org/forests/forests-in-the-ece-region-2015.html) accessed 4 August 2015.

Urban, M. C., 2015, 'Accelerating extinction risk from climate change', *Science* 348(6234), 571–573 (doi: 10.1126/science.aaa4984).

Urban, M. C., Tewksbury, J. J. and Sheldon, K. S., 2012, 'On a collision course: Competition and dispersal differences create no-analogue communities and cause extinctions during climate change', *Proceedings of the Royal Society B: Biological Sciences* 279(1735), 2 072–2 080 (doi: 10.1098/rspb.2011.2367).

Urhausen, S., Brienen, S., Kapala, A. and Simmer, C., 2011, 'Climatic conditions and their impact on viticulture in the Upper Moselle region', *Climatic Change* 109(3–4), 349–373 (doi: 10.1007/s10584-011-0059-z).

Urli, M., Delzon, S., Eyermann, A., Couallier, V., García-Valdés, R., Zavala, M. A. and Porté, A. J., 2014, 'Inferring shifts in tree species distribution using asymmetric distribution curves: A case study in the Iberian mountains', *Journal of Vegetation Science* 25(1), 147–159 (doi: 10.1111/jvs.12079).

Van Dyck, H., Bonte, D., Puls, R., Gotthard, K. and Maes, D., 2015, 'The lost generation hypothesis: could climate change drive ectotherms into a developmental trap?', *Oikos* 124(1), 54–61 (doi: 10.1111/oik.02066).

Van Wagner, C. E., 1987, *Development and structure of the Canadian Forest Fire Weather Index System*, Forestry Technical Report No 35, Canadian Forestry Service Headquarters, Ottawa.

Vilà, M., Basnou, C., Pyšek, P., Josefsson, M., Genovesi, P., Gollasch, S., Nentwig, W., Olenin, S., Roques, A., Roy, D. and Hulme, P. E., 2010, 'How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment', *Frontiers in Ecology and the Environment* 8, 135–144 (doi: 10.1890/080083).

Vilà, M., Espinar, J. L., Hejda, M., Hulme, P. E., Jarošík, V., Maron, J. L., Pergl, J., Schaffner, U., Sun, Y. and Pyšek, P., 2011, 'Ecological impacts of invasive alien plants: A meta-analysis of their effects on species, communities and ecosystems', *Ecology Letters* 14(7), 702–708 (doi: 10.1111/j.1461-0248.2011.01628.x).

Virkkala, R., Heikkinen, R. K., Fronzek, S., Kujala, H. and Leikola, N., 2013, 'Does the protected area network preserve bird species of conservation concern in a rapidly changing climate?', *Biodiversity and Conservation* 22(2), 459–482 (doi: 10.1007/s10531-012-0423-y).

Virkkala, R., Pöyry, J., Heikkinen, R. K., Lehikoinen, A. and Valkama, J., 2014, 'Protected areas alleviate climate change effects on northern bird species of conservation concern', *Ecology and Evolution* 4(15), 2 991–3 003 (doi: 10.1002/ece3.1162).

Visser, M. E. and Holleman, L. J. M., 2001, 'Warmer springs disrupt the synchrony of oak and winter moth phenology', *Proceedings of the Royal Society of London. Series B: Biological Sciences* 268(1464), 289 (doi: 10.1098/rspb.2000.1363).

Visser, M. E., Perdeck, A. C., Van Balen, J. H. and Both, C., 2009, 'Climate change leads to decreasing bird migration distances', *Global Change Biology* 15(8), 1 859–1 865 (doi: 10.1111/j.1365-2486.2009.01865.x).

Vitasse, Y., François, C., Delpierre, N., Dufrêne, E., Kremer, A., Chuine, I. and Delzon, S., 2011, 'Assessing the effects of climate change on the phenology of European temperate trees', *Agricultural and Forest Meteorology* 151(7), 969–980 (doi: 10.1016/j.agrformet.2011.03.003).

Volney, W. J. A. and Fleming, R. A., 2000, 'Climate change and impacts of boreal forest insects', *Agriculture, Ecosystems & Environment* 82(1–3), 283–294 (doi: 10.1016/S0167-8809(00)00232-2).

Walther, G. R., Gritti, E. S., Berger, S., Hickler, T., Tang, Z. and Sykes, M. T., 2007, 'Palms tracking climate change', *Global Ecology and Biogeography* 16(6), 801–809 (doi: 10.1111/j.1466-8238.2007.00328.x).

Walther, G. R., Roques, A., Hulme, P. E., Sykes, M. T., Pysek, P., Kuhn, I., Zobel, M., Bacher, S., Botta-Dukát, Z., Bugmann, H., Czúcz, B., Dauber, J., Hickler, T., Jarosík, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W. et al., 2009, 'Alien species in a warmer world: Risks and opportunities', *Trends in Ecology & Evolution* 24(12), 686–693 (doi: 10.1016/j.tree.2009.06.008).

Watson, J. E. M., Iwamura, T. and Butt, N., 2013, 'Mapping vulnerability and conservation adaptation strategies under climate change', *Nature Climate Change* 3(11), 989–994 (doi: 10.1038/nclimate2007).

Willmer, P., 2012, 'Ecology: pollinator–plant synchrony tested by climate change', *Current Biology* 22(4), R131–R132 (doi: 10.1016/j.cub.2012.01.009).

Winter, M., Fiedler, W., Hochachka, W. M., Koehncke, A., Meiri, S. and De la Riva, I., 2016, 'Patterns and biases in climate change research on amphibians and reptiles: a systematic review', *Royal Society Open Science* 3(9), 160158 (doi: 10.1098/rsos.160158).

Wolkovich, E. M., Cook, B. I., Allen, J. M., Crimmins, T. M., Betancourt, J. L., Travers, S. E., Pau, S., Regetz, J., Davies, T. J., Kraft, N. J. B., Ault, T. R., Bolmgren, K., Mazer, S. J., McCabe, G. J., McGill, B. J., Parmesan, C., Salamin, N., Schwartz, M. D. and Cleland, E. E., 2012, 'Warming experiments underpredict plant phenological responses to climate change', *Nature* 485, 494–497 (doi: 10.1038/nature11014).

Zarnetske, P. L., Skelly, D. K. and Urban, M. C., 2012, 'Biotic multipliers of climate change', *Science* 336(6088), 1 516–1 518 (doi: 10.1126/science.1222732).

Section 4.5: Ecosystems and their services

Bahn, M., Reichstein, M., Dukes, J. S., Smith, M. D. and McDowell, N. G., 2014, 'Climate-biosphere interactions in a more extreme world', *New Phytologist* 202(2), 356–359 (doi: 10.1111/nph.12662).

Bellard, C., Thuiller, W., Leroy, B., Genovesi, P., Bakkenes, M. and Courchamp, F., 2013, 'Will climate change promote future invasions?', *Global Change Biology* 19(12), 3 740–3 748 (doi: 10.1111/gcb.12344).

Burrows, M. T., Schoeman, D. S., Richardson, A. J., Molinos, J. G., Hoffmann, A., Buckley, L. B., Moore, P. J., Brown, C. J., Bruno, J. F., Duarte, C. M., Halpern, B. S., Hoegh-Guldberg, O., Kappel, C. V., Kiessling, W., O'Connor, M. I., Pandolfi, J. M., Parmesan, C., Sydeman, W. J., Ferrier, S. et al., 2014, 'Geographical limits to species-range shifts are suggested by climate velocity', *Nature* 507(7493), 492–495 (doi: 10.1038/nature12976).

Ceballos, G., Ehrlich, P. R., Barnosky, A. D., García, A., Pringle, R. M. and Palmer, T. M., 2015, 'Accelerated modern human–induced species losses: Entering the sixth mass extinction', *Science Advances* 1(5), e1400253 (doi: 10.1126/sciadv.1400253).

Dunford, R. W., Smith, A. C., Harrison, P. A. and Hanganu, D., 2015, 'Ecosystem service provision in a changing Europe: Adapting to the impacts of combined climate and socio-economic change', *Landscape Ecology* 30(3), 443–461 (doi: 10.1007/s10980-014-0148-2).

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2015a, 'Exposure of ecosystems to acidification, eutrophication and ozone (CSI 005) — Assessment published Nov 2015' (http://www.eea.europa.eu/data-and-maps/indicators/exposure-of-ecosystems-to-acidification-3/assessment-1) accessed 24 August 2016.

EEA, 2015b, *SOER 2015: The European environment — state and outlook 2015*, European Environment Agency.

EEA, 2015c, *State of Europe's seas*, EEA Report No 2/2015, European Environment Agency.

EEA, 2016a, *Mapping and assessing the condition of Europe's ecosystems: Progress and challenges*, EEA Report No 3/2016, European Environment Agency.

EEA, 2016b, 'Use of freshwater resources' (http://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-1) accessed 15 March 2016.

Harrison, P. A., Berry, P. M., Simpson, G., Haslett, J. R., Blicharska, M., Bucur, M., Dunford, R., Egoh, B., Garcia-Llorente, M., Geamănă, N., Geertsema, W., Lommelen, E., Meiresonne, L. and Turkelboom, F., 2014, 'Linkages between biodiversity attributes and ecosystem services: A systematic review', *Ecosystem Services* 9, 191–203 (doi: 10.1016/j.ecoser.2014.05.006).

Harrison, P. A., Dunford, R., Savin, C., Rounsevell, M. D. A., Holman, I. P., Kebede, A. S. and Stuch, B., 2015, 'Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors', *Climatic Change* 128(3–4), 279–292 (doi: 10.1007/s10584-014-1239-4).

Hauck, J., Winkler, K. J. and Priess, J. A., 2015, 'Reviewing drivers of ecosystem change as input for environmental and ecosystem services modelling', *Sustainability of Water Quality and Ecology* 5, 9–30 (doi: 10.1016/j.swaqe.2015.01.003).

Karp, D. S., Tallis, H., Sachse, R., Halpern, B., Thonicke, K., Cramer, W., Mooney, H., Polasky, S., Tietjen, B., Waha, K., Walz, A. and Wolny, S., 2015, 'National indicators for observing ecosystem service change', *Global Environmental Change* 35, 12–21 (doi: 10.1016/j.gloenvcha.2015.07.014).

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Liquete, C., Kleeschulte, S., Dige, G., Maes, J., Grizzetti, B., Olah, B. and Zulian, G., 2015, 'Mapping green infrastructure based on ecosystem services and ecological networks: A Pan-European case study', *Environmental Science & Policy* 54, 268–280 (doi: 10.1016/j.envsci.2015.07.009).

MCCIP, 2013, *Marine climate change impacts report card 2013*, Summary Report, MCCIP, Lovestoft.

Millennium Ecosystem Assessment, 2005, *Ecosystems and human well-being: Biodiversity synthesis*, World Resources Institute, Washington, DC.

Nelson, E. J., Kareiva, P., Ruckelshaus, M., Arkema, K., Geller, G., Girvetz, E., Goodrich, D., Matzek, V., Pinsky, M., Reid, W., Saunders, M., Semmens, D. and Tallis, H., 2013, 'Climate change's impact on key ecosystem services and the human well-being they support in the US', *Frontiers in Ecology and the Environment* 11(9), 483–893 (doi: 10.1890/120312).

Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., Börger, L., Bennett, D. J., Choimes, A., Collen, B., Day, J., De Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M. J., Feldman, A., Garon, M., Harrison, M. L. K., Alhusseini, T. et al., 2015, 'Global effects of land use on local terrestrial biodiversity', *Nature* 520(7545), 45–50 (doi: 10.1038/nature14324).

Potschin, M., Haines-Young, R. H., Fish, R. and Turner, R. K. (eds), 2016, *Routledge handbook of ecosystem services*, Routledge, Taylor & Francis Group, London; New York.

Rounsevell, M., Dawson, D. P. and Harrison, P. A., 2010, 'A conceptual framework to assess the effects of environmental change on ecosystem services', *Biodiversity and Conservation* 19, 2 823–2 842 (doi: 10.1007/s10531-010-9838-5).

Schulp, C. J. E., Burkhard, B., Maes, J., Van Vliet, J. and Verburg, P. H., 2014, 'Uncertainties in ecosystem service maps: A comparison on the European scale', *PLoS ONE* 9(10), e109643 (doi: 10.1371/journal.pone.0109643).

Chapter 5: Climate change impacts on society

Setion 5.1: Impacts of climate-related extremes

Barredo, J. I., 2009, 'Normalised flood losses in Europe: 1970–2006', *Natural Hazards and Earth System Sciences* 9, 97–104 (doi: 10.5194/nhess-9-97-2009).

Barredo, J. I., 2010, 'No upward trend in normalised windstorm losses in Europe: 1970–2008', *Natural Hazards and Earth System Science* 10(1), 97–104 (doi: 10.5194/nhess-10-97-2010).

Bindoff, N. L., Stott, P. A., Allen, M. R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Overland, J., Perlwitz, J., Sebbari, R. and Zhang, X., 2013, 'Detection and attribution of climate change: From global to regional', in: Mokhov, I. I., Stocker, T. F., Qin, D., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 867–952.

Bouwer, L. M., Bubeck, P. and Aerts, J. C. J. H., 2010, 'Changes in future flood risk due to climate and development in a Dutch polder area', *Global Environmental Change* 20(3), 463–471 (doi: 10.1016/j.gloenvcha.2010.04.002).

De Groeve, T., Poljansek, K. and Ehrlich, D., 2013, *Recording disaster losses recommendations for a European approach*, European Commission — Joint Research Centre: Institute for the Protection and the Security of the Citizen, Ispra.

De Groeve, T., Poljansek, K., Ehrlich, D. and Corbane, C., 2014, *Current status and best practices for disaster loss data recording in EU Member States*, European Commission — Joint Research Centre: Institute for the Protection and the Security of the Citizen, Ispra.

EC, 2013, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — An EU Strategy on adaptation to climate change, COM(2013) 216 final of 16 April 2013.

EEA, 2011, *Mapping the impacts of natural hazards and technological accidents in Europe*, EEA Technical report No 13/2010, European Environment Agency.

EU, 2002, Council Regulation (EC) No 2012/2002 of 11 November 2002 establishing the European Union Solidarity Fund, OJ L 311, 14.11.2002, pp. 3–8.

EU, 2013, Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism, OJ L 347, 20.12.2013, pp. 924–947.

EU, 2014, Regulation (EU) No 661/2014 of the European Parliament and of the Council of 15 May 2014 amending Council Regulation (EC) No 2012/2002 establishing the European Union Solidarity Fund, OJ L 189, 27.6.2014, pp. 143–154.

Feyen, L., Dankers, R., Bódis, K., Salamon, P. and Barredo, J. I., 2012, 'Fluvial flood risk in Europe in present and future climates', *Climatic Change* 112(1), 47–62 (doi: 10.1007/s10584-011-0339-7).

Forzieri, G., Bianchi, A., Marin Herrera, M. A., Batista e Silva, F., Feyen, L., Lavalle, C., European Commission, Joint Research Centre and Institute for the Protection and the Security of the Citizen, 2015, *Resilience of large investments and critical infrastructures in Europe to climate change*, Publications Office, Luxembourg.

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R. and Cid, A., 2016, 'Multi-hazard assessment in Europe under climate change', *Climatic Change* 137, 105–119 (doi: 10.1007/s10584-016-1661-x).

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014a, *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014b, *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IRDR, 2015, *Guidelines on measuring losses from disasters: Human and economic impact indicators*, DATA Project Report No 2, Integrated Research on Disaster Risk Programme, Beijing.

JRC, 2015, *Guidance for recording and sharing disaster damage and loss data: Towards the development of operational indicators to translate the Sendai Framework into action*, JRC Science and Policy Reports, Joint Research Centre, Institute for the Protection and Security of the Citizen and the EU expert working group on disaster damage and loss data, Ispra.

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

te Linde, A. H., Bubeck, P., Dekkers, J. E. C., de Moel, H. and Aerts, J. C. J. H., 2011, 'Future flood risk estimates along the river Rhine', *Natural Hazards and Earth System Science* 11(2), 459–473 (doi: 10.5194/nhess-11-459-2011).

Maaskant, B., Jonkman, S. N. and Bouwer, L. M., 2009, 'Future risk of flooding: An analysis of changes in potential loss of life in South Holland (The Netherlands)', *Environmental Science & Policy* 12(2), 157–169 (doi: 10.1016/j.envsci.2008.11.004).

OECD, 2014, *Improving the evidence base on the costs of disasters: Towards an OECD framework for accounting risk management expenditures and losses of disasters. 4th meeting of the OECD High Level Risk Forum*, GOV/PGC/HLRF(2014)8, OECD.

Rojas, R., Feyen, L. and Watkiss, P., 2013, 'Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation', *Global Environmental Change* 23(6), 1 737–1 751 (doi: 10.1016/j.gloenvcha.2013.08.006).

Thieken, A. H., Kienzler, S., Kreibich, H., Kuhlicke, C., Kunz, M., Mühr, B., Müller, M., Otto, A., Petrow, T., Pisi, S. and Schröter, K., 2016, 'Review of the flood risk management system in Germany after the major flood in 2013', *Ecology and Society* 21(2), 51 (doi: 10.5751/ES-08547-210251).

UN, 2015, Sendai Framework for Disaster Risk Reduction 2015–2030, A/RES/69/283, General Assembly, 69th session.

Visser, H., Bouwman, A., Petersen, A. and Ligtvoet, W., 2012, *Weather-related disasters: Past, present and future*, PBL publication 555076001, Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

WHO and PHE, 2013, *Floods in the WHO European region: Health effects and their prevention*, World Health Organization, Regional Office for Europe; Public Health England, United Kingdom.

Section 5.2: Human health

Ahmed, S. M., Lopman, B. A. and Levy, K., 2013, 'A systematic review and meta-analysis of the global seasonality of norovirus', *PLoS One* 8(10), e75922 (doi: 10.1371/journal.pone.0075922).

Aksoy, U., Akisu, C., Sahin, S., Usluca, S., Yalcin, G., Kuralay, F. and Oral, A. M., 2007, 'First reported waterborne outbreak of cryptosporidiosis with *Cyclospora* co-infection in Turkey', *Eurosurveillance* 12(7), Article 4.

Altizer, S., Ostfeld, R. S., Johnson, P. T. J., Kutz, S. and Harvell, C. D., 2013, 'Climate change and infectious diseases: From evidence to a predictive framework', *Science* 341(6145), 514–519 (doi: 10.1126/science.1239401).

Analitis, A., Georgiadis, I. and Katsouyanni, K., 2012, 'Forest fires are associated with elevated mortality in a dense urban setting', *Occupational and Environmental Medicine* 69(3), 158–162 (doi: 10.1136/oem.2010.064238).

Analitis, A., Katsouyanni, K., Biggeri, A., Baccini, M., Forsberg, B., Bisanti, L., Kirchmayer, U., Ballester, F., Cadum, E., Goodman, P. G., Hojs, A., Sunyer, J., Tiittanen, P. and Michelozzi, P., 2008, 'Effects of cold weather on mortality: Results from 15 European cities within the PHEWE project', *American Journal of Epidemiology* 168(12), 1 397–1 408 (doi: 10.1093/aje/kwn266).

Analitis, A., Michelozzi, P., D'Ippoliti, D., de'Donato, F., Menne, B., Matthies, F., Atkinson, R. W., Iñiguez, C., Basagaña, X., Schneider, A., Lefranc, A., Paldy, A., Bisanti, L. and Katsouyanni, K., 2014, 'Effects of heat waves on mortality: Effect modification and confounding by air pollutants', *Epidemiology* 25(1), 15–22 (doi: 10.1097/EDE.0b013e31828ac01b).

Arbuthnott, K., Hajat, S., Heaviside, C. and Vardoulakis, S., 2016, 'Changes in population susceptibility to heat and cold over time: Assessing adaptation to climate change', *Environmental Health* 15(S1), 33 (doi: 10.1186/s12940-016-0102-7).

Armitage, J. M., Quinn, C. L. and Wania, F., 2011, 'Global climate change and contaminants — An overview of opportunities and priorities for modelling the potential implications for long-term human exposure to organic compounds in the Arctic', *Journal of Environmental Monitoring* 13(6), 1 532–1 546 (doi: 10.1039/c1em10131e).

Aström, C., Orru, H., Rocklöv, J., Strandberg, G., Ebi, K. L. and Forsberg, B., 2013, 'Heat-related respiratory hospital admissions in Europe in a changing climate: A health impact assessment', *BMJ Open* 3(1), e001842 (doi: 10.1136/bmjopen-2012-001842).

Baccini, M., Kosatsky, T., Analitis, A., Anderson, H. R., D'Ovidio, M., Menne, B., Michelozzi, P., Biggeri, A. and PHEWE Collaborative Group, 2011, 'Impact of heat on mortality in 15 European cities: Attributable deaths under different weather scenarios', *Journal of Epidemiology and Community Health* 65(1), 64–70 (doi: 10.1136/jech.2008.085639).

Baker-Austin, C., Trinanes, J. A., Salmenlinna, S., Lofdahl, M., Siitonen, A., Taylor, N. G. H. and Martinez-Urtaza, J., 2016, 'Heatwave-associated vibriosis, Sweden and Finland, 2014', *Emerging Infectious Diseases* 22(7), 1 216–1 220 (doi: 10.32032/eid2207.151996).

Baker-Austin, C., Trinanes, J. A., Taylor, N. G. H., Hartnell, R., Siitonen, A. and Martinez-Urtaza, J., 2012, 'Emerging Vibrio risk at high latitudes in response to ocean warming', *Nature Climate Change* 3(1), 73–77 (doi: 10.1038/nclimate1628).

Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. and Garcia-Herrera, R., 2011, 'The hot summer of 2010: Redrawing the temperature record map of Europe', *Science* 332(6026), 220–224 (doi: 10.1126/science.1201224).

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J. and Medina-Ramón, M., 2011, 'Heat waves and cause-specific mortality at all ages', *Epidemiology (Cambridge, Mass.)* 22(6), 765–772 (doi: 10.1097/EDE.0b013e31823031c5).

Bittner, M.-I., Matthies, E. F., Dalbokova, D. and Menne, B., 2014, 'Are European countries prepared for the next big heat-wave?', *European Journal of Public Health* 24(4), 615–619 (doi: 10.1093/eurpub/ckt121).

Boeckmann, M. and Joyner, T. A., 2014, 'Old health risks in new places? An ecological niche model for I. ricinus tick distribution in Europe under a changing climate', *Health and Place* 30, 70–77 (doi: 10.1016/j.healthplace.2014.08.004).

Bosello, F., Nicholls, R. J., Richards, J., Roson, R. and Tol, R. S. J., 2011, 'Economic impacts of climate change in Europe: Sea-level rise', *Climatic Change* 112(1), 63–81 (doi: 10.1007/s10584-011-0340-1).

Breitner, S., Wolf, K., Peters, A. and Schneider, A., 2014, 'Short-term effects of air temperature on cause-specific cardiovascular mortality in Bavaria, Germany', *Heart (British Cardiac Society)* 100(16), 1 272–1 280 (doi: 10.1136/heartjnl-2014-305578).

Brown, L. and Murray, V., 2013, 'Examining the relationship between infectious diseases and flooding in Europe', *Disaster Health* 1(2), 117–127 (doi: 10.4161/dish.25216).

Burkart, K., Canário, P., Breitner, S., Schneider, A., Scherber, K., Andrade, H., Alcoforado, M. J. and Endlicher, W., 2013, 'Interactive short-term effects of equivalent temperature and air pollution on human mortality in Berlin and Lisbon', *Environmental Pollution (Barking, Essex: 1987)* 183, 54–63 (doi: 10.1016/j.envpol.2013.06.002).

Caminade, C., Kovats, S., Rocklov, J., Tompkins, A. M., Morse, A. P., Colon-Gonzalez, F. J., Stenlund, H., Martens, P. and Lloyd, S. J., 2014, 'Impact of climate change on global malaria distribution', *Proceedings of the National Academy of Sciences* 111(9), 3 286–3 291 (doi: 10.1073/pnas.1302089111).

Caminade, C., Medlock, J. M., Ducheyne, E., McIntyre, K. M., Leach, S., Baylis, M. and Morse, A. P., 2012, 'Suitability of European climate for the Asian tiger mosquito Aedes albopictus: Recent trends and future scenarios', *Journal of The Royal Society Interface* 9(75), 2 708–2 717 (doi: 10.1098/rsif.2012.0138).

Charrel, R. N., de Lamballerie, X. and Raoult, D., 2008, 'Seasonality of mosquitoes and chikungunya in Italy', *The Lancet Infectious Diseases* 8(1), 5–6.

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre, Institute for Prospective Technological Studies, Institute for Environment and Sustainability.

Ciscar, J. C., Iglesias, A., Feyen, L., Szabo, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O. B., Dankers, R., Garrote, L., Goodess, C. M., Hunt, A., Moreno, A., Richards, J. and Soria, A., 2011, 'Physical and economic consequences of climate change in Europe', *Proceedings of the National Academy of Sciences* 108(7), 2 678–2 683 (doi: 10.1073/pnas.1011612108).

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K. L., Hauengue, M., Kovats, R. S., Revich, B. and Woodward, A., 2007, 'Human health', in: Parry, M. L., Canziani, O. F., Palutikof, J. P., et al. (eds), *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, pp. 391–431.

Conza, L., Casati, S., Limoni, C. and Gaia, V., 2013, 'Meteorological factors and risk of community-acquired Legionnaires' disease in Switzerland: An epidemiological study', *BMJ Open* 3(3), e002428 (doi: 10.1136/bmjopen-2012-002428).

Coumou, D., Robinson, A. and Rahmstorf, S., 2013, 'Global increase in record-breaking monthly-mean temperatures', *Climatic Change* 118(3–4), 771–782 (doi: 10.1007/s10584-012-0668-1).

Craig, D., Fallowfield, H. J. and Cromar, N. J., 2003, 'Effectiveness of guideline faecal indicator organism values in estimation of exposure risk at recreational coastal sites', *Water Science and Technology* 47(3), 191–198.

CRED, 2016, *Disaster data: A balanced perspective*, Cred Crunch Newsletter No 41, CRED, Brussels.

Daniel, M., Danielova, V., Kriz, B., Jirsa, A. and Nozicka, J., 2003, 'Shift of the tick Ixodes ricinus and tick-borne encephalitis to higher altitudes in central Europe', *European Journal of Clinical Microbiology & Infectious Diseases* 22(5), 327–328 (doi: 10.1007/s10096-003-0918-2).

De Sario, M., Katsouyanni, K. and Michelozzi, P., 2013, 'Climate change, extreme weather events, air pollution and respiratory health in Europe', *European Respiratory Journal* 42(3), 826–843 (doi: 10.1183/09031936.00074712).

Dear, K. and Wang, Z., 2015, 'Climate and health: mortality attributable to heat and cold', *Lancet (London, England)* 386(9991), 320–322 (doi: 10.1016/S0140-6736(15)60897-2).

Delisle, E., Rousseau, C., Broche, B., Leparc-Goffart, I., L'ambert, G., Cochet, A., Prat, C., Foulongne, V., Ferré, J. B., Catelinois, O., Flusin, O., Tchernonog, E., Moussion, I. E., Wiegandt, A., Septfons, A., Mendy, A., Moyano, M. B., Laporte, L., Maurel, J. et al., 2015, 'Chikungunya outbreak in Montpellier, France, September to October 2014', *Eurosurveillance* 20(17), 21108 (doi: 10.2807/1560-7917.ES2015.20.17.21108).

D'Ippoliti, D., Michelozzi, P., Marino, C., de'Donato, F., Menne, B., Katsouyanni, K., Kirchmayer, U., Analitis, A., Medina-Ramón, M., Paldy, A., Atkinson, R., Kovats, S., Bisanti, L., Schneider, A., Lefranc, A., Iñiguez, C. and Perucci, C. A., 2010, 'The impact of heat waves on mortality in 9 European cities: Results from the EuroHEAT project', *Environmental Health: A Global Access Science Source* 9, 37 (doi: 10.1186/1476-069X-9-37).

Ebi, K. L. and Mills, D., 2013, 'Winter mortality in a warming climate: a reassessment: Winter mortality in a warming climate', *Wiley Interdisciplinary Reviews: Climate Change* 4(3), 203–212 (doi: 10.1002/wcc.211).

EC, 2013, *EU Strategy on adaptation to climate change*, COM(2013) 216, European Commission, Brussels.

ECDC, 2012, *The climatic suitability for dengue transmission in continental Europe*, ECDC Technical Report, European Centre for Disease Prevention and Control, Stockholm.

ECDC, 2013, *Dengue outbreak in Madeira, Portugal*, Mission Report, European Centre for Disease Prevention and Control, Stockholm.

ECDC, 2014, *Annual epidemiologic report 2014: Emerging and vector-borne diseases*, European Centre for Disease Prevention and Control, Stockholm.

ECDC, 2015, *Rapid risk assessment: Chikungunya case in Spain without travel history to endemic areas*, European Centre for Disease Prevention and Control, Stockholm.

ECDC, 2016, 'E3 Geoportal: Vibrio Tool' (https://e3geoportal.ecdc.europa.eu/SitePages/Vibrio%20Map%20Viewer.aspx) accessed 9 February 2016.

EEA, 2010, *The European environment — state and outlook 2010: Synthesis*, European Environment Agency.

EEA, 2011a, *Mapping the impacts of natural hazards and technological accidents in Europe*, EEA Technical report No 13/2010, European Environment Agency.

EEA, 2011b, *Safe water and healthy water services in a changing environment*, EEA Technical report No 7/2011, European Environment Agency.

EEA, 2015, 'Effects of climate change: Air pollution due to ozone and health impacts' (http://www.eea.europa.eu/data-and-maps/indicators/air-pollution-by-ozone-2/assessment) accessed 10 February 2016.

Estrada-Peña, A., Ayllón, N. and de la Fuente, J., 2012, 'Impact of climate trends on tick-borne pathogen transmission', *Frontiers in Physiology* 3, 64 (doi: 10.3389/fphys.2012.00064).

Estrada-Peña, A., Jameson, L., Medlock, J., Vatansever, Z. and Tishkova, F., 2012, 'Unraveling the ecological complexities of tick-associated crimean-congo hemorrhagic fever virus transmission: A gap analysis for the western palearctic', *Vector-Borne and Zoonotic Diseases* 12(9), 743–752 (doi: 10.1089/vbz.2011.0767).

Estrada-Pena, A., Ortega, C., Sanchez, N., DeSimone, L., Sudre, B., Suk, J. E. and Semenza, J. C., 2011, 'Correlation of Borrelia burgdorferi sensu lato prevalence in questing Ixodes ricinus ticks with specific abiotic traits in the Western Palearctic', *Applied and Environmental Microbiology* 77(11), 3 838–3 845 (doi: 10.1128/AEM.00067-11).

EU, 2013, Decision No 1082/2013/EU of the European Parliament and of the Council of 22 October 2013 on serious cross-border threats to health and repealing Decision No 2119/98/EC, OJ L 293, 5.11.2013, pp. 1-15.

Feyen, L. and Watkiss, P., 2011, *The impacts and economic costs of river floods in Europe, and the costs and benefits of adaptation. Results from the EC RTD ClimateCost Project. Final Report*, Technical Policy Briefing Note 3, Stockholm Environment Institute, Sweden.

Fischer, D., Moeller, P., Thomas, S. M., Naucke, T. J. and Beierkuhnlein, C., 2011, 'Combining climatic projections and dispersal ability: A method for estimating the responses of sandfly vector species to climate change', *PLoS Neglected Tropical Diseases* 5(11), e1407 (doi: 10.1371/journal.pntd.0001407).

Fischer, D., Thomas, S. M. and Beierkuhnlein, C., 2010, 'Temperature-derived potential for the establishment of phlebotomine sandflies and visceral leishmaniasis in Germany', *Geospatial Health* 5(1), 59–69.

Fischer, D., Thomas, S. M., Suk, J. E., Sudre, B., Hess, A., Tjaden, N. B., Beierkuhnlein, C. and Semenza, J. C., 2013, 'Climate change effects on chikungunya transmission in Europe: Geospatial analysis of vector's climatic suitability and virus' temperature requirements', *International Journal of Health Geographics* 12, 51 (doi: 10.1186/1476-072X-12-51).

Florescu, S. A., Popescu, C. P., Calistru, P., Ceausu, E., Nica, M., Toderan, A., Zaharia, M. and Parola, P., 2011, 'Plasmodium vivax malaria in a Romanian traveller returning from Greece, August 2011', *Eurosurveillance* 16(35), pii=19954.

Gale, P., Brouwer, A., Ramnial, V., Kelly, L., Kosmider, R., Fooks, A. R. and Snary, E. L., 2009, 'Assessing the impact of climate change on vector-borne viruses in the EU through the elicitation of expert opinion', *Epidemiology and Infection* 138(2), 214.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M. L., Guo, Y.-L. L., Wu, C., Kan, H., Yi, S.-M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P. H. N. et al., 2015, 'Mortality risk attributable to high and low ambient temperature: a multicountry observational study', *Lancet (London, England)* 386(9991), 369–375 (doi: 10.1016/S0140-6736(14)62114-0).

Gertler, M., Durr, M., Renner, P., Poppert, S., Askar, M., Breidenbach, J., Frank, C., Preussel, K., Schielke, A., Werber, D., Chalmers, R., Robinson, G., Feuerpfeil, I., Tannich, E., Groger, C., Stark, K. and Wilking, H., 2015, 'Outbreak of Cryptosporidium hominis following river flooding in the city of Halle (Saale), Germany, August 2013', *BMC Infectious Diseases* 15, 88 (doi: 10.1186/s12879-015-0807-1).

Gething, P. W., Smith, D. L., Patil, A. P., Tatem, A. J., Snow, R. W. and Hay, S. I., 2010, 'Climate change and the global malaria recession', *Nature* 465(7296), 342–345.

Gjenero-Margan, I., Aleraj, B., Krajcar, D., Lesnikar, V., Klobučar, A., Pem-Novosel, I., Kurečić-Filipović, S. and Mlinarić-Galinović, G., 2011, 'Autochthonous dengue fever in Croatia, August–September 2010', *Eurosurveillance* 16(9), pii=19805.

Gould, E. A. and Higgs, S., 2009, 'Impact of climate change and other factors on emerging arbovirus diseases', *Transactions of the Royal Society of Tropical Medicine and Hygiene* 103(2), 109–121.

Gouriet, F., Rolain, J. M. and Raoult, D., 2006, 'Rickettsia slovaca infection, France', *Emerging Infectious Diseases* 12(3), 521–523.

Grandadam, M., Caro, V., Plumet, S., Thiberge, J.-M., Souarès, Y., Failloux, A.-B., Tolou, H. J., Budelot, M., Cosserat, D., Leparc-Goffart, I. and Desprès, P., 2011, 'Chikungunya Virus, Southeastern France', *Emerging Infectious Diseases* 17(5), 910–913 (doi: 10.3201/eid1705.101873).

Hales, S., Kovats, S., Lloyd, S. and Campbell-Lendrum, D., 2014, *WHO | Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*, World Health Organization, Geneva.

Healy, J. D., 2003, 'Excess winter mortality in Europe: A cross country analysis identifying key risk factors', *Journal of Epidemiology & Community Health* 57(10), 784–789 (doi: 10.1136/jech.57.10.784).

Heinz, F. X., Stiasny, K., Holzmann, H., Kundi, M., Six, W., Wenk, M., Kainz, W., Essl, A. and Kunz, C., 2015, 'Emergence of tick-borne encephalitis in new endemic areas in Austria: 42 years of surveillance', *Eurosurveillance* 20(13), 21 077 (doi: /10.2807/1560-7917.ES2015.20.13.21077).

Hemmer, C. J., Frimmel, S., Kinzelbach, R., Gurtler, L. and Reisinger, E. C., 2007, ‚Global warming: Trailblazer for tropical infections in Germany?', *Deutsche medizinische Wochenschrift* 132(48), 2 583–2 589.

Hoek, M. R., Oliver, I., Barlow, M., Heard, L., Chalmers, R. and Paynter, S., 2008, 'Outbreak of *Cryptosporidium parvum* among children after a school excursion to an adventure farm, south west England', *Journal of Water and Health* 6(3), 333–338 (doi: 10.2166/wh.2008.060).

Holmér, I., Hassi, J., Ikäheimo, T. M. and Jaakkola, J. J. K., 2012, 'Cold stress: Effects on performance and health', in: Bingham, E., Cohrssen, B., and Powell, C. H. (eds), *Patty's Toxicology*, John Wiley & Sons, Inc., Hoboken, NJ, pp. 1–26.

Holt, E., 2014, 'Disease outbreaks predicted in flood-ravaged Balkans', *The Lancet* 383(9933), 1959 (doi: 10.1016/S0140-6736(14)60940-5).

Honda, Y., Kondo, M., McGregor, G., Kim, H., Guo, Y.-L., Hijioka, Y., Yoshikawa, M., Oka, K., Takano, S., Hales, S. and Kovats, R. S., 2014, 'Heat-related mortality risk model for climate change impact projection', *Environmental Health and Preventive Medicine* 19(1), 56–63 (doi: 10.1007/s12199-013-0354-6).

Hov, Ø., Cubasch, U., Fischer, E., Höppe, P., Iversen, T., Kvamstø, N. G., Kundzewicz, Z. W., Rezacova, D., Rios, D., Duarte Santos, F., Schädler, B., Veisz, O., Zerefos, C., Benestad, R., Murlis, J., Donat, M., Leckebusch, G. C. and Ulbrich, U., 2013, *Extreme weather events in Europe: Preparing for climate change adaptation*, Norwegian Meteorological Institute, Oslo.

Huang, C., Barnett, A. G., Wang, X., Vaneckova, P., FitzGerald, G. and Tong, S., 2011, 'Projecting future heat-related mortality under climate change scenarios: A systematic review', *Environmental Health Perspectives* 119(12), 1 681–1 690 (doi: 10.1289/ehp.1103456).

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation — Special report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013, *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014a, *Climate change 2014: Impacts, adaptation and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

IPCC, 2014b, *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge; New York.

Jaenson, T. G. T., Jaenson, D. G. E., Eisen, L., Petersson, E. and Lindgren, E., 2012, 'Changes in the geographical distribution and abundance of the tick Ixodes ricinus during the past 30 years in Sweden', *Parasites and Vectors* 5(1), 8 (doi: 10.1186/1756-3305-5-8).

Jaenson, T. G. T. and Lindgren, E., 2011, 'The range of Ixodes ricinus and the risk of contracting Lyme borreliosis will increase northwards when the vegetation period becomes longer', *Ticks and Tick-borne Diseases* 2(1), 44–49.

Jones, K., Patel, N., Levy, M., Storeygard, A., Balk, D., Gittleman, J. and Daszak, P., 2008, 'Global trends in emerging infectious diseases', *Nature* 451, 990–994.

Josseran, L., Caillère, N., Brun-Ney, D., Rottner, J., Filleul, L., Brucker, G. and Astagneau, P., 2009, 'Syndromic surveillance and heat wave morbidity: A pilot study based on emergency departments in France', *BMC Medical Informatics and Decision Making* 9, 14 (doi: 10.1186/1472-6947-9-14).

Katsouyanni, K. and Analitis, A., 2009, 'Investigating the synergistic effects between meteorological variables and air pollutants: Results from the European PHEWE, EUROHEAT and CIRCE Projects', *Epidemiology* 20, S264 (doi: 10.1097/01.ede.0000362883.27030.8f).

Kinney, P. L., Schwartz, J., Pascal, M., Petkova, E., Tertre, A. L., Medina, S. and Vautard, R., 2015, 'Winter season mortality: Will climate warming bring benefits?', *Environmental Research Letters* 10(6), 64 016 (doi: 10.1088/1748-9326/10/6/064016).

Kirch, W., Menne, B. and Bertollini, R. (eds), 2005, *Extreme weather events and public health responses*, Springer, Berlin; Heidelberg; New York.

Kovats, R. S., Edwards, S. J., Charron, D., Cowden, J., D'Souza, R. M., Ebi, K. L., Gauci, C., Gerner-Smidt, P., Hajat, S., Hales, S., Hernandez Pezzi, G., Kriz, B., Kutsar, K., McKeown, P., Mellou, K., Menne, B., O'Brien, S., van Pelt, W. and Schmid, H., 2005, 'Climate variability and campylobacter infection: An international study', *International Journal of Biometeorology* 49(4), 207–214 (doi: 10.1007/s00484-004-0241-3).

Kovats, R. S., Lloyd, S., Hunt, A. and Watkiss, P., 2011, *The impacts and economic costs on health in Europe and the costs and benefits of adaptation. Results of the EC RTD ClimateCost Project. Final Report*, The ClimateCost Project. Volume 1: Europe, Stockholm Environment Institute, Sweden.

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Kundzewicz, Z. W., Pińskwar, I. and Brakenridge, G. R., 2013, 'Large floods in Europe, 1985–2009', *Hydrological Sciences Journal* 58(1), 1–7 (doi: 10.1080/02626667.2012.745082).

La Ruche, G., Souares, Y., Armengaud, A., Peloux-Petiot, F., Delaunay, P., Despres, P. and Gastellu-Etchegorry, M., 2010, 'First two autochthonous dengue virus infections in metropolitan France, September 2010', *Eurosurveillance* 15(39), pii=19676.

Lindgren, E., Andersson, Y., Suk, J. E., Sudre, B. and Semenza, J. C., 2012, 'Monitoring EU emerging infectious disease risk due to climate change', *Science* 336(6080), 418–419 (doi: 10.1126/science.1215735).

Louis, V. R., Gillespie, I. A., O'Brien, S. J., Russek-Cohen, E., Pearson, A. D. and Colwell, R. R., 2005, 'Temperature-driven Campylobacter seasonality in England and Wales', *Applied and Environmental Microbiology* 71(1), 85–92 (doi: 10.1128/aem.71.1.85-92.2005).

Lucas, R. A. I., Epstein, Y. and Kjellstrom, T., 2014, 'Excessive occupational heat exposure: A significant ergonomic challenge and health risk for current and future workers', *Extreme Physiology & Medicine* 3(1), 14 (doi: 10.1186/2046-7648-3-14).

Ludwig, R., Roson, R., Zografos, C. and Kallis, G., 2011, 'Towards an inter-disciplinary research agenda on climate change, water and security in Southern Europe and neighboring countries', *Environmental Science & Policy* 14(7), 794–803 (doi: 10.1016/j.envsci.2011.04.003).

Lung, T., Lavalle, C., Hiederer, R., Dosio, A. and Bouwer, L. M., 2013, 'A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change', *Global Environmental Change* 23(2), 522–536 (doi: 10.1016/j.gloenvcha.2012.11.009).

Maltezou, H. C. and Papa, A., 2010, 'Crimean–Congo hemorrhagic fever: Risk for emergence of new endemic foci in Europe?', *Travel Medicine and Infectious Disease* 8(3), 139–143.

Marcantonio, M., Rizzoli, A., Metz, M., Rosa, R., Marini, G., Chadwick, E. and Neteler, M., 2015, 'Identifying the environmental conditions favouring West Nile Virus outbreaks in Europe', *PLoS One* 10(3), e0121158 (doi: 10.1371/journal.pone.0121158).

Maroli, M., Rossi, L., Baldelli, R., Capelli, G., Ferroglio, E., Genchi, C., Gramiccia, M., Mortarino, M., Pietrobelli, M. and Gradoni, L., 2008, 'The northward spread of leishmaniasis in Italy: Evidence from retrospective and ongoing studies on the canine reservoir and phlebotomine vectors', *Tropical Medicine & International Health* 13(2), 256–264 (doi: 10.1111/j.1365–3156.2007.01998.x).

Marshall, J. A. and Bruggink, L. D., 2011, 'The dynamics of norovirus outbreak epidemics: Recent insights', *International Journal of Environmental Research and Public Health* 8(4), 1 141–1 149 (doi: 10.3390/ijerph8041141).

Martinez-Urtaza, J., Saco, M., de Novoa, J., Perez-Pineiro, P., Peiteado, J., Lozano-Leon, A. and Garcia-Martin, O., 2004, 'Influence of environmental factors and human activity on the presence of *Salmonella* serovars in a marine environment', *Applied and Environmental Microbiology* 70(4), 2 089–2 097 (doi: 10.1128/AEM.70.4.2089-2097.2004).

McMichael, A. J., 2013, 'Globalization, climate change, and human health', *New England Journal of Medicine* 368(14), 1 335–1 343.

McMichael, T., Montgomery, H. and Costello, A., 2012, 'Health risks, present and future, from global climate change', *British Medical Journal* 344, e1359 (doi: 10.1136/bmj.e1359).

Medlock, J. M., Hansford, K. M., Bormane, A., Derdakova, M., Estrada-Peña, A., George, J. C., Golovljova, I., Jaenson, T. G. T., Jensen, J. K., Jensen, P. M., Kazimirova, M., Oteo, J. A., Papa, A., Pfister, K., Plantard, O., Randolph, S. E., Rizzoli, A., Santos-Silva, M. M., Sprong, H. et al., 2013, 'Driving forces for changes in geographical distribution of Ixodes ricinus ticks in Europe', *Parasites and Vectors* 6, 1 (doi: 10.1186/1756-3305-6-1).

Medlock, J. M. and Leach, S. A., 2015, 'Effect of climate change on vector-borne disease risk in the UK', *The Lancet Infectious Diseases* 15(6), 721–730 (doi: 10.1016/S1473-3099(15)70091-5).

Miossec, L., Le Guyader, F., Haugarreau, L. and Pommepuy, M., 2000, 'Magnitude of rainfall on viral contamination of the marine environment during gastroenteritis epidemics in human coastal population', *Revue d'Épidémiologie et de Santé Publique* 48(2), S62–S71.

Naumova, E. N., Jagai, J. S., Matyas, B., De Maria, A., MacNeill, I. B. and Griffiths, J. K., 2006, 'Seasonality in six enterically transmitted diseases and ambient temperature', *Epidemiology and Infection* 135(2), 281 (doi: 10.1017/S0950268806006698).

Nichols, G. L., Richardson, J. F., Sheppard, S. K., Lane, C. and Sarran, C., 2012, 'Campylobacter epidemiology: A descriptive study reviewing 1 million cases in England and Wales between 1989 and 2011', *BMJ Open* 2(4), e001179 (doi: 10.1136/bmjopen-2012-001179).

Nichols, G., Lane, C., Asgari, N., Verlander, N. Q. and Charlett, A., 2009, 'Rainfall and outbreaks of drinking water related disease and in England and Wales', *Journal of Water and Health* 7(1), 1–8 (doi: 10.2166/wh.2009.143).

Nylen, G., Dunstan, F., Palmer, S. R., Andersson, Y., Bager, F., Cowden, J., Feierl, G., Galloway, Y., Kapperud, G., Megraud, F., Molbak, K., Petersen, L. R. and Ruutu, P., 2002, 'The seasonal distribution of campylobacter infection in nine European countries and New Zealand', *Epidemiology and Infection* 128(3), 383–390.

Ostfeld, R. S. and Brunner, J. L., 2015, 'Climate change and Ixodes tick-borne diseases of humans', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1665), 1–11 (doi: 10.1098/rstb.2014.0051).

Paci, D., 2014, *Human health impacts of climate change in Europe. Report for the PESETA II project*, Report EUR 26494EN, Joint Research Centre, European Commission, Seville.

Parham, P. E., Waldock, J., Christophides, G. K., Hemming, D., Agusto, F., Evans, K. J., Fefferman, N., Gaff, H., Gumel, A., Ladeau, S., Lenhart, S., Mickens, R. E., Naumova, E. N., Ostfeld, R. S., Ready, P. D., Thomas, M. B., Velasco-Hernandez, J. and Michael, E., 2015, 'Climate, environmental and socio-economic change: Weighing up the balance in vector-borne disease transmission', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1665), 1–17 (doi: 10.1098/rstb.2013.0551).

Paz, S., Malkinson, D., Green, M. S., Tsioni, G., Papa, A., Danis, K., Sirbu, A., Ceianu, C., Katalin, K., Ferenczi, E., Zeller, H. and Semenza, J. C., 2013, 'Permissive summer temperatures of the 2010 European West Nile fever upsurge', *PLoS One* 8(2), e56398 (doi: 10.1371/journal.pone.0056398).

Paz, S. and Semenza, J. C., 2013, 'Environmental drivers of West Nile fever epidemiology in Europe and Western Asia — A review', *International Journal of Environmental Research and Public Health* 10(8), 3 543–3 562 (doi: 10.3390/ijerph10083543).

Petersen, L. R., Brault, A. C. and Nasci, R. S., 2013, 'West Nile virus: Review of the literature', *JAMA* 310(3), 308–315 (doi: 10.1001/jama.2013.8042).

Porretta, D., Mastrantonio, V., Amendolia, S., Gaiarsa, S., Epis, S., Genchi, C., Bandi, C., Otranto, D. and Urbanelli, S., 2013, 'Effects of global changes on the climatic niche of the tick Ixodes ricinus inferred by species distribution modelling', *Parasites and Vectors* 6, 271 (doi: 10.1186/1756-3305-6-271).

Proestos, Y., Christophides, G. K., Ergüler, K., Tanarhte, M., Waldock, J. and Lelieveld, J., 2015, 'Present and future projections of habitat suitability of the Asian tiger mosquito, a vector of viral pathogens, from global climate simulation', *Philosophical Transactions of the Royal Society B: Biological Sciences* 370(1665), 1–16 (doi: 10.1098/rstb.2013.0554).

Radovic, V., Vitale, K. and Tchounwou, P. B., 2012, 'Health facilities safety in natural disasters: Experiences and challenges from South East Europe', *International Journal of Environmental Research and Public Health* 9(5), 1 677–1 686 (doi: 10.3390/ijerph9051677).

Randolph, S. E., 2008, 'Tick-borne encephalitis incidence in Central and Eastern Europe: Consequences of political transition', *Microbes and Infection* 10(3), 209–216.

Randolph, S. E. and Rogers, D. J., 2010, 'The arrival, establishment and spread of exotic diseases: Patterns and predictions', *Nature Reviews Microbiology* 8(5), 361–371.

Ready, P. D., 2010, 'Leishmaniasis emergence in Europe', *Eurosurveillance* 15(10), pii=19505.

Rezza, G., Nicoletti, L., Angelini, R., Romi, R., Finarelli, A., Panning, M., Cordioli, P., Fortuna, C., Boros, S., Magurano, F., Silvi, G., Angelini, P., Dottori, M., Ciufolini, M., Majori, G. and Cassone, A., 2007, 'Infection with chikungunya virus in Italy: An outbreak in a temperate region', *The Lancet* 370(9602), 1 840–1 846 (doi: 10.1016/S0140-6736(07)61779-6).

Robine, J.-M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.-P. and Herrmann, F. R., 2008, 'Death toll exceeded 70,000 in Europe during the summer of 2003', *Comptes Rendus Biologies* 331(2), 171–178 (doi: 10.1016/j.crvi.2007.12.001).

Rodó, X., Pascual, M., Doblas-Reyes, F. J., Gershunov, A., Stone, D. A., Giorgi, F., Hudson, P. J., Kinter, J., Rodríguez-Arias, M. À., Stenseth, N. C., Alonso, D., García-Serrano, J. and Dobson, A. P., 2013, 'Climate change and infectious diseases: Can we meet the needs for better prediction?', *Climatic Change* 118(3–4), 625–640 (doi: 10.1007/s10584-013-0744-1).

Rogers, D. J., Suk, J. E. and Semenza, J. C., 2014, 'Using global maps to predict the risk of dengue in Europe', *Acta Tropica* 129(1), 1–14 (doi: 10.1016/j.actatropica.2013.08.008).

Roiz, D., Neteler, M., Castellani, C., Arnoldi, D. and Rizzoli, A., 2011, 'Climatic factors driving invasion of the tiger mosquito (*Aedes albopictus*) into new areas of Trentino, northern Italy', *Public Library of Science ONE* 6(4), e14800 (doi: 10.1371/journal.pone.0014800).

Rojas, R., Feyen, L., Bianchi, A. and Dosio, A., 2012, 'Assessment of future flood hazard in Europe using a large ensemble of bias corrected regional climate simulations', *Journal of Geophysical Research* 117, D17109 (doi: 10.1029/2012JD017461).

Rojas, R., Feyen, L. and Watkiss, P., 2013, 'Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation', *Global Environmental Change* 23(6), 1 737–1 751 (doi: 10.1016/j.gloenvcha.2013.08.006).

Ryti, N. R. I., Guo, Y. and Jaakkola, J. J. K., 2015, 'Global association of cold spells and adverse health effects: A systematic review and meta-analysis', *Environmental Health Perspectives* 124(1), 12–22 (doi: 10.1289/ehp.1408104).

Schmid, D., Lederer, I., Much, P., Pichler, A.-M. and Allerberger, F., 2005, 'Outbreak of norovirus infection associated with contaminated flood water, Salzburg, 2005', *Eurosurveillance* 10(24), pii=2727.

Semenza, J. C., Herbst, S., Rechenburg, A., Suk, J. E., Hoser, C., Schreiber, C. and Kistemann, T., 2012, 'Climate change impact assessment of food- and waterborne diseases', *Critical Reviews in Environmental Science and Technology* 42(8), 857–890 (doi: 10.1080/10643389.2010.534706).

Semenza, J. C., Houser, C., Herbst, S., Rechenburg, A., Suk, J. E., Frechen, T. and Kistemann, T., 2012, 'Knowledge mapping for climate change and food- and waterborne diseases', *Critical Reviews in Environmental Science and Technology* 42(4), 378–411 (doi: 10.1080/10643389.2010.518520).

Semenza, J. C. and Menne, B., 2009, 'Climate change and infectious diseases in Europe', *The Lancet Infectious Diseases* 9(6), 365–375 (doi: 10.1016/S1473-3099(09)70104-5).

Semenza, J. C., Sudre, B., Miniota, J., Rossi, M., Hu, W., Kossowsky, D., Suk, J. E., Van Bortel, W. and Khan, K., 2014, 'International dispersal of dengue through air travel: Importation risk for Europe', *PLoS Neglected Tropical Diseases* 8(12), e3278 (doi: 10.1371/journal.pntd.0003278).

Semenza, J. C., Tran, A., Espinosa, L., Sudre, B., Domanovic, D. and Paz, S., 2016, 'Climate change projections of West Nile virus infections in Europe: Implications for blood safety practices', *Environmental Health* 15(1), 125–136 (doi: 10.1186/s12940-016-0105-4).

Sinisi, L. and Aertgeerts, R. (eds), 2011, *Guidance on water cupply and sanitation in extreme weather events*, World Health Organization, Geneva.

Stanke, C., Murray, V., Amlôt, R., Nurse, J. and Williams, R., 2012, 'The effects of flooding on mental health: Outcomes and recommendations from a review of the literature', *Public Library of Science Currents Disasters* 1 (doi: 10.1371/4f9f1fa9c3cae).

Sterk, A., Schets, F. M., de Roda Husman, A. M., de Nijs, T. and Schijven, J. F., 2015, 'Effect of climate change on the concentration and associated risks of Vibrio spp. in Dutch recreational waters', *Risk Analysis* 35(9), 1 717–1 729 (doi: 10.1111/risa.12365).

Sudre, B., Rossi, M., Van Bortel, W., Danis, K., Baka, A., Vakalis, N. and Semenza, J. C., 2013, 'Mapping environmental suitability for malaria transmission, Greece', *Emerging Infectious Diseases* 19(5), 784–786 (doi: 10.3201/eid1905.120811).

Suk, J. E., Ebi, K. L., Vose, D., Wint, W., Alexander, N., Mintiens, K. and Semenza, J. C., 2014, 'Indicators for tracking European vulnerabilities to the risks of infectious disease transmission due to climate change', *International Journal of Environmental Research and Public Health* 11(2), 2 218–2 235 (doi: 10.3390/ijerph110202218).

Suk, J. E. and Semenza, J. C., 2011, 'Future infectious disease threats to Europe', *American Journal of Public Health* 101(11), 2 068–2 079 (doi: 10.2105/AJPH.2011.300181).

Süss, J., Klaus, C., Diller, R., Schrader, C., Wohanka, N. and Abel, U., 2006, 'TBE incidence versus virus prevalence and increased prevalence of the TBE virus in Ixodes ricinus removed from humans', *International Journal of Medical Microbiology* 296, 63–68.

Tam, C. C., Rodrigues, L. C., O'Brien, S. J. and Hajat, S., 2006, 'Temperature dependence of reported Campylobacter infection in England, 1989–1999', *Epidemiology and Infection* 134(1), 119–125 (doi: 10.1017/s0950268805004899).

Teran, T., Lamon, L. and Marcomini, A., 2012, 'Climate change effects on POPs' environmental behavior: A scientific perspective for future regulatory actions', *Atmospheric Pollution Research* 3(4), 466–476 (doi: 10.5094/APR.2012.054).

Trájer, A. J., Bede-Fazekas, Á., Hufnagel, L., Horváth, L., Bobvos, J. and Páldy, A., 2013, 'The effect of climate change on the potential distribution of the european phlebotomus species', *Applied Ecology and Environmental Research* 11(2), 189–208.

Tran, A., Sudre, B., Paz, S., Rossi, M., Desbrosse, A., Chevalier, V. and Semenza, J. C., 2014, 'Environmental predictors of West Nile fever risk in Europe', *International Journal of Health Geographics* 13, 26 (doi: 10.1186/1476-072x-13-26).

UN, 2015, 'Sendai Framework for Disaster Risk Reduction 2015–2030' (http://www.wcdrr.org/preparatory/post2015) accessed 12 August 2015.

Van Bortel, W., Dorleans, F., Rosine, J., Blateau, A., Rousseau, D., Matheus, S., Leparc-Goffart, I., Flusin, O., Prat, C. M., Césaire, R., Najioullah, F., Ardillon, V., Balleydier, E., Carvalho, L., Lemaître, A., Noël, H., Servas, V., Six, C., Zurbaran, M. et al., 2014, 'Chikungunya outbreak in the Caribbean region, December 2013 to March 2014, and the significance for Europe', *Eurosurveillance* 19(13), 20759 (doi: 10.2807/1560-7917.ES2014.19.13.20759).

Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C. and Eggen, B., 2014, 'Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia', *Environmental Health Perspectives* 122(12), 1 285–1 292 (doi: 10.1289/ehp.1307524).

Vezzulli, L., Grande, C., Reid, P. C., Hélaouët, P., Edwards, M., Höfle, M. G., Brettar, I., Colwell, R. R. and Pruzzo, C., 2016, 'Climate influence on Vibrio and associated human diseases during the past half-century in the coastal North Atlantic', *Proceedings of the National Academy of Sciences* 113(34), E5062–E5071 (doi: 10.1073/pnas.1609157113).

Visser, H., Bouwman, A., Petersen, A. and Ligtvoet, W., 2012, *Weather-related disasters: Past, present and future*, PBL publication 555076001, Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

Wardekker, J. A., de Jong, A., van Bree, L., Turkenburg, W. C. and van der Sluijs, J. P., 2012, 'Health risks of climate change: An assessment of uncertainties and its implications for adaptation policies', *Environmental Health* 11(1), 67 (doi: 10.1186/1476-069X-11-67).

Watkiss, P. and Hunt, A., 2012, 'Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: Human health', *Climatic Change* 112(1), 101–126 (doi: 10.1007/s10584-011-0342-z).

Watts, N., Adger, W. N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P. M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A. et al., 2015, 'Health and climate change: Policy responses to protect public health', *The Lancet* 386(10006), 1 861–1 914 (doi: 10.1016/S0140-6736(15)60854-6).

WHO, 2008, Climate change and health, WHA61/2008/REC/1, Resolution WHA61.19.

WHO, 2010a, Commitment to Act, EUR/55934/5.2 Rev. 2.

WHO, 2010b, Parma Declaration on Environment and Health, EUR/55934/5.1 Rev. 2.

WHO, 2011, *Public health advice on preventing health effects of heat*, World Health Organization, Regional Office for Europe, Copenhagen.

WHO, 2014, Health and the environment. Climate and health: Outcome of the WHO Conference on Health and Climate, EB136/16.

WHO, 2015, *Improving environment and health in Europe: How far have we gotten*, World Health Organization, Regional Office for Europe, Copenhagen.

WHO and PHE, 2013, *Floods in the WHO European Region: Health effects and their prevention*, World Health Organization, Regional Office for Europe; Public Health England, United Kingdom.

Widerstrom, M., Schonning, C., Lilja, M., Lebbad, M., Ljung, T., Allestam, G., Ferm, M., Bjorkholm, B., Hansen, A., Hiltula, J., Langmark, J., Lofdahl, M., Omberg, M., Reuterwall, C., Samuelsson, E., Widgren, K., Wallensten, A. and Lindh, J., 2014, 'Large outbreak of Cryptosporidium hominis infection transmitted through the public water supply, Sweden', *Emerging Infectious Diseases* 20(4), 581–589 (doi: 10.3201/eid2004.121415).

WMO and WHO, 2015, *Heatwaves and health: guidance on warning-system development*, World Meteorological Organization and World Health Organization, Geneva.

Wolf, T., Lyne, K., Martinez, G. S. and Kendrovski, V., 2015, 'The health effects of climate change in the WHO European Region', *Climate* 3(4), 901–936 (doi: 10.3390/cli3040901).

Ye, X., Wolff, R., Yu, W., Vaneckova, P., Pan, X. and Tong, S., 2011, 'Ambient temperature and morbidity: A review of epidemiological evidence', *Environmental Health Perspectives* 120(1), 19–28 (doi: 10.1289/ehp.1003198).

Zhang, Y., Bi, P. and Hiller, J., 2007, 'Climate variations and salmonellosis transmission in Adelaide, South Australia: A comparison between regression models', *International Journal of Biometeorology* 52(3), 179–187 (doi: 10.1007/s00484-007-0109-4).

Zolina, O., Simmer, C., Gulev, S. and Kollet, S., 2010, 'Changing structure of European precipitation: Longer wet periods leading to more abundant rainfalls', *Geophysical Research Letters* 37, 1–5.

Section 5.3: Agriculture

Ainsworth, E. A. and Long, S. P., 2005, 'What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2', *New Phytologist* 165, 351–372 (doi: 10.1111/j.1469-8137.2004.01224.x).

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P. J., Rötter, R. P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P. K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A. J., Doltra, J. et al., 2013, 'Uncertainty in simulating wheat yields under climate change', *Nature Climate Change* 3(9), 827–832 (doi: 10.1038/nclimate1916).

Audsley, E., Pearn, K. R., Simota, C., Cojocaru, G., Koutsidou, E., Rounsevell, M. D. A., Trnka, M. and Alexandrov, V., 2006, 'What can scenario modelling tell us about future European scale agricultural land use, and what not?', *Environmental Science & Policy* 9(2), 148–162 (doi: 10.1016/j.envsci.2005.11.008).

aus der Beek, T., Flörke, M., Lapola, D. M., Schaldach, R., Voß, F. and Teichert, E., 2010, 'Modelling historical and current irrigation water demand on the continental scale: Europe', *Advances in Geosciences* 27, 79–85 (doi: 10.5194/adgeo-27-79-2010).

Bindi, M. and Olesen, J. E., 2011, 'The responses of agriculture in Europe to climate change', *Regional Environmental Change* 11, 151–158 (doi: 10.1007/s10113-010-0173-x).

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X. and Huard, F., 2010, 'Why are wheat yields stagnating in Europe? A comprehensive data analysis for France', *Field Crops Research* 119(1), 201–212 (doi: 10.1016/j.fcr.2010.07.012).

Broom, D. M., Galindo, F. A. and Murgueitio, E., 2013, 'Sustainable, efficient livestock production with high biodiversity and good welfare for animals', *Proceedings of the Royal Society B: Biological Sciences* 280(1771), 20132025 (doi: 10.1098/rspb.2013.2025).

Camps, J. O. and Ramos, M. C., 2012, 'Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-east Spain with a Mediterranean climate', *International Journal of Biometeorology* 56(5), 853–864 (doi: 10.1007/s00484-011-0489-3).

Caubel, J., García de Cortázar-Atauri, I., Launay, M., de Noblet-Ducoudré, N., Huard, F., Bertuzzi, P. and Graux, A.-I., 2015, 'Broadening the scope for ecoclimatic indicators to assess crop climate suitability according to ecophysiological, technical and quality criteria', *Agricultural and Forest Meteorology* 207, 94–106 (doi: 10.1016/j.agrformet.2015.02.005).

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R. and Chhetri, N., 2014, 'A meta-analysis of crop yield under climate change and adaptation', *Nature Climate Change* 4(4), 287–291 (doi: 10.1038/nclimate2153).

Chang, J., Viovy, N., Vuichard, N., Ciais, P., Campioli, M., Klumpp, K., Martin, R., Leip, A. and Soussana, J.-F., 2015, 'Modeled changes in potential grassland productivity and in grass-fed ruminant livestock density in Europe over 1961–2010', *PLoS ONE* 10(5), e0127554 (doi: 10.1371/journal.pone.0127554).

Chmielewski, F.-M., Müller, A. and Bruns, E., 2004, 'Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000', *Agricultural and Forest Meteorology* 121(1–2), 69–78 (doi: 10.1016/S0168-1923(03)00161-8).

Ciscar, J.-C., Iglesias, A., Feyen, L., Szabo, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O. B., Dankers, R., Garrote, L., Goodess, C. M., Hunt, A., Moreno, A., Richards, J. and Soria, A., 2011, 'Physical and economic consequences of climate change in Europe', *Proceedings of the National Academy of Sciences* 108(7), 2 678–2 683 (doi: 10.1073/pnas.1011612108).

Dunn, R. J. H., Mead, N. E., Willett, K. M. and Parker, D. E., 2014, 'Analysis of heat stress in UK dairy cattle and impact on milk yields', *Environmental Research Letters* 9(6), 64006 (doi: 10.1088/1748-9326/9/6/064006).

EEA, 2009, *Water resources across Europe — Confronting water scarcity and drought*, EEA Report No 2/2009, European Environment Agency.

Elsgaard, L., Børgesen, C. D., Olesen, J. E., Siebert, S., Ewert, F., Peltonen-Sainio, P., Rötter, R. P. and Skjelvåg, A. O., 2012, 'Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe', *Food Additives & Contaminants: Part A* 29(10), 1 514–1 526 (doi: 10.1080/19440049.2012.700953).

Eurostat, 2016, Eurostat Database, European Commission, Eurostat.

Ewert, F., Rötter, R. P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K. C., Olesen, J. E., van Ittersum, M. K., Janssen, S., Rivington, M., Semenov, M. A., Wallach, D., Porter, J. R., Stewart, D., Verhagen, J., Gaiser, T., Palosuo, T., Tao, F., Nendel, C. et al., 2015, 'Crop modelling for integrated assessment of risk to food production from climate change', *Environmental Modelling & Software* 72, 287–303 (doi: 10.1016/j.envsoft.2014.12.003).

Eyshi Rezaei, E., Webber, H., Gaiser, T., Naab, J. and Ewert, F., 2015, 'Heat stress in cereals: Mechanisms and modelling', *European Journal of Agronomy* 64, 98–113 (doi: 10.1016/j.eja.2014.10.003).

Falloon, P. and Betts, R., 2010, 'Climate impacts on European agriculture and water management in the context of adaptation and mitigation—The importance of an integrated approach', *Science of The Total Environment* 408(23), 5 667–5 687 (doi: 10.1016/j.scitotenv.2009.05.002).

FAO, 2016, FAOSTAT database, Food and Agriculture Organization of the United Nations.

Ferrise, R., Moriondo, M. and Bindi, M., 2011, 'Probabilistic assessments of climate change impacts on durum wheat in the Mediterranean region', *Natural Hazards and Earth System Sciences* 11(5), 1 293–1 302 (doi: 10.5194/nhess-11-1293-2011).

Frank, S., Witzke, H., Zimmermann, A., Havlík, P. and Ciaian, P., 2014, 'Climate change impacts on European agriculture: A multi model perspective', conference paper presented at: EAAE 2014 Congress: Agri-Food and Rural Innovations for Healthier Societies, Ljubljana, August 2014.

Garrett, K. A., Dobson, A. D. M., Kroschel, J., Natarajan, B., Orlandini, S., Tonnang, H. E. Z. and Valdivia, C., 2013, 'The effects of climate variability and the color of weather time series on agricultural diseases and pests, and on decisions for their management', *Agricultural and Forest Meteorology* 170, 216–227 (doi: 10.1016/j.agrformet.2012.04.018).

Gauly, M., Bollwein, H., Breves, G., Brügemann, K., Dänicke, S., Daş, G., Demeler, J., Hansen, H., Isselstein, J., König, S., Lohölter, M., Martinsohn, M., Meyer, U., Potthoff, M., Sanker, C., Schröder, B., Wrage, N., Meibaum, B., von Samson-Himmelstjerna, G. et al., 2013, 'Future consequences and challenges for dairy cow production systems arising from climate change in Central Europe — A review', *Animal* 7(5), 843–859 (doi: 10.1017/S1751731112002352).

Gregory, P. J. and Marshall, B., 2012, 'Attribution of climate change: a methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960', *Global Change Biology* 18(4), 1 372–1 388 (doi: 10.1111/j.1365-2486.2011.02601.x).

Hawkins, E., Fricker, T. E., Challinor, A. J., Ferro, C. A. T., Ho, C. K. and Osborne, T. M., 2013, 'Increasing influence of heat stress on French maize yields from the 1960s to the 2030s', *Global Change Biology* 19(3), 937–947 (doi: 10.1111/gcb.12069).

Höglind, M., Thorsen, S. M. and Semenov, M. A., 2013, 'Assessing uncertainties in impact of climate change on grass production in Northern Europe using ensembles of global climate models', *Agricultural and Forest Meteorology* 170, 103–113 (doi: 10.1016/j.agrformet.2012.02.010).

Högy, P., Wieser, H., Köhler, P., Schwadorf, K., Breuer, J., Erbs, M., Weber, S. and Fangmeier, A., 2012, 'Does elevated atmospheric CO 2 allow for sufficient wheat grain quality in the future?', *Journal of Applied Botany and Food Quality* 82(2), 114–121.

Iglesias, A., Garrote, L., Diz, A., Schlickenrieder, J. and Moneo, M., 2013, 'Water and people: Assessing policy priorities for climate change adaptation in the Mediterranean', in: Navarra, A. and Tubiana, L. (eds), *Regional assessment of climate change in the Mediterranean*, Advances in Global Change Research, Springer, Dordrecht, pp. 201–233.

Iglesias, A., Garrote, L., Flores, F. and Moneo, M., 2007, 'Challenges to manage the risk of water scarcity and climate change in the Mediterranean', *Water Resources Management* 21, 775–788 (doi: 10.1007/s11269-006-9111-6).

Iglesias, A., Garrote, L., Quiroga, S. and Moneo, M., 2012, 'A regional comparison of the effects of climate change on agricultural crops in Europe', *Climatic Change* 112(1), 29–46 (doi: 10.1007/s10584-011-0338-8).

Iglesias, A., Mougou, R., Moneo, M. and Quiroga, S., 2010, 'Towards adaptation of agriculture to climate change in the Mediterranean', *Regional Environmental Change* 11, 159–166 (doi: 10.1007/s10113-010-0187-4).

Ingvordsen, C. H., Backes, G., Lyngkjær, M. F., Peltonen-Sainio, P., Jensen, J. D., Jalli, M., Jahoor, A., Rasmussen, M., Mikkelsen, T. N., Stockmarr, A. and Jørgensen, R. B., 2015, 'Significant decrease in yield under future climate conditions: Stability and production of 138 spring barley accessions', *European Journal of Agronomy* 63, 105–113 (doi: 10.1016/j.eja.2014.12.003).

Jeong, S., Ho, C., Gim, H. and Brown, M. E., 2011, 'Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008', *Global Change Biology* 17(7), 2 385–2 399 (doi: 10.1111/j.1365-2486.2011.02397.x).

Konzmann, M., Gerten, D. and Heinke, J., 2013, 'Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model', *Hydrological Sciences Journal* 58(1), 88–105 (doi: 10.1080/02626667.2013.746495).

Kristensen, K., Schelde, K. and Olesen, J. E., 2011, 'Winter wheat yield response to climate variability in Denmark', *The Journal of Agricultural Science* 149(1), 33–47 (doi: 10.1017/S0021859610000675).

Kruijt, B., Witte, J.-P. M., Jacobs, C. M. J. and Kroon, T., 2008, 'Effect of rising atmospheric CO_2 on evapotranspiration and soil moisture: A practical approach for the Netherlands', *Journal of Hydrology* 349, 257–267 (doi: 10.1016/j.jhydrol.2007.10.052).

Launay, M., Caubel, J., Bourgeois, G., Huard, F., Garcia de Cortazar-Atauri, I., Bancal, M.-O. and Brisson, N., 2014, 'Climatic indicators for crop infection risk: Application to climate change impacts on five major foliar fungal diseases in Northern France', *Agriculture, Ecosystems & Environment* 197, 147–158 (doi: 10.1016/j.agee.2014.07.020).

Leclère, D., Jayet, P.-A. and de Noblet-Ducoudré, N., 2013, 'Farm-level autonomous adaptation of European agricultural supply to climate change', *Ecological Economics* 87, 1–14 (doi: 10.1016/j.ecolecon.2012.11.010).

Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., David Simpson, Sutton, M. A., Vries, W. de, Weiss, F. and Westhoek, H., 2015, 'Impacts of European livestock production: Nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity', *Environmental Research Letters* 10(11), 115004 (doi: 10.1088/1748-9326/10/11/115004).

Lesk, C., Rowhani, P. and Ramankutty, N., 2016, 'Influence of extreme weather disasters on global crop production', *Nature* 529(7584), 84–87 (doi: 10.1038/nature16467).

Lobell, D. B. and Field, C. B., 2007, 'Global scale climate–crop yield relationships and the impacts of recent warming', *Environmental Research Letters* 2, 14002 (doi: 10.1088/1748-9326/2/1/014002).

Lüscher, A., Mueller-Harvey, I., Soussana, J. F., Rees, R. M. and Peyraud, J. L., 2014, 'Potential of legume-based grassland–livestock systems in Europe: A review', *Grass and Forage Science* 69(2), 206–228 (doi: 10.1111/gfs.12124).

Makowski, D., Asseng, S., Ewert, F., Bassu, S., Durand, J. L., Li, T., Martre, P., Adam, M., Aggarwal, P. K., Angulo, C., Baron, C., Basso, B., Bertuzzi, P., Biernath, C., Boogaard, H., Boote, K. J., Bouman, B., Bregaglio, S., Brisson, N. et al., 2015, 'A statistical analysis of three ensembles of crop model responses to temperature and CO_2 concentration', *Agricultural and Forest Meteorology* 214–215, 483–493 (doi: 10.1016/j.agrformet.2015.09.013).

Menzel, A., Jakobi, G., Ahas, R., Scheifinger, H. and Estrella, N., 2003, 'Variations of the climatological growing season (1951–2000) in Germany compared with other countries', *International Journal of Climatology* 23(7), 793–812 (doi: 10.1002/joc.915).

Mínguez, M. I., Ruiz-Ramos, M., Díaz-Ambrona, C. H., Quemada, M. and Sau, F., 2007, 'First-order impacts on winter and summer crops assessed with various high-resolution climate models in the Iberian Peninsula', *Climatic Change* 81, 343–355 (doi: 10.1007/s10584-006-9223-2).

Mitter, H., Kirchner, M., Schmid, E. and Schönhart, M., 2014, 'The participation of agricultural stakeholders in assessing regional vulnerability of cropland to soil water erosion in Austria', *Regional Environmental Change* 14(1), 385–400 (doi: 10.1007/s10113-013-0506-7).

Moore, F. C. and Lobell, D. B., 2014, 'Adaptation potential of European agriculture in response to climate change', *Nature Climate Change* 4(7), 610–614 (doi: 10.1038/nclimate2228).

Moriondo, M., Giannakopoulos, C. and Bindi, M., 2011, 'Climate change impact assessment: The role of climate extremes in crop yield simulation', *Climatic Change* 104, 679–701.

Olesen, J. E. and Bindi, M., 2002, 'Consequences of climate change for European agricultural productivity, land use and policy', *European Journal of Agronomy* 16(4), 239–262 (doi: 10.1016/S1161-0301(02)00004-7).

Olesen, J. E., Børgensen, C. D., Elsgaard, L., Palosuo, T., Rötter, R., Skjelvåg, A. O., Peltonen-Sainio, P., Börjesson, T., Trnka, M., Ewert, F., Siebert, S., Brisson, N., Eitzinger, J., van der Fels-Klerx, H. J. and van Asselt, E., 2012, 'Changes in time of sowing, flowering and maturity of cereals in Europe under climate change', *Food Additives and Contaminants: Part A* 29(10), 1 527–1 542 (doi: 10.1080/19440049.2012.712060).

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J. and Micale, F., 2011, 'Impacts and adaptation of European crop production systems to climate change', *European Journal of Agronomy* 34(2), 96–112 (doi: 10.1016/j.eja.2010.11.003).

Peltonen-Sainio, P., Jauhiainen, L. and Hakala, K., 2011, 'Crop responses to temperature and precipitation according to long-term multi-location trials at high-latitude conditions', *The Journal of Agricultural Science* 149(1), 49–62 (doi: 10.1017/S0021859610000791).

Peltonen-Sainio, P., Jauhiainen, L., Trnka, M., Olesen, J. E., Calanca, P., Eckersten, H., Eitzinger, J., Gobin, A., Kersebaum, K. C., Kozyra, J., Kumar, S., Marta, A. D., Micale, F., Schaap, B., Seguin, B., Skjelvåg, A. O. and Orlandini, S., 2010, 'Coincidence of variation in yield and climate in Europe', *Agriculture, Ecosystems & Environment* 139(4), 483–489 (doi: 10.1016/j.agee.2010.09.006).

Perry, B. D., Grace, D. and Sones, K., 2013, 'Current drivers and future directions of global livestock disease dynamics', *Proceedings of the National Academy of Sciences* 110(52), 20 871–20 877 (doi: 10.1073/pnas.1012953108).

Reidsma, P. and Ewert, F. A., 2008, 'Regional farm diversity can reduce vulnerability of food production to climate change', *Ecology and Society* 13(1), 1–16.

Reidsma, P., Ewert, F. A., Lansink, A. O. and Leemans, R., 2010, 'Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses', *European Journal of Agronomy* 32(1), 91–102 (doi: 10.1016/j.eja.2009.06.003).

Roos, J., Hopkins, R., Kvarnheden, A. and Dixelius, C., 2010, 'The impact of global warming on plant diseases and insect vectors in Sweden', *European Journal of Plant Pathology* 129, 9–19 (doi: 10.1007/s10658-010-9692-z).

Rötter, R., Carter, T. R., Olesen, J. E. and Porter, J. R., 2011, 'Crop-climate models need an overhaul', *Nature Climate Change* 1, 175–177 (doi: 10.1038/nclimate1152).

Rötter, R. and Höhn, J., 2015, 'An overview of climate change impact on crop production and its variability in Europe, related uncertainties and research challenges', in: Elbehri, A. (ed), *Climate change and food systems: Global assessments and implications for food security and trade,* Food and Agriculture Organization of the United Nations, Rome, pp. 106–141.

Savé, R., de Herralde, F., Aranda, X., Pla, E., Pascual, D., Funes, I. and Biel, C., 2012, 'Potential changes in irrigation requirements and phenology of maize, apple trees and alfalfa under global change conditions in Fluvià watershed during XXIst century: Results from a modeling approximation to watershed-level water balance', *Agricultural Water Management* 114, 78–87 (doi: 10.1016/j.agwat.2012.07.006).

Schönhart, M. and Nadeem, I., 2015, 'Direct climate change impacts on cattle indicated by THI models', *Advances in Animal Biosciences* 6(1), 17–20 (doi: 10.1017/S2040470014000430).

Schwartz, M. D., Ahas, R. and Aasa, A., 2006, 'Onset of spring starting earlier across the Northern Hemisphere', *Global Change Biology* 12(2), 343–351 (doi: 10.1111/j.1365-2486.2005.01097.x).

Semenov, M. A., Stratonovitch, P., Alghabari, F. and Gooding, M. J., 2014, 'Adapting wheat in Europe for climate change', *Journal of Cereal Science* 59(3), 245–256 (doi: 10.1016/j.jcs.2014.01.006).

Siebert, S. and Ewert, F., 2012, 'Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length', *Agricultural and Forest Meteorology* 152, 44–57 (doi: 10.1016/j.agrformet.2011.08.007).

Soussana, J.-F., Fereres, E., Long, S. P., Mohren, F. G., Pandya-Lorch, R., Peltonen-Sainio, P., Porter, J. R., Rosswall, T. and von Braun, J., 2012, 'A European science plan to sustainably increase food security under climate change', *Global Change Biology* 18(11), 3269–3271 (doi: 10.1111/j.1365-2486.2012.02746.x).

Supit, I., van Diepen, C. A., de Wit, A. J. W., Kabat, P., Baruth, B. and Ludwig, F., 2010, 'Recent changes in the climatic yield potential of various crops in Europe', *Agricultural Systems* 103(9), 683–694 (doi: 10.1016/j.agsy.2010.08.009).

Taube, F., Gierus, M., Hermann, A., Loges, R. and Schönbach, P., 2014, 'Grassland and globalization — Challenges for north-west European grass and forage research', *Grass and Forage Science* 69(1), 2–16 (doi: 10.1111/gfs.12043).

Trnka, M., Brázdil, R., Dubrovský, M., Semerádová, D., Štěpánek, P., Dobrovolný, P., Možný, M., Eitzinger, J., Málek, J., Formayer, H., Balek, J. and Žalud, Z., 2011, 'A 200-year climate record in Central Europe: Implications for agriculture', *Agronomy for Sustainable Development* 31, 631–641 (doi: 10.1007/s13593-011-0038-9).

Trnka, M., Eitzinger, J., Semerádová, D., Hlavinka, P., Balek, J., Dubrovský, M., Kubu, G., Štěpánek, P., Thaler, S., Možný, M. and Žalud, Z., 2011, 'Expected changes in agroclimatic conditions in Central Europe', *Climatic Change* 108, 261–289 (doi: 10.1007/s10584-011-0025-9).

Trnka, M., Hlavinka, P. and Semenov, M. A., 2015, 'Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change', *Journal of The Royal Society Interface* 12(112), 20150721 (doi: 10.1098/rsif.2015.0721).

Trnka, M., Olesen, J. E., Kersebaum, K. C., Skjelvåg, A. O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vučetić, V., Nejedlik, P. et al., 2011, 'Agroclimatic conditions in Europe under climate change', *Global Change Biology* 17(7), 2 298–2 318 (doi: 10.1111/j.1365-2486.2011.02396.x).

Trnka, M., Rötter, R. P., Ruiz-Ramos, M., Kersebaum, K. C., Olesen, J. E., Žalud, Z. and Semenov, M. A., 2014, 'Adverse weather conditions for European wheat production will become more frequent with climate change', *Nature Climate Change* 4(7), 637–643 (doi: 10.1038/nclimate2242).

Vadez, V., Berger, J. D., Warkentin, T., Asseng, S., Ratnakumar, P., Rao, K. P. C., Gaur, P. M., Munier-Jolain, N., Larmure, A., Voisin, A.-S., Sharma, H. C., Pande, S., Sharma, M., Krishnamurthy, L. and Zaman, M. A., 2011, 'Adaptation of grain legumes to climate change: A review', *Agronomy for Sustainable Development* 32(1), 31–44 (doi: 10.1007/s13593-011-0020-6).

van der Velde, M., Wriedt, G. and Bouraoui, F., 2010, 'Estimating irrigation use and effects on maize yield during the 2003 heatwave in France', *Agriculture, Ecosystems & Environment* 135(1–2), 90–97 (doi: 10.1016/j.agee.2009.08.017).

Vermeulen, S. J., Aggarwal, P. K., Ainslie, A., Angelone, C., Campbell, B. M., Challinor, A. J., Hansen, J. W., Ingram, J. S. I., Jarvis, A., Kristjanson, P., Lau, C., Nelson, G. C., Thornton, P. K. and Wollenberg, E., 2012, 'Options for support to agriculture and food security under climate change', *Environmental Science & Policy* 15(1), 136–144 (doi: 10.1016/j.envsci.2011.09.003).

Vitali, A., Segnalini, M., Bertocchi, L., Bernabucci, U., Nardone, A. and Lacetera, N., 2009, 'Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows', *Journal of Dairy Science* 92(8), 3 781–3 790 (doi: 10.3168/jds.2009-2127).

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., Stacke, T., Tessler, Z. and Schewe, J., 2013, 'Multimodel projections and uncertainties of irrigation water demand under climate change', *Geophysical Research Letters* 40(17), 4 626–4 632 (doi: 10.1002/grl.50686).

Wang, D., Heckathorn, S. A., Wang, X. and Philpott, S. M., 2011, 'A meta-analysis of plant physiological and growth responses to temperature and elevated CO_2', *Oecologia* 169(1), 1–13 (doi: 10.1007/s00442-011-2172-0).

Wriedt, G., Van der Velde, M., Aloe, A. and Bouraoui, F., 2009, 'Estimating irrigation water requirements in Europe', *Journal of Hydrology* 373(3–4), 527–544 (doi: 10.1016/j.jhydrol.2009.05.018).

Section 5.4: Energy

Benestad, R. E., 2008, *Heating degree days, cooling degree days and precipitation in Europe*, met.no report No 4/2008, Norwegian Meteorological Institute, Oslo.

Bonjean Stanton, M. C., Dessai, S. and Paavola, J., 2016, 'A systematic review of the impacts of climate variability and change on electricity systems in Europe', *Energy* 109, 1 148–1 159 (doi: 10.1016/j.energy.2016.05.015).

Brown, S., Hanson, S. and Nicholls, R. J., 2014, 'Implications of sea-level rise and extreme events around Europe: A review of coastal energy infrastructure', *Climatic Change* 122(1–2), 81–95 (doi: 10.1007/s10584-013-0996-9).

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre, Institute for Prospective Technological Studies, Institute for Environment and Sustainability.

De Cian, E., Lanzi, E. and Roson, R., 2012, 'Seasonal temperature variations and energy demand', *Climatic Change* 116(3–4), 805–825 (doi: 10.1007/s10584-012-0514-5).

Dowling, P., 2013, 'The impact of climate change on the European energy system', *Energy Policy* 60, 406–417 (doi: 10.1016/j.enpol.2013.05.093).

EC, 2011, Communication from the Commission to the Council and the European Parliament on the interim report on the comprehensive risk and safety assessments ('stress tests') of nuclear power plants in the European Union, COM(2011) 784 final, SEC(2011) 1395 final, Brussels.

EC, 2013, *Commission Staff Working Document — Adapting infrastructure to climate change*, SWD(2013) 137 final, 16.4.2013, European Commission.

EC, 2015, 'Monitoring Agricultural ResourceS (MARS)' (https://ec.europa.eu/jrc/en/mars) accessed 10 February 2016.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J. C., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C. and Zwickel, T., 2014, *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

ENSREG, 2012, *Stress tests performed on European nuclear power plants*, Peer review report, European Nuclear Safety Regulators Group.

EPA, 2014, Climate change indicators in the United States: Heating and cooling degree days, US Environmental Protection Agency.

Eskeland, G. S. and Mideksa, T. K., 2010, 'Electricity demand in a changing climate', *Mitigation and Adaptation Strategies for Global Change* 15(8), 877–897 (doi: 10.1007/s11027-010-9246-x).

Eurostat, 2014, 'Energy statistics — Heating degree days (nrg_esdgr)' (http://ec.europa.eu/eurostat/cache/metadata/en/nrg_esdgr_esms.htm) accessed 10 February 2016.

Förster, H. and Lilliestam, J., 2009, 'Modeling thermoelectric power generation in view of climate change', *Regional Environmental Change* 10(4), 327–338 (doi: 10.1007/s10113-009-0104-x).

Hamududu, B. and Killingtveit, A., 2012, 'Assessing climate change impacts on global hydropower', *Energies* 5(12), 305–322 (doi: 10.3390/en5020305).

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D. and New, M., 2008, 'A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006', *Journal of Geophysical Research: Atmospheres* 113(D20), D20119 (doi: 10.1029/2008JD010201).

IAEA, 2011, *Meteorological and hydrological hazards in site evaluation for nuclear installations*, IAEA Safety Standards Series, Specific Safety Guide SSG-18, International Atomic Energy Agency, Vienna.

Klein Tank, A. and Wijngaard, J., 2002, 'Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment', *International Journal of Climatology* 22(12), 1 441–1 453 (doi: 10.1002/joc.773).

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Lehner, B., Czisch, G. and Vassolo, S., 2005, 'The impact of global change on the hydropower potential of Europe: A model-based analysis', *Energy Policy* 33(7), 839–855 (doi: 10.1016/j.enpol.2003.10.018).

Ligtvoet, W., van Oostenbrugge, R., Knoop, J., Muilwijk, H. and Vonk, M., 2015, *Adaptation to climate change in the Netherlands — Studying related risks and opportunities*, PBL publication number 1632, PBL Netherlands Environmental Assessment Agency, The Hague.

Linnerud, K., Mideska, T. K. and Eskeland, G. S., 2011, 'The impact of climate change on nuclear power supply', *The Energy Journal* 32(1), 149–168 (doi: 10.5547/ISSN0195-6574-EJ-Vol32-No1-6).

Menne, M. J., Durre, I., Vose, R. S., Gleason, B. E. and Houston, T. G., 2012, 'An overview of the global historical climatology network-daily database', *Journal of Atmospheric and Oceanic Technology* 29(7), 897–910 (doi: 10.1175/JTECH-D-11-00103.1).

Mideksa, T. K. and Kallbekken, S., 2010, 'The impact of climate change on the electricity market: A review', *Energy Policy* 38(7), 3 579–3 585 (doi: 16/j.enpol.2010.02.035).

Mima, S. and Criqui, P., 2015, 'The costs of climate change for the European energy system, an assessment with the POLES model', *Environmental Modeling & Assessment* 20(4), 303–319 (doi: 10.1007/s10666-015-9449-3).

Mima, S., Criqui, P. and Watkiss, P., 2012, *The impacts and economic costs of climate change on energy in the European Union*, Technical Policy Briefing Note 4, Stockholm Environment Institute, Stockholm.

Mirasgedis, S., Sarafidis, Y., Georgopoulou, E., Kotroni, V., Lagouvardos, K. and Lalas, D. P., 2007, 'Modeling framework for estimating impacts of climate change on electricity demand at regional level: Case of Greece', *Energy Conversion and Management* 48(5), 1 737–1 750 (doi: 16/j.enconman.2006.10.022).

Panagea, I. S., Tsanis, I. K., Koutroulis, A. G. and Grillakis, M. G., 2014, 'Climate change impact on photovoltaic energy output: The case of Greece', *Advances in Meteorology* 2014, e264506 (doi: 10.1155/2014/264506).

Pašičko, R., Branković, Č. and Šimić, Z., 2012, 'Assessment of climate change impacts on energy generation from renewable sources in Croatia', *Renewable Energy* 46, 224–231 (doi: 10.1016/j.renene.2012.03.029).

Perrels, A., Heyndrickx, C., Prettenthaler, F., Kortschak, D., Ciari, F., Bösch, P., Kiviluoma, J., Azevedo, M., Ekholm, T., Crawford-Brown, D. and Thompson, A., 2015, *Sectoral and cross-cutting multi-sector adaptation strategies for energy, transport and tourism*, ToPDAd project, Deliverable 2.4.

Pilli-Sihvola, K., Aatola, P., Ollikainen, M. and Tuomenvirta, H., 2010, 'Climate change and electricity consumption — Witnessing increasing or decreasing use and costs?', *Energy Policy* 38(5), 2 409–2 419 (doi: 16/j.enpol.2009.12.033).

Rademaekers, K., van der Laan, J., Boeve, S., Lise, W. and Kirchsteiger, C., 2011, *Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change*, EUR 24769, European Commission, Directorate-General for Energy.

Raible, C. C. and CH2014-Impacts Initiative (eds), 2014, *CH2014-Impacts: Toward quantitative scenarios of climate change impacts in Switzerland*, Universität Bern, Oeschger Centre for Climate Change Research (OCCR), Bern.

Rübbelke, D. and Vögele, S., 2012, 'Short-term distributional consequences of climate change impacts on the power sector: who gains and who loses?', *Climatic Change* 116(2), 191–206 (doi: 10.1007/s10584-012-0498-1).

SGHL and CHy, 2011, *Auswirkungen der Klimaänderung auf die Wasserkraftnutzung — Synthesebericht*, Beiträge zur Hydrologie der Schweiz No 38, Schweizerische Gesellschaft für Hydrologie und Limnologie (SGHL), Hydrologische Kommission (CHy), Bern.

Spinoni, J., Vogt, J. and Barbosa, P., 2015, 'European degree-day climatologies and trends for the period 1951–2011', *International Journal of Climatology* 35(1), 25–36 (doi: 10.1002/joc.3959).

Tobin, I., Jerez, S., Vautard, R., Thais, F., van Meijgaard, E., Prein, A., Déqué, M., Kotlarski, S., Maule, C. F., Nikulin, G., Noël, T. and Teichmann, C., 2016, 'Climate change impacts on the power generation potential of a European mid-century wind farms scenario', *Environmental Research Letters* 11(3), 34013 (doi: 10.1088/1748-9326/11/3/034013).

Tobin, I., Vautard, R., Balog, I., Bréon, F.-M., Jerez, S., Ruti, P. M., Thais, F., Vrac, M. and Yiou, P., 2015, 'Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections', *Climatic Change* 128(1–2), 99–112 (doi: 10.1007/s10584-014-1291-0).

ToPDAd, 2015, Securing the EU's energy future — Adapting our energy system to climate change, ToPDAd Policy Brief.

van Vliet, M. T. H., van Beek, L. P. H., Eisner, S., Flörke, M., Wada, Y. and Bierkens, M. F. P., 2016, 'Multi-model assessment of global hydropower and cooling water discharge potential under climate change', *Global Environmental Change* 40, 156–170 (doi: 10.1016/j.gloenvcha.2016.07.007).

van Vliet, M. T. H., Vögele, S. and Rübbelke, D., 2013, 'Water constraints on European power supply under climate change: Impacts on electricity prices', *Environmental Research Letters* 8(3), 35010 (doi: 10.1088/1748-9326/8/3/035010).

van Vliet, M. T. H., Wiberg, D., Leduc, S. and Riahi, K., 2016, 'Power-generation system vulnerability and adaptation to changes in climate and water resources', *Nature Climate Change* 6(4), 375–380 (doi: 10.1038/nclimate2903).

van Vliet, M. T. H., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P. and Kabat, P., 2012, 'Vulnerability of US and European electricity supply to climate change', *Nature Climate Change* 2(9), 676–681 (doi: 10.1038/nclimate1546).

Vonk, M., Bouwman, A., Van Dorland, R. and Eerens, H., 2015, *Worldwide climate effects: Risks and opportunities for the Netherlands*, PBL publication number 1412, PBL Netherlands Environmental Assessment Agency, The Hague.

Wachsmuth, J., Blohm, A., Gößling-Reisemann, S., Eickemeier, T., Ruth, M., Gasper, R. and Stührmann, S., 2013, 'How will renewable power generation be affected by climate change? The case of a Metropolitan Region in Northwest Germany', *Energy* 58, 192–201 (doi: 10.1016/j.energy.2013.06.035).

Section 5.5: Transport

Altvater, S., van de Sandt, K., Marinova, N., de Block, D., Klostermann, J., Swart, R., Bouwma, I., McCallum, S., Dworak, T. and Osberghaus, D., 2011, *Assessment of the most significant threats to the EU posed by the changing climate in the short, medium and long term — Task 1 report*, Ecologic, Berlin.

Becker, A., Fischer, M., Schwegler, B. and Inoue, S., 2011, *Considering climate change: A survey of global seaport administrators*, CIFE Working Paper No 128, Stanford University, Stanford, CA.

Beuthe, M., Jourquin, B., Urbain, N., Lingemann, I. and Ubbels, B., 2014, 'Climate change impacts on transport on the Rhine and Danube: A multimodal approach', *Transportation Research Part D: Transport and Environment* 27, 6–11 (doi: 10.1016/j.trd.2013.11.002).

Bruinsma, F., Korster, P., Holtmann, B., van Heumen, E., Beuthe, M., Urbain, N., Jourquin, B., Ubbels, B. and Quispel, M., 2012, *Consequences of climate change for inland waterway transport*, ECCONET project, Deliverable 3.3.

CEDEX, 2013, *Climate change adaptation needs of the core network of transport infrastructure in Spain*, Final Report, Working Group for the analysis of the Climate change adaptation needs of the core network of transport infrastructure in Spain, Madrid.

CEDR, 2011, *Adaptation to climate change*, Conference of European Directors of Roads (CEDR), Project Group on Climate Change, Oslo.

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

DEFRA, 2012, *UK climate change risk assessment: Government report*, Department for Environment, Food & Rural Affairs, London.

DGAC/STAC, 2013, *Vulnérabilité des aérodromes face au changement climatique*, Direction générale de l'Aviation civile, Bonneuil-sur-Marne.

Doll, C., Kühn, A., Peters, A., Juga, I., Kral, S., Enei, R., Pietroni, F., Mitsakis, E., Stamos, I., Schultmann, F., Wiens, M., Schätter, F., Meng, S., Bartsch, M., Kynnös, K., Hietajärvi, A.-M., Kostiainen, J., Mantisnen, H. and Hinkka, V., 2014, *Guidebook for enhancing resilience of European road transport in extreme weather events*, MOWE-IT project, Deliverable 3.

EASA, EEA and Eurocontrol, 2016, *European aviation environmental report 2016*, European Aviation Safety Agency (EASA), Cologne.

EC, 2012, *Developing a European Union Policy towards the Arctic Region: Progress since 2008 and next steps*, JOIN(2012) 19 final, European Commission, Brussels.

EC, 2013, *Commission staff working paper: Adapting infrastructure to climate change. Accompanying the document Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: An EU Strategy on adaptation to climate change*, SWD(2013) 137, European Commission, Brussels.

Enei, R., Doll, C., Klug, S., Partzsch, I., Sedlacek, N., Nesterova, N., Kiel, J., Rudzikaite, L., Papanikolau, A. and Mitsakis, Evangelos, 2011, *Vulnerability of transport systems*, WEATHER project, Deliverable 2.

Eurocontrol, 2013, *Climate change risk and resilience*, Task 8 report, Eurocontrol, Brussels.

Eurocontrol, 2014, Adapting aviation to a changing climate, Eurocontrol.

FOEN, 2012, *Adaptation to climate change in Switzerland*, UD-1055-E, Federal Office for the Environment, Bern.

Giannopoulos, G., Gagatsi, E., Mitsakis, E. and Salanova, J., 2011, 'Risks and impacts of climate change on the transport sector', in: *The environmental, economic and social impacts of climate change in Greece*, Bank of Greece, Athens, pp. 260–267.

Golikov, G., Nazarenko, M., Nokkala, M., Hutchinson, P., Kopsala, P., Michaelides, S., Tymvios, F., Papadakis, M. and Athanasatos, S., 2014, *Guidebook for enhancing resilience of European maritime transport in extreme weather events*, MOWE-IT project, Deliverable 6.1.

HAL, 2011, *Heathrow Airport climate change adaptation reporting power report*, Heathrow Airport Limited.

Hamburg, 2013, *Aktionsplan Anpassung an den Klimawandel*, Drucksache 20/8492, Bürgerschaft der Freien und Hansestadt Hamburg, Hamburg.

Jaroszweski, D., Quinn, A., Baker, C., Hooper, E., Kochsiek, J., Schultz, S. and Sille, A., 2014, *Guidebook for enhancing resilience of European rail transport in extreme weather events*, MOWE-IT project, Deliverable 4.

Klimatilspassning, 2014, 'Copenhagen Airport ready with climate' (http://en.klimatilpasning.dk/recent/cases/items/copenhagen-airport-ready-with-climate-plan.aspx) accessed 28 July 2015.

Koetse, M. J. and Rietveld, P., 2009, 'The impact of climate change and weather on transport: An overview of empirical findings', *Transportation Research Part D: Transport and Environment* 14(3), 205–221 (doi: 10.1016/j.trd.2008.12.004).

Leviäkangas, P. and Saarikivi, P., 2012, *European extreme weather risk management — Needs, opportunities, costs and recommendations*, EWENT project, Deliverable 6.

Leviäkangas, P., Tuominen, A., Molarius, R. and Kojo, H., 2011, *Extreme weather impacts on transport systems*, VTT Working Papers 168, VTT.

McCallum, S., Dworak, T., Prutsch, A., Kent, N., Mysiak, J., Bosello, F., Klostermann, J., Dlugolecki, A., Williams, E., König, M., Leitner, M., Miller, K., Harley, M., Smithers, R., Berglund, M., Glas, N., Romanovska, L., van de Sandt, K., Bachschmidt, R. et al., 2013, *Support to the development of the EU Strategy for Adaptation to Climate Change: Background report to the Impact Assessment, Part I — Problem definition, policy context and assessment of policy options*, Environment Agency Austria, Vienna.

Moser, H., Cullman, J., Kolfalk, S., Mai, S., Nilson, E., Rösner, S., Becker, P., Gratzki, A. and Schreiber, K. J., 2012, 'BfG — KLIWAS: An integrated climate service for the transboundary river basin and coastal management of Germany', in: *Climate Exchange*, Tudor Rose, Leicester, pp. 88–91.

Nemry, F. and Demirel, H., 2012, *Impacts of climate change on transport: A focus on road and rail transport infrastructures*, European Commission, Joint Research Centre — Institute for Prospective Technological Studies, Luxembourg.

Nilson, E., Lingemann, I., Klein, B. and Krahe, P., 2012, *Impact of Hydrological Change on Navigation Conditions*, ECCONET Deliverable 1.4, Bundesanstalt für Gewässerkunde.

Nokkala, M., Leviäkangas, P. and Oiva, K., 2012, *The costs of extreme weather for the European transport systems*, EWENT project, Deliverable 4, VTT Technology.

Nolte, R., Kamburow, C. and Rupp, J., 2011, *ARISCC. Adaptation of railway infrastructure to climate change. Final report*, Institute for Future Studies and Technology Assessment (IZT), Berlin.

Perrels, A., Heyndrickx, C., Prettenthaler, F., Kortschak, D., Ciari, F., Bösch, P., Kiviluoma, J., Azevedo, M., Ekholm, T., Crawford-Brown, D. and Thompson, A., 2015, *Sectoral and cross-cutting multi-sector adaptation strategies for energy, transport and tourism*, ToPDAd project, Deliverable 2.4.

PIANC, 2008, *Climate change and navigation — Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation*, EnviCom TG 3.

Przyluski, V., Hallegatte, S., Nadaud, F., Tomozeiu, R., Cacciamani, C., Pavan, V. and Doll, C., 2011, *Weather trends and economy-wide impacts: WEATHER Project D1*, WEATHER project, Deliverable 1, Fraunhofer — ISI, Karlsruhe.

République Française, 2011, *Plan national d'adaptation de la France aux effets du changement climatique (2011-2015)*, Ministere de l'Écologie, du Développement durable et de l'Énergie, Paris.

Rothstein, B. and Halbig, G., 2010, 'Weather sensitivity of electricity supply and data services of the German Met Office', in: Troccoli, A. (ed), *Management of Weather and Climate Risk in the Energy Industry*, Springer Netherlands, Dordrecht, pp. 253–266.

Rotterdam Climate Initiative, 2009, 'Rotterdam Climate Initiative' (http://www.rotterdamclimateinitiative.nl/en) accessed 27 February 2014.

Siedl, N. and Schweighofer, J., 2014, *Guidebook for enhancing resilience of European inland waterway transport in extreme weather events*, MOWE-IT project, Deliverable 6.2.

Steininger, K. W., König, M., Bednar-Friedl, B., Kranzl, L., Loibl, W. and Prettenthaler, F. (eds), 2015, *Economic evaluation of climate change impacts: Development of a cross-sectoral framework and results for Austria*, Springer, Cham.

Temme, A., Kreuz, M., Mühlhausen, T., Schmitz, R., Hyvärinen, O., Kral, S., Schätter, F., Bartsch, M., Michaelides, S., Tymvios, F., Papadakis, M. and Athanasatos, S., 2014, *Guidebook for enhancing resilience of European air traffic in extreme weather events*, MOWE-IT project, Deliverable 5.

Thornes, J., Rennie, M., Marsden, H. and Chapman, L., 2012, *Climate change risk assessment for the transport sector*, Defra Project Code GA0204, Department for Environment, Food and Rural Affairs, London.

ToPDAd, 2015, Adaptation and resilience of the transport sector, ToPDAd Policy Brief.

Vellinga, T. and Jong, M., 2012, 'Approach to climate change adaptation in the Port of Rotterdam', in: Asariotis, R. and Benamara, H. (eds), *Maritime transport and the climate change challenge*, Routledge, Oxford, pp. 305–319.

Section 5.6: Tourism

Agrawala, S., 2007, *Climate change in the European Alps: Adapting winter tourism and natural hazards management*, Organisation for Economic Co-operation and Development, Paris.

Amelung, B. and Moreno, A., 2009, *Impacts of climate change in tourism in Europe*, JRC Scientific and Technical Reports, European Commission — Joint Research Centre, Institute for Prospective Technological Studies.

Amelung, B. and Moreno, A., 2011, 'Costing the impact of climate change on tourism in Europe: Results of the PESETA project', *Climatic Change* 112(1), 83–100 (doi: 10.1007/s10584-011-0341-0).

Barrios, S. and Ibañez Rivas, J. N., 2013, *Tourism demand, climatic conditions and transport costs report for the PESETA II study on the impact of climate change in Europe*, European Commission, Joint Research Centre, Institute for Prospective Technological Studies, Luxembourg.

Beniston, M., Keller, F., Koffi, B. and Goyette, S., 2003, 'Estimates of snow accumulation and volume in the Swiss Alps under changing climatic conditions', *Theoretical and Applied Climatology* 76(3–4), 125–140 (doi: 10.1007/s00704-003-0016-5).

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

Ciscar, J. C., Iglesias, A., Feyen, L., Goodess, C. M., Szabo, L., Christensen, O. B., Nicholls, R., Amelung, B., Watkiss, P. and Bosello, F., 2009, *Climate change impacts in Europe. Final report of the PESETA research project*, EUR 24093 EN, JRC55391, JRC-IPTS, Seville.

Damm, A., Köberl, J. and Prettenthaler, F., 2014, 'Does artificial snow production pay under future climate conditions? – A case study for a vulnerable ski area in Austria', *Tourism Management* 43, 8–21 (doi: 10.1016/j.tourman.2014.01.009).

ECORYS, 2009, *Study on the competitiveness of the EU tourism industry*, Within the Framework Contract of Sectoral Competitiveness Studies — ENTR/06/054, ECORYS SCS Group, Rotterdam.

Endler, C. and Matzarakis, A., 2011, 'Climatic potential for tourism in the Black Forest, Germany — Winter season', *International Journal of Biometeorology* 55(3), 339–351 (doi: 10.1007/s00484-010-0342-0).

Eurostat, 2015a, 'Seasonality in tourism demand — Statistics explained' (http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Seasonality_in_tourism_demand&oldid=261762) accessed 21 November 2015.

Eurostat, 2015b, 'Tourism statistics — Top destinations' (http://ec.europa.eu/eurostat/statistics-explained/index.php/Tourism_statistics_-_top_destinations) accessed 30 July 2015.

Eurostat, 2015c, 'Tourism statistics at regional level — Statistics explained' (http://ec.europa.eu/eurostat/statistics-explained/index.php/Tourism_statistics_at_regional_level) accessed 21 November 2015.

de Freitas, C. R., Scott, D. and McBoyle, G., 2008, 'A second generation climate index for tourism (CIT): Specification and verification', *International Journal of Biometeorology* 52(5), 399–407 (doi: 10.1007/s00484-007-0134-3).

Gössling, S., Hall, C. M., Peeters, P. and Scott, D., 2010, 'The future of tourism: Can tourism growth and climate policy be reconciled? A Mitigation perspective', *Tourism Recreation Research* 35(2), 119–130 (doi: 10.1080/02508281.2010.11081628).

Hantel, M., Ehrendorfer, M. and Haslinger, A., 2000, 'Climate sensitivity of snow cover duration in Austria', *International Journal of Climatology* 20(6), 615–640 (doi: 10.1002/(SICI)1097-0088(200005)20:6<615::AID-JOC489>3.0.CO;2-0).

Kaján, E., 2014, 'Arctic tourism and sustainable adaptation: Community perspectives to vulnerability and climate change', *Scandinavian Journal of Hospitality and Tourism* 14(1), 60–79 (doi: 10.1080/15022250.2014.886097).

Kovats, R. S., Valentini, R., Bouwer, L. M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M. and Soussana, J.-F., 2014, 'Europe', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 267–1 326.

Magnan, A., Hamilton, J., Rosselló, J., Bujosa, A. and Bille, R., 2012, 'Mediterranean tourism and climate change: Identifying future demand and assessing destinations' vulnerability', in: Navarra, A. and Tubiana, L. (eds), *Regional assessment of climate change in the Mediterranean*, Springer, Dordrecht.

Mieczkowski, Z., 1985, 'The tourism climatic index: A method of evaluating world climates for tourism', *The Canadian Geographer/Le Géographe Canadien* 29(3), 220–233 (doi: 10.1111/j.1541-0064.1985.tb00365.x).

Moen, J. and Fredman, P., 2007, 'Effects of climate change on Alpine skiing in Sweden', *Journal of Sustainable Tourism* 15(4), 418–437 (doi: 10.2167/jost624.0).

Nicholls, S. and Amelung, B., 2015, 'Implications of climate change for rural tourism in the Nordic region', *Scandinavian Journal of Hospitality and Tourism* 15(1–2), 48–72 (doi: 10.1080/15022250.2015.1010325).

Perch-Nielsen, S. L., Amelung, B. and Knutti, R., 2010, 'Future climate resources for tourism in Europe based on the daily Tourism Climatic Index', *Climatic Change* 103(3–4), 363–381 (doi: 10.1007/s10584-009-9772-2).

Perrels, A., Heyndrickx, C., Prettenthaler, F., Kortschak, D., Ciari, F., Bösch, P., Kiviluoma, J., Azevedo, M., Ekholm, T., Crawford-Brown, D. and Thompson, A., 2015, *Sectoral and cross-cutting multi-sector adaptation strategies for energy, transport and tourism*, ToPDAd project, Deliverable 2.4.

Pons, M., López-Moreno, J. I., Rosas-Casals, M. and Jover, È., 2015, 'The vulnerability of Pyrenean ski resorts to climate-induced changes in the snowpack', *Climatic Change* 131(4), 591–605 (doi: 10.1007/s10584-015-1400-8).

Rixen, C., Teich, M., Lardelli, C., Gallati, D., Pohl, M., Pütz, M. and Bebi, P., 2011, 'Winter tourism and climate change in the Alps: An assessment of resource consumption, snow reliability, and future snowmaking potential', *Mountain Research and Development* 31(3), 229–236 (doi: 10.1659/MRD-JOURNAL-D-10-00112.1).

Rosselló, J. and Santana-Gallego, M., 2014, 'Recent trends in international tourist climate preferences: A revised picture for climatic change scenarios', *Climatic Change* 124(1–2), 119–132 (doi: 10.1007/s10584-014-1086-3).

Rosselló-Nadal, J., 2014, 'How to evaluate the effects of climate change on tourism', *Tourism Management* 42, 334–340 (doi: 10.1016/j.tourman.2013.11.006).

Steger, C., Kotlarski, S., Jonas, T. and Schär, C., 2013, 'Alpine snow cover in a changing climate: A regional climate model perspective', *Climate Dynamics* 41(3–4), 735–754 (doi: 10.1007/s00382-012-1545-3).

Steiger, R., 2011, 'The impact of snow scarcity on ski tourism: An analysis of the record warm season 2006/2007 in Tyrol (Austria)', *Tourism Review* 66(3), 4–13 (doi: 10.1108/16605371111175285).

Steiger, R., 2012, 'Scenarios for skiing tourism in Austria: Integrating demographics with an analysis of climate change', *Journal of Sustainable Tourism* 20(6), 867–882 (doi: 10.1080/09669582.2012.680464).

Steiger, R. and Stötter, J., 2013, 'Climate change impact assessment of ski tourism in Tyrol', *Tourism Geographies* 15(4), 577–600 (doi: 10.1080/14616688.2012.762539).

Tervo-Kankare, K., Hall, C. M. and Saarinen, J., 2013, 'Christmas tourists' perceptions to climate change in Rovaniemi, Finland', *Tourism Geographies* 15(2), 292–317 (doi: 10.1080/14616688.2012.726265).

ToPDAd, 2015, How will climate change affect tourism flows in Europe? Adaptation options for beach and ski tourists assessed by ToPDAd models, ToPDAd Policy Brief.

Chapter 6: Multi-sectoral vulnerability and risks

Section 6.1: Socio-economic scenarios for Europe

Acosta, L., Klein, R. J. T., Reidsma, P., Metzger, M. J., Rounsevell, M. D. A., Leemans, R. and Schröter, D., 2013, 'A spatially explicit scenario-driven model of adaptive capacity to global change in Europe', *Global Environmental Change* 23(5), 1 211–1 224 (doi: 10.1016/j.gloenvcha.2013.03.008).

Audsley, E., Trnka, M., Sabaté, S., Maspons, J., Sanchez, A., Sandars, D., Balek, J. and Pearn, K., 2014, 'Interactively modelling land profitability to estimate European agricultural and forest land use under future scenarios of climate, socio-economics and adaptation', *Climatic Change* 128(3–4), 215–227 (doi: 10.1007/s10584-014-1164-6).

Cuaresma, J. C., 2015, 'Income projections for climate change research: A framework based on human capital dynamics', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.02.012).

Dellink, R., Chateau, J., Lanzi, E. and Magné, B., 2015, 'Long-term economic growth projections in the Shared Socioeconomic Pathways', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.06.004).

Dunford, R., Harrison, P. A., Jäger, J., Rounsevell, M. D. A. and Tinch, R., 2015, 'Exploring climate change vulnerability across sectors and scenarios using indicators of impacts and coping capacity', *Climatic Change* 128(3–4), 339–354 (doi: 10.1007/s10584-014-1162-8).

EC, 2014a, 'CAP context indicators' (http://ec.europa.eu/agriculture/cap-indicators/context/index_en.htm) accessed 10 February 2016.

EC, 2014b, *The 2015 ageing report: Underlying assumptions and projection methodologies*, European Economy No 8/2014, European Commission, Brussels.

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2015, *The European environment — state and outlook 2015: Assessment of global megatrends*, European Environment Agency.

ESPON Climate, 2011, *Climate change and territorial effects on regions and local economies*, Scientific Report, Institute of Spatial Planning (IRPUD), TU Dortmund University, Dortmund.

Eurostat, 2013, 'Europop2013' (http://ec.europa.eu/eurostat/web/population-demography-migration-projections/population-projections-data) accessed 17 September 2015.

IPCC, 2014, *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jiang, L. and O'Neill, B. C., 2015, 'Global urbanization projections for the Shared Socioeconomic Pathways', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.03.008).

Kok, K., Bärlund, I., Flörke, M., Holman, I., Gramberger, M., Sendzimir, J., Stuch, B. and Zellmer, K., 2015, 'European participatory scenario development: Strengthening the link between stories and models', *Climatic Change* 128(3–4), 187–200 (doi: 10.1007/s10584-014-1143-y).

Kok, K., Christensen, J. H., Madsen, M. S., Pedde, S., Gramberger, M. and Carter, T. R., 2015, *Evaluation of existing climate and socio-economic scenarios including a detailed description of the final selection*, EU FP7 IMPRESSIONS project, Deliverable 2.1, University of Oxford, Wageningen University.

Kok, K., Pedde, S., Jaeger, J. and Harrison, P. A., 2015, *European Shared Socioeconomic Pathways*, Report of the FP7 project IMPRESSIONS, University of Oxford, Oxford.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K. L., Kram, T., Riahi, K., Winkler, H. and Vuuren, D. P. van, 2014, 'A new scenario framework for climate change research: The concept of shared climate policy assumptions', *Climatic Change* 122(3), 401–414 (doi: 10.1007/s10584-013-0971-5).

Leimbach, M., Kriegler, E., Roming, N. and Schwanitz, J., 2015, 'Future growth patterns of world regions — A GDP scenario approach', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.02.005).

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W., 2015, 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.01.004).

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R. and Vuuren, D. P. van, 2014, 'A new scenario framework for climate change research: The concept of shared socioeconomic pathways', *Climatic Change* 122(3), 387–400 (doi: 10.1007/s10584-013-0905-2).

Samir, K. C. and Lutz, W., 2015, 'The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2014.06.004).

Tinch, R., Jäger, J., Omann, I., Harrison, P. A., Wesely, J. and Dunford, R., 2015, 'Applying a capitals framework to measuring coping and adaptive capacity in integrated assessment models', *Climatic Change* 128(3–4), 323–337 (doi: 10.1007/s10584-014-1299-5).

UNDESA, 2015, *World Population Prospects, the 2015 revision — Key findings and advance tables*, United Nations Department of Economic and Social Affairs, New York, NY.

van Vuuren, D. P. and Carter, T. R., 2014, 'Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old', *Climatic Change* 122(3), 415–429 (doi: 10.1007/s10584-013-0974-2).

van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. and Winkler, H., 2014, 'A new scenario framework for Climate Change Research: Scenario matrix architecture', *Climatic Change* 122(3), 373–386 (doi: 10.1007/s10584-013-0906-1).

Wimmer, F., Audsley, E., Malsy, M., Savin, C., Dunford, R., Harrison, P. A., Schaldach, R. and Flörke, M., 2014, 'Modelling the effects of cross-sectoral water allocation schemes in Europe', *Climatic Change* 128(3–4), 229–244 (doi: 10.1007/s10584-014-1161-9).

Section 6.2: Multi-sectoral impacts and vulnerabilities across Europe

Adelphi, PRC and EURAC, 2015, *Vulnerabilität Deutschlands gegenüber dem Klimawandel*, Climate Change 24/2015, Umweltbundesamt, Dessau-Roβlau.

BASE project, 2016, *Process tool for testing and evaluating future plans for adaptation – using storylines and pathways for adaptation to CC across Europe*, Deliverable 6.4.

Dunford, R., Harrison, P. A., Jäger, J., Rounsevell, M. D. A. and Tinch, R., 2015, 'Exploring climate change vulnerability across sectors and scenarios using indicators of impacts and coping capacity', *Climatic Change* 128(3–4), 339–354 (doi: 10.1007/s10584-014-1162-8).

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

ESPON Climate, 2011, *Climate change and territorial effects on regions and local economies*, Scientific Report, Institute of Spatial Planning (IRPUD), TU Dortmund University, Dortmund.

Forzieri, G., Bianchi, A., Marin Herrera, M. A., Batista e Silva, F., Feyen, L., Lavalle, C., European Commission, Joint Research Centre and Institute for the Protection and the Security of the Citizen, 2015, *Resilience of large investments and critical infrastructures in Europe to climate change*, Publications Office, Luxembourg.

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R. and Cid, A., 2016, 'Multi-hazard assessment in Europe under climate change', *Climatic Change* 137, 105–119 (doi: 10.1007/s10584-016-1661-x).

Harrison, P. A., Dunford, R., Savin, C., Rounsevell, M. D. A., Holman, I. P., Kebede, A. S. and Stuch, B., 2015, 'Cross-sectoral impacts of climate change and socio-economic change for multiple, European land- and water-based sectors', *Climatic Change* 128(3–4), 279–292 (doi: 10.1007/s10584-014-1239-4).

Huber, V., Schellnhuber, H. J., Arnell, N. W., Frieler, K., Friend, A. D., Gerten, D., Haddeland, I., Kabat, P., Lotze-Campen, H., Lucht, W., Parry, M., Piontek, F., Rosenzweig, C., Schewe, J. and Warszawski, L., 2014, 'Climate impact research: Beyond patchwork', *Earth System Dynamics* 5(2), 399–408 (doi: 10.5194/esd-5-399-2014).

IMPACT2C project, 2015, *IMPACT2C project — final report*, Helmholtz-Zentrum Geesthacht (HZG), Geesthacht.

Jäger, J., Rounsevell, M. D. A., Harrison, P. A., Omann, I., Dunford, R., Kammerlander, M. and Pataki, G., 2015, 'Assessing policy robustness of climate change adaptation measures across sectors and scenarios', *Climatic Change* 128(3–4), 395–407 (doi: 10.1007/s10584-014-1240-y).

Kebede, A. S., Dunford, R., Mokrech, M., Audsley, E., Harrison, P. A., Holman, I. P., Nicholls, R. J., Rickebusch, S., Rounsevell, M. D. A., Sabaté, S., Sallaba, F., Sanchez, A., Savin, C., Trnka, M. and Wimmer, F., 2015, 'Direct and indirect impacts of climate and socio-economic change in Europe: A sensitivity analysis for key land- and water-based sectors', *Climatic Change* 128(3–4), 261–277 (doi: 10.1007/s10584-014-1313-y).

Kok, K., Bärlund, I., Flörke, M., Holman, I., Gramberger, M., Sendzimir, J., Stuch, B. and Zellmer, K., 2015, 'European participatory scenario development: Strengthening the link between stories and models', *Climatic Change* 128(3–4), 187–200 (doi: 10.1007/s10584-014-1143-y).

Lung, T., Lavalle, C., Hiederer, R., Dosio, A. and Bouwer, L. M., 2013, 'A multi-hazard regional level impact assessment for Europe combining indicators of climatic and non-climatic change', *Global Environmental Change* 23(2), 522–536 (doi: 10.1016/j.gloenvcha.2012.11.009).

Parry, M., Canziani, O., Palutikof, J., van der Linden, P. and Hanson, C., 2007, *Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Piontek, F., Müller, C., Pugh, T. A. M., Clark, D. B., Deryng, D., Elliott, J., González, F. de J. C., Flörke, M., Folberth, C., Franssen, W., Frieler, K., Friend, A. D., Gosling, S. N., Hemming, D., Khabarov, N., Kim, H., Lomas, M. R., Masaki, Y., Mengel, M. et al., 2014, 'Multisectoral climate impact hotspots in a warming world', *Proceedings of the National Academy of Sciences* 111(9), 3 233–3 238 (doi: 10.1073/pnas.1222471110).

Section 6.3: Projected economic impacts of climate change in Europe

ASC, 2014, *Managing climate risks to well-being and the economy*, Adaptation Sub-Committee Progress Report 2014, UK Committee on Climate Change, Adaptation Sub-Committee (ASC), London.

Barrios, S., Ibañez Rivas, J. N. and Institute for Prospective Technological Studies, 2013, *Tourism demand, climatic conditions and transport costs report for the PESETA II study on the impact of climate change in Europe*, Publications Office, Luxembourg.

BoG, 2011, *The environmental, economic, and social impacts of climate change in Greece*, Bank of Greece, Athens.

Brown, S., Lincke, D., Nicholls, R. and Hinkel, J., 2015, *The impacts of sea-level rise on European coasts in a 2°C world. Results and analysis of task 6.5 prepared as part of IMPACT2C: Quantifying project impacts under 2°C warming*, IMPACT2C project, Deliverable 6.2, University of Southampton, Southampton.

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

Delta Programme, 2010, *Delta Programme 2011: Working on the delta — Investing in a safe and attractive Netherlands, now and in the future*, The Ministry of Infrastructure and the Environment, The Ministry of Economic Affairs, The Hague.

Delta Programme, 2013, *Delta Programme 2014: Working on the delta — Promising solutions for tasking and ambitions*, The Ministry of Infrastructure and the Environment, The Ministry of Economic Affairs, The Hague.

Deltacommissie, 2008, Working together with water. A living land builds for its future. Findings of the Deltacommissie.

EA, 2012, *Thames estuary 2100: Managing flood risk through London and the Thames estuary. TE2100 plan*, UK Environment Agency, Bristol.

EA, 2014, *Flood and coastal erosion risk management — Long-term investment scenarios (LTIS) 2014*, UK Environment Agency, Bristol.

ECONADAPT, 2015, *The costs and benefits of adaptation: Results from the ECONADAPT project*, ECONADAPT Policy Report 1, ECONADAPT consortium.

Eijgenraam, C., Kind, J., Bak, C., Brekelmans, R., den Hertog, D., Duits, M., Roos, K., Vermeer, P. and Kuijken, W., 2014, 'Economically efficient standards to protect the Netherlands against flooding', *Interfaces* 44(1), 7–21 (doi: 10.1287/inte.2013.0721).

HMG, 2013, *The national adaptation programme report: Analytical annex — Economics of the national adaptation programme*, HM Government, London.

IMPACT2C project, 2015, *IMPACT2C project - final report*, Helmholtz-Zentrum Geesthacht (HZG), Geesthacht.

Kind, J. M., 2014, 'Economically efficient flood protection standards for the Netherlands', *Journal of Flood Risk Management* 7(2), 103–117 (doi: 10.1111/jfr3.12026).

Kovats, S., Lloyd, S., Hunt, A. and Watkiss, P., 2011, *The impacts and economic costs on health in Europe and the costs and benefits of adaptation*, Technical policy briefing note 5, FP7 ClimateCost project.

Lacressonnière, G., Vautard, R., Siour, G., Cheiney, A., Forêt, G., Beekmann, M., Watson, L., Marécal, V., Josse, B., Gauss, M., Nyiri, A., Engardt, M., Andersson, C., Watkiss, P., Hunt, A., Kendrovski, V., Menne, B., Wolf, T., Sanchez Martinez, G. et al., 2015, *Design and production of an ensemble of air quality simulations and evaluation of health impacts*, IMPACT2C project, Deliverable 6.2, CNRS-IPS.

Mima, S. and Criqui, P., 2015, 'The costs of climate change for the European energy system, an assessment with the POLES model', *Environmental Modeling & Assessment* 20(4), 303–319 (doi: 10.1007/s10666-015-9449-3).

Mima, S., Criqui, P. and Watkiss, P., 2011, 'The impacts and economic costs of climate change on energy in Europe', in: Watkiss, P. (ed), *The ClimateCost Project. Final Report*, Stockholm Environment Institute, Stockholm.

Navarra, A. and Tubiana, L. (eds), 2013, *Regional assessment of climate change in the Mediterranean*, Advances in Global Change Research, Springer Netherlands, Dordrecht.

Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., Lampe, M. V., Lotze-Campen, H., d'Croz, D. M., Meijl, H. van, Mensbrugghe, D. van der, Müller, C., Popp, A., Robertson, R. et al., 2014, 'Climate change effects on agriculture: Economic responses to biophysical shocks', *Proceedings of the National Academy of Sciences* 111(9), 3 274–3 279 (doi: 10.1073/pnas.1222465110).

Nokkala, M., Leviäkangas, P. and Oiva, K., 2012, *The costs of extreme weather for the European transport systems*, EWENT project, Deliverable 4, VTT Technology.

Perrels, A., Heyndrickx, C., Prettenthaler, F., Kortschak, D., Ciari, F., Bösch, P., Kiviluoma, J., Azevedo, M., Ekholm, T., Crawford-Brown, D. and Thompson, A., 2015, *Sectoral and cross-cutting multi-sector adaptation strategies for energy, transport and tourism*, ToPDAd project, Deliverable 2.4.

Przyluski, V., Hallegatte, S., Nadaud, F., Tomozeiu, R., Cacciamani, C., Pavan, V. and Doll, C., 2011, *Weather trends and economy-wide impacts: WEATHER Project D1*, WEATHER project, Deliverable 1, Fraunhofer — ISI, Karlsruhe.

Rosselló-Nadal, J., 2014, 'How to evaluate the effects of climate change on tourism', *Tourism Management* 42, 334–340 (doi: 10.1016/j.tourman.2013.11.006).

Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W. and Ludwig, F., 2016, 'Projections of future floods and hydrological droughts in Europe under a +2°C global warming', *Climatic Change* 135, 341–355 (doi: 10.1007/s10584-015-1570-4).

SCCV, 2007, *Sweden facing climate change — Threats and opportunities*, Final report from the Swedish Commission on Climate and Vulnerability (SCCV), Stockholm.

Tröltzsch, J., Görlach, B., Lückge, H., Peter, M. and Sartorius, C., 2012, *Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel — Analyse von 28 Anpassungsmaßnahmen in Deutschland*, Climate Change 10/2012, Federal Environment Agency, Dessau.

Urban, H. and Steininger, K. W., 2015, 'Manufacturing and trade: Labour productivity losses', in: Steininger, K. W., König, M., Bednar-Friedl, B., et al. (eds), *Economic evaluation of climate change impacts: Development of a cross-sectoral framework and results for Austria*, Springer Climate, Springer International Publishing, pp. 301–322.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O., Nikulin, G., Teichmann, C. and Jacob, D., 2014, 'The European climate under a 2 °C global warming', *Environmental Research Letters* 9(3), 34006 (doi: 10.1088/1748-9326/9/3/034006).

Watkiss, P. (ed), 2011, *The ClimateCost Project. Final Report*, Stockholm Environment Institute, Stockholm.

Watkiss, P., Hunt, A., Rouillard, J., Tröltzsch, J. and Lago, M., 2015, 'Chapter 3: Overview of costs and benefits of adaptation at the national and regional scale', in: *Climate change risks and adaptation — Linking policy and economics*, OECD Publishing, Paris.

Section 6.4: Europe's vulnerability to climate change impacts outside Europe

Arent, D. J., Tol, R. S. J., Faust, E., Hella, J. P., Kumar, S., Strzepek, K. M., Tóth, F. L. and Yan, D., 2014, 'Key economic sectors and services', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 659–708.

Barnett, Duffy, L., de Carlos, A., Tyrer, D., Esparrago, J., Williams, E., Chenot, B., Barker, A., Stenning, J., McGiunn, J., Cools, J., Nolet, G., Hernandez, G. and Lawlor, N., 2013, *Assessing the spillover effects in the EU of the adverse effects of climate change in the rest of the world, in particular the EU's Neighbourhood countries*, A report commissioned by the European Commission — DG CLIMA, AMEC Environment and Infrastructure UK, Bio Intelligence Service, Cambridge Econometrics and Milieu Limited.

Benzie, M., Hedlund, J. and Carlsen, H., 2016, *Introducing the transnational climate impacts index: Indicators of country-level exposure — Methodology report*, SEI Working Paper No 2016-07, Stockholm Environment Institute, Stockholm.

Biermann, F. and Boas, I., 2010, 'Preparing for a warmer world: Towards a global governance system to protect climate refugees', *Global Environmental Politics* 10(1), 60–88.

Birkmann, J. and Welle, T., 2015, 'Assessing the risk of loss and damage: Exposure, vulnerability and risk to climate-related hazards for different country classifications', *International Journal of Global Warming* 8(2), 191 (doi: 10.1504/IJGW.2015.071963).

Brauch, H. G., 2010, *Climate change and Mediterranean security: International, national, environmental and human security impacts for the Euro-Mediterranean region during the 21st century — Proposals and perspectives*, Institut Europeu de la Mediterrània (IEMed).

Burke, M., Hsiang, S. M. and Miguel, E., 2015, 'Global non-linear effect of temperature on economic production', *Nature* 527(7577), 235–239 (doi: 10.1038/nature15725).

Challinor, A. and Adger, W. N., 2016, 'International dimensions', in: *UK Climate Change Risk Assessment 2017: Evidence Report*, Committee on Climate Change, London, chapter 7.

Chen, C., Noble, I., Hellmann, J., Coffee, J., Murillo, M. and Chawla, N., 2015, *University of Notre Dame Global Adaptation Index — Country index technical report*, University of Notre Dame, South Bend, Indiana.

Coghlan, C., Muzammil, M., Ingram, J., Vervoort, J., Otto, F. and James, R., 2014, *A sign of things to come? Examining four major climate-related disasters, 2010-2013, and their impacts on food security*, Oxfam Research Reports, Oxfam.

Dell, M., Jones, B. F. and Olken, B. A., 2012, 'Temperature Shocks and Economic Growth: Evidence from the Last Half Century', *American Economic Journal: Macroeconomics* 4(3), 66–95 (doi: 10.1257/mac.4.3.66).

Dell, M., Jones, B. F. and Olken, B. A., 2014, 'What Do We Learn from the Weather? The New Climate-Economy Literature', *Journal of Economic Literature* 52(3), 740–798 (doi: 10.1257/jel.52.3.740).

Diffenbaugh, N. S. and Giorgi, F., 2012, 'Climate change hotspots in the CMIP5 global climate model ensemble', *Climatic Change* 114(3–4), 813–822 (doi: 10.1007/s10584-012-0570-x).

EC, 2013, Joint Communication to the European Parliament and the Council 'The EU's comprehensive approach to external conflict and crises', JOIN(2013) 30 final.

EC, 2015a, Achieving the 10% electricity interconnection target making Europe's electricity grid fit for 2020, COM/2015/082 final, Brussels.

EC, 2015b, *Migration in response to environmental change*, Science for Environment Policy, Publications Office, Luxembourg.

EEA, 2015, *The European environment — state and outlook 2015: Assessment of global megatrends*, European Environment Agency.

Eurostat, 2016, 'International trade statistics' (http://ec.europa.eu/eurostat/web/international-trade/data/database) accessed 3 May 2016.

Foresight, 2011, *International dimensions of climate change*, Final project report, The Government Office for Science, London.

Gemenne, F., 2011, 'Climate-induced population displacements in a 4°C+ world', *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 369(1934), 182–195 (doi: 10.1098/rsta.2010.0287).

Gleick, P. H., 2014, 'Water, drought, climate change, and conflict in Syria', *Weather, Climate, and Society* 6(3), 331–340 (doi: 10.1175/WCAS-D-13-00059.1).

Groundstroem, F., Carter, T. R. and Hildén, M., 2015, *International dimensions of climate change: Implications for Finland*, Finnish Environment Institute (SYKE), Helsinki.

Hallegatte, S., 2012, 'A framework to investigate the economic growth impact of sea level rise', *Environmental Research Letters* 7(1), 15604 (doi: 10.1088/1748-9326/7/1/015604).

Herweijer, C., Ranger, N. and Ward, R. E., 2009, 'Adaptation to climate change: Threats and opportunities for the insurance industry', *The Geneva Papers* 34(3), 360–380 (doi: 10.1057/gpp.2009.13).

Hewitson, B., Janetos, A. C., Carter, T. R., Giorgi, F., Jones, R. G., Kwon, W.-T., Mearns, L. O., Schipper, E. L. F. and van Aalst, M., 2014, 'Regional context', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 1 133–1 197.

Houghton, K. J., Vafeidis, A. T., Neumann, B. and Proelss, A., 2010, 'Maritime boundaries in a rising sea', *Nature Geoscience* 3(12), 813–816 (doi: 10.1038/ngeo1029).

Hsiang, S. M., Burke, M. and Miguel, E., 2013, 'Quantifying the influence of climate on human conflict', *Science* 341(6151), 1235367 (doi: 10.1126/science.1235367).

IDMC and NRC, 2015, *Global estimates 2015: People displaced by disasters*, Internal Displacement Monitoring Centre and Norwegian Refugee Council, Geneva.

IPCC, 2012, *Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2013, 'Summary for policymakers', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York.

IPCC, 2014, 'Summary for policymakers', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 1–32.

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R. and Kushnir, Y., 2015, 'Climate change in the Fertile Crescent and implications of the recent Syrian drought', *Proceedings of the National Academy of Sciences* 112(11), 3 241–3 246 (doi: 10.1073/pnas.1421533112).

Kron, W., 2012, 'Coasts: The high-risk areas of the world', *Natural Hazards* 66(3), 1 363–1 382 (doi: 10.1007/s11069-012-0215-4).

Lilleør, H. B. and Van den Broeck, K., 2011, 'Economic drivers of migration and climate change in LDCs', *Global Environmental Change* 21(Suppl. 1), S70–S81 (doi: 10.1016/j.gloenvcha.2011.09.002).

Mabey, N., Cook, R., Schulz, S. and Schwartzkoppff, J., 2014, *Underfunded, underprepared, underwater? Cities at risk*, E3G, London.

Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., Sanchez, J. J., Kaiser, L. R., Stender, Y. O., Anderson, J. M., Ambrosino, C. M., Fernandez-Silva, I., Giuseffi, L. M. and Giambelluca, T. W., 2013, 'The projected timing of climate departure from recent variability', *Nature* 502(7470), 183–187 (doi: 10.1038/nature12540).

Mulligan, M., Burke, S. and Douglas, C., 2014, 'Environmental change and migration between Europe and its neighbours', in: Piguet, E. and Laczko, F. (eds), *People on the move in a changing climate*, Global Migration Issues, Springer Netherlands, Dordrecht, pp. 49–79.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, E., Lennard, C., Padgham, J. and Urquhart, P., 2014, 'Africa', in: Barros, V. R., Field, C. B., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 1 199–1 265.

Nicholls, R. J. and Kebede, A. S., 2012, 'Indirect impacts of coastal climate change and sea-level rise: The UK example', *Climate Policy* 12(Suppl. 1), S28–S52 (doi: 10.1080/14693062.2012.728792).

Oh, C. H. and Reuveny, R., 2010, 'Climatic natural disasters, political risk, and international trade', *Global Environmental Change* 20(2), 243–254 (doi: 10.1016/j.gloenvcha.2009.11.005).

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B. and Takahashi, K., 2014, 'Emergent risks and key vulnerabilities', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 1 039–1 099.

Pal, J. S. and Eltahir, E. A. B., 2016, 'Future temperature in southwest Asia projected to exceed a threshold for human adaptability', *Nature Climate Change* 6, 197–200 (doi: 10.1038/nclimate2833).

Porter, J. R., Xie, L., Challinor, A. J., Cochrane, K., Howden, S. M., Iqbal, M. M., Lobell, D. B. and Travasso, M. I., 2014, 'Food security and food production systems', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York, pp. 485–533.

PwC, 2013, *International threats and opportunities of climate change for the UK*, A study commissioned by the UK Government's National Adaptation Programme, PricewaterhouseCoopers.

Rodrigues De Brito, R., 2012, 'The securitisation of climate change in the European Union', in: *Global Security Risks and West Africa*, OECD Publishing, Paris.

Rüttinger, L., Smith, D., Stang, G., Tänzler, D. and Vivekananda, J., 2015, *A new climate for peace — Taking action on climate and fragility risks*, An independent report commissioned by the G7 members, Adelphi, International alert, The Wilson Center, The European Union Institute for Security Studies.

Smith, L. C. and Stephenson, S. R., 2013, 'New Trans-Arctic shipping routes navigable by midcentury', *Proceedings of the National Academy of Sciences* 110(13), 4 871–4 872 (doi: 10.1073/pnas.1214212110).

Stephan, G. and Schenker, O., 2012, *International trade and the adaptation to climate change and variability*, Research Paper 2012/01, NCCR Climate, Bern.

Stephenson, S. R., Smith, L. C., Brigham, L. W. and Agnew, J. A., 2013, 'Projected 21st-century changes to Arctic marine access', *Climatic Change* 118(3–4), 885–899 (doi: 10.1007/s10584-012-0685-0).

Theisen, O. M., Gleditsch, N. P. and Buhaug, H., 2013, 'Is climate change a driver of armed conflict?', *Climatic Change* 117(3), 613–625 (doi: 10.1007/s10584-012-0649-4).

Trostle, R., Marti, D., Rosen, S. and Westcott, P., 2011, *Why have food commodity prices risen again?*, A Report from the Economic Research Service WRS-1103, United States Department of Agriculture, Washington, DC.

UNEP, 2011, *Livelihood security — Climate change, migration and conflict in the Sahel*, United Nations Environment Program, Geneva.

US Government, 2015, National security strategy, February 2015, White House, Washington, DC.

Vonk, M., Bouwman, A., Van Dorland, R. and Eerens, H., 2015, *Worldwide climate effects: Risks and opportunities for the Netherlands*, PBL publication number 1412, PBL Netherlands Environmental Assessment Agency, The Hague.

Welle, T. and Birkmann, J., 2015, 'The World Risk Index — An approach to assess risk and vulnerability on a global scale', *Journal of Extreme Events* 2(1), 1550003 (doi: 10.1142/S2345737615500037).

Section 6.5: Vulnerability to climate change in European macro-regions

ACA, 2009, *Agua y cambio climático — Diagnosis de los impactos previstos en Cataluña*, Agència Catalana de l'Aigua, Barcelona.

AEMET, 2008, 'Generación de escenarios regionalizados de cambio climatico' (http://www.aemet.es/es/idi/clima/escenarios_CC) accessed 30 August 2016.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A. et al., 2010, 'A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests', *Forest Ecology and Management* 259(4), 660–684 (doi: 10.1016/j.foreco.2009.09.001).

AMAP, 2011, *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate change and the cryosphere*, Arctic Monitoring and Assessment Programme, Oslo.

AMAP, 2013, *Adaptation actions for a changing Arctic*, Part A, Arctic Monitoring and Assessment Programme, Oslo.

AMAP, 2014, *Arctic Ocean acidification 2013: An overview*, Arctic Monitoring and Assessment Programme, Oslo.

Arctic Council, 2013, *Arctic resilience interim report 2013*, Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm.

Arias, R., Rodríguez-Blanco, M., Taboada-Castro, M., Nunes, J., Keizer, J. and Taboada-Castro, M., 2014, 'Water resources response to changes in temperature, rainfall and CO_2 concentration: A first approach in NW Spain', *Water* 6(10), 3 049–3 067 (doi: 10.3390/w6103049).

Auer, I., Böhm, R., Jurkovic, A., Lipa, W., Orlik, A., Potzmann, R., Schöner, W., Ungersböck, M., Matulla, C., Briffa, K., Jones, P., Efthymiadis, D., Brunetti, M., Nanni, T., Maugeri, M., Mercalli, L., Mestre, O., Moisselin, J.-M., Begert, M. et al., 2007, 'HISTALP — Historical instrumental climatological surface time series of the Greater Alpine Region', *International Journal of Climatology* 27(1), 17–46 (doi: 10.1002/joc.1377).

Auer, I., Böhm, R., Jurkovic, A., Orlik, A., Potzmann, R., Schöner, W., Ungersbäck, M., Brunetti, M., Nanni, T., Maugeri, M., Briffa, K., Jones, P., Efthymiadis, D., Mestre, O., Moisselin, J.-M., Begert, M., Brazdil, R., Bochnicek, O., Cegnar, T. et al., 2005, 'A new instrumental precipitation dataset for the greater alpine region for the period 1800–2002', *International Journal of Climatology* 25(2), 139–166 (doi: 10.1002/joc.1135).

Auer, I., Foelsche, U., Böhm, R., Chimani, B., Haimberger, L., Kerschner, H., Koinig, K. A., Nicolussi, K. and Spötl, C., 2014, ‚Vergangene Klimaänderung in Österreich', in: *Österreichischer Sachstandsbericht Klimawandel 2014 [Austrian assessment report 2014] (AAR14)*, Verlag der Österreichischen Akademie der Wissenschaften, Wien, pp. 227–300.

Ballarin-Denti, A., Cetara, L. and Idone, M. T. (eds), 2014, Guidelines for climate change adaptation at the local level in the Alps, Alpine Convention.

Barcza, Z., Bodea, L., Csóka, G., Dobor, L., Galvánek, D., György, D., Hidy, D., Hlásny, T., Holusa, J., Ionascu, A., Iosif, A., Janisová, M., Lukásová, K., Mális, F., Mátyás, C., Merganic, J., Merganicová, K., Monnier, C., Musat, C. et al., 2013, *In-depth study on the impacts of climate change threats on ecosystems*, CarpathCC project, Deliverable Final Report for SR 2, The Regional Environmental Center for Central and Eastern Europe, Szentendre.

Benzaken, D. and Renard, Y. (eds), 2011, *Future directions for biodiversity action in Europe overseas*, IUCN, Gland.

BMU, 2008, *Klimawandel in den Alpen. Fakten — Folgen — Anpassung*, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, BMU, Berlin.

Boisvert, L. N. and Stroeve, J. C., 2015, 'The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder', *Geophysical Research Letters* 42(11), 4 439–4 446 (doi: 10.1002/2015GL063775).

Bréda, N., Huc, R., Granier, A. and Dreyer, E., 2006, 'Temperate forest trees and stands under severe drought: A review of ecophysiological responses, adaptation processes and long-term consequences', *Annals of Forest Science* 63(6), 625–644 (doi: 10.1051/forest:2006042).

Brisson, N. and Levrault, F., 2012, *Livre vert du projet CLIMATOR: 2007-2010 — Changement climatique, agriculture et forêt en France: Simulations d'impacts sur les principales espèces*, ADEME, Angers.

Chierici, M. and Fransson, A., 2009, 'Calcium carbonate saturation in the surface water of the Arctic Ocean: Undersaturation in freshwater influenced shelves', *Biogeosciences* 6(11), 2 421–2 431 (doi: 10.5194/bg-6-2421-2009).

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G. et al., 2005, 'Europe-wide reduction in primary productivity caused by the heat and drought in 2003', *Nature* 437(7058), 529–533 (doi: 10.1038/nature03972).

CliC, AMAP and IASC, 2016, *The Arctic freshwater system in a changing climate*, WCRP Climate and Cryosphere (CliC) Project, Arctic Monitoring and Assessment Programme (AMAP), International Arctic Science Committee (IASC).

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M., 2013, 'Long-term climate change: Projections, commitments and irreversibility', in: Stocker, T. F., Qin, D., Plattner, G.-K., et al. (eds), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 1 029–1 136.

Confederación Hidrográfica del Ebro, 2005, *Evaluación preliminar de la incidencia del cambio climático en los recursos hídricos de la cuenca del Ebro*, Ministerio de Medio Ambiente, Madrid.

CTP and OPCC, 2012, *Pyrenees Climate Change Observatory — Integrating climate change adaptation into your activities and policies*, OPCC (Observatoire Pyrénéen du Changement Climatique), CTP (Communauté de Travail des Pyrénées), Jaca.

Déqué, M. (ed), 2012, *Scénarios Climatiques Adaptés aux zones de Montagne: Phénomènes extrêmes, Enneigement et Incertitudes*, Scampei — Project ANR-08-VULN-0009-01, Agence Nationale de la Recherche, Paris.

Dullinger, S., Gattringer, A., Thuiller, W., Moser, D., Zimmermann, N. E., Guisan, A., Willner, W., Plutzar, C., Leitner, M., Mang, T., Caccianiga, M., Dirnböck, T., Ertl, S., Fischer, A., Lenoir, J., Svenning, J.-C., Psomas, A., Schmatz, D. R., Silc, U. et al., 2012, 'Extinction debt of high-mountain plants under twenty-first-century climate change', *Nature Climate Change* 2(8), 619–622 (doi: 10.1038/nclimate1514).

EC, 2009a, *The economics of climate change adaptation in EU coastal areas. Country overview and assessment: Outermost regions*, European Commission, Brussels.

EC, 2009b, *The economics of climate change adaptation in EU coastal areas. Study done on behalf of the European Commission*, European Commission, Brussels.

EC, 2014a, *The economic impact of climate change and adaptation in the Outermost Regions. Executive summary.*, Publications Office, Luxembourg.

EC, 2014b, *The economic impact of climate change and adaptation in the Outermost Regions. Final report*, European Commission, Luxembourg.

EC, 2015a, 'Overseas Countries and Territories environmental profiles (2015)' (https://ec.europa.eu/europeaid/overseas-countries-and-territories-environmental-profiles-2015_en) accessed 17 March 2016.

EC, 2015b, *Overseas Countries and Territories: Environmental profiles. Part 1 — Main report*, EuropeAid/127054/C/SER/multi, European Commission, Brussels.

EEA, 2009, *Regional climate change and adaptation — The Alps facing the challenge of changing water resources*, EEA Report No 8/2009, European Environment Agency.

EEA, 2010, *Europe's ecological backbone: Recognising the true value of our mountains*, EEA Report No 6/2010, European Environment Agency.

EEA, 2012, *Climate change, impacts and vulnerability in Europe 2012*, EEA Report No 12/2012, European Environment Agency.

EEA, 2015, *SOER 2015: The European environment — state and outlook 2015*, European Environment Agency.

Engler, R., Randin, C. F., Thuiller, W., Dullinger, S., Zimmermann, N. E., AraúJo, M. B., Pearman, P. B., Le Lay, G., Piedallu, C., Albert, C. H., Choler, P., Coldea, G., De LAMO, X., DirnböCk, T., GéGout, J.-C., GóMez-GarcíA, D., Grytnes, J.-A., Heegaard, E., HøIstad, F. et al., 2011, '21st century climate change threatens mountain flora unequally across Europe: Climate change impacts on mountain florae', *Global Change Biology* 17(7), 2 330–2 341 (doi: 10.1111/j.1365-2486.2010.02393.x).

Felten, B., 2010, *Projet VALIDATE: Vulnérabilité des prairies et des élevages au changement climatique et aux évènements extrêmes, Rapport intermédiaire de la contribution au WP5 'adaptation des fermes d'élevage'*, INRA.

Fuhrer, J., Beniston, M., Fischlin, A., Frei, C., Goyette, S., Jasper, K. and Pfister, C., 2006, 'Climate risks and their impact on agriculture and forests in Switzerland', *Climatic Change* 79(1–2), 79–102 (doi: 10.1007/s10584-006-9106-6).

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta-Martínez, T. and Beguería, S., 2011, 'Mediterranean water resources in a global change scenario', *Earth-Science Reviews* 105(3), 121–139.

Giorgi, F., 2006, 'Climate change hot-spots', *Geophysical Research Letters* 33(8), L08707 (doi: 10.1029/2006GL025734).

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J. and Stoffel, M., 2014, '21st century climate change in the European Alps — A review', *Science of The Total Environment* 493, 1 138–1 151 (doi: 10.1016/j.scitotenv.2013.07.050).

Gofman, V. and Smith, M., 2009, *Bering Sea Sub-Network Pilot Phase Final Report 2009*, CAFF Monitoring Series Report No. 2, Conservation of Arctic Flora and Fauna, Akureyri.

Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barančok, P., Benito Alonso, J. L., Coldea, G., Dick, J., Erschbamer, B., Fernández Calzado, M. R., Kazakis, G., Krajči, J., Larsson, P., Mallaun, M., Michelsen, O., Moiseev, D., Moiseev, P., Molau, U., Merzouki, A. et al., 2012, 'Continent-wide response of mountain vegetation to climate change', *Nature Climate Change* 2(2), 111–115 (doi: 10.1038/nclimate1329).

Gräwe, U. and Burchard, H., 2012, 'Storm surges in the Western Baltic Sea: The present and a possible future', *Climate Dynamics* 39(1–2), 165–183 (doi: 10.1007/s00382-011-1185-z).

Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., Braun, A., Calmanti, S., Carillo, A., Dell'Aquila, A., Déqué, M., Dubois, C., Elizalde, A., Harzallah, A., Jacob, D., L'Hévéder, B., May, W., Oddo, P., Ruti, P. et al., 2013, 'The CIRCE simulations: Regional climate change projections with realistic representation of the Mediterranean Sea', *Bulletin of the American Meteorological Society* 94(1), 65–81 (doi: 10.1175/BAMS-D-11-00136.1).

Gunawardhana, L. N. and Kazama, S., 2012, 'A water availability and low-flow analysis of the Tagliamento River discharge in Italy under changing climate conditions', *Hydrology and Earth System Sciences* 16(3), 1 033–1 045 (doi: 10.5194/hess-16-1033-2012).

Haslinger, K., Schöner, W. and Anders, I., 2015, 'Future drought probabilities in the Greater Alpine Region based on COSMO-CLM experiments — Spatial patterns and driving forces', *Meteorologische Zeitschrift* 25(2), 127–138 (doi: 10.1127/metz/2015/0604).

Herrmann, C., Bregnballe, T., Larsson, K. and Rattiste, K., 2014, Population development of Baltic bird species: Great cormorant (Phalacrocorax carbo sinensis), HELCOM Baltic Sea environment fact sheets. Available at: http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/.

Hinrichsen, H.-H., Huwer, B., Makarchouk, A., Petereit, C., Schaber, M. and Voss, R., 2011, 'Climate-driven long-term trends in Baltic Sea oxygen concentrations and the potential consequences for eastern Baltic cod (Gadus morhua)', *ICES Journal of Marine Science* 68(10), 2 019–2 028 (doi: 10.1093/icesjms/fsr145).

Hoff, H., 2013, 'Vulnerability of Ecosystem Services in the Mediterranean Region to Climate Changes in Combination with Other Pressures', in: Navarra, A. and Tubiana, L. (eds), *Regional Assessment of Climate Change in the Mediterranean*, Advances in Global Change Research, Springer Netherlands, Dordrecht, pp. 9–29.

Huss, M., 2012, 'Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100', *The Cryosphere* 6(4), 713–727 (doi: 10.5194/tc-6-713-2012).

IPCC, 2014, *Climate change 2014: Impacts, adaptation and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

Jump, A. S., Hunt, J. M. and Peñuelas, J., 2006, 'Rapid climate change-related growth decline at the southern range edge of Fagus sylvatica', *Global Change Biology* 12(11), 2 163–2 174 (doi: 10.1111/j.1365-2486.2006.01250.x).

Kuglitsch, F., Toreti, A., Xoplaki, E., Della-Marta, P., Zerefos, C., Türkeş, M. and Luterbacher, J., 2010, 'Heat wave changes in the eastern Mediterranean since 1960', *Geophysical Research Letters* 37, L04802 (doi: 10.1029/2009GL041841).

López-Moreno, J. I. and Beniston, M., 2009, 'Daily precipitation intensity projected for the 21st century: Seasonal changes over the Pyrenees', *Theoretical and Applied Climatology* 95(3–4), 375–384 (doi: 10.1007/s00704-008-0015-7).

López-Moreno, J. I., Goyette, S. and Beniston, M., 2008, 'Climate change prediction over complex areas: Spatial variability of uncertainties and predictions over the Pyrenees from a set of regional climate models', *International Journal of Climatology* 28(11), 1 535–1 550 (doi: 10.1002/joc.1645).

MEDDE, 2013, *Synthèse du projet Explore 2070 — Hydrologie de surface*, Ministère de l'Écologie, du Développement durable et de l'Énergie, Paris.

Meier, H. E. M., Müller-Karulis, B., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G., Höglund, A., Hordoir, R., Kuznetsov, I., Neumann, T., Ranjbar, Z., Savchuk, O. P. and Schimanke, S., 2012, 'Impact of climate change on ecological quality indicators and biogeochemical fluxes in the Baltic Sea: A multi-model ensemble study', *AMBIO* 41(6), 558–573 (doi: 10.1007/s13280-012-0320-3).

Meltofte, H. (ed), 2013, *Arctic biodiversity assessment. Status and trends in Arctic biodiversity*, Conservation of Arctic Flora and Fauna, Akureyri.

Mereu, V., Iocola, I., Spano, D., Murgia, V., Duce, P., Cesaraccio, C., Tubiello, F. N. and Fischer, G., 2008, 'Land suitability and potential yield variations of wheat and olive crops determined by climate change in Italy', *Italian Journal of Agronomy* 3(3, Suppl.), 797–798.

Mitter, H., Schönhart, M., Meyer, I., Mechtler, K., Schmid, E., Sinabell, F., Bachner, G. and Bednar-Friedl, B., 2015, ,Agriculture', in: Steininger, K., König, M., Bednar-Friedl, B., et al. (eds), *Economic evaluation of climate change impacts: Development of a cross-sectoral framework and results for Austria*, Springer, Cham, pp. 123–146.

Navarra, A. and Tubiana, L. (eds), 2013a, *Regional assessment of climate change in the Mediterranean. Volume 1: Air, Sea and precipitation and water*, Advances in Global Change Research, Springer Netherlands, Dordrecht.

Navarra, A. and Tubiana, L. (eds), 2013b, *Regional assessment of climate change in the Mediterranean. Volume 2: Agriculture, forests and ecosystem services and people*, Advances in Global Change Research, Springer Netherlands, Dordrecht.

Neumann, T., 2010, 'Climate-change effects on the Baltic Sea ecosystem: A model study', *Journal of Marine Systems* 81(3), 213–224 (doi: 10.1016/j.jmarsys.2009.12.001).

Neumann, T., Eilola, K., Gustafsson, B., Müller-Karulis, B., Kuznetsov, I., Meier, H. E. M. and Savchuk, O. P., 2012, 'Extremes of temperature, oxygen and blooms in the Baltic Sea in a changing climate', *AMBIO* 41(6), 574–585 (doi: 10.1007/s13280-012-0321-2).

Nordström, M., Högmander, J., Laine, J., Nummelin, J., Laanetu, N. and Korpimäki, E., 2003, 'Effects of feral mink removal on seabirds, waders and passerines on small islands in the Baltic Sea', *Biological Conservation* 109(3), 359–368 (doi: 10.1016/S0006-3207(02)00162-3).

Omstedt, A., Edman, M., Claremar, B., Frodin, P., Gustafsson, E., Humborg, C., Hägg, H., Mörth, M., Rutgersson, A., Schurgers, G., Smith, B., Wällstedt, T. and Yurova, A., 2012, 'Future changes in the Baltic Sea acid–base (pH) and oxygen balances', *Tellus B* 64, 19586 (doi: 10.3402/tellusb.v64i0.19586).

OPCC, 2015, *PROYECTO OPCC-POCTEFA — Resultados Mayo 2014 Revisión 201*, OPCC (Observatoire Pyrénéen du Changement Climatique), CTP (Communauté de Travail des Pyrénées), Jaca.

OPCC and CTP, 2013, *Observatoire Pyrénéen du Changement Climatique — Etude sur l'adaptation au changement climatique dans les Pyrénées*, OPCC (Observatoire Pyrénéen du Changement Climatique), CTP (Communauté de Travail des Pyrénées), Jaca.

Overland, J., Hanna, E., Hanssen-Bauer, I., Kim, S.-J., Walsh, J., Wang, M. and Bhatt, U. S., 2014, 'Air temperature' (http://www.arctic.noaa.gov/reportcard/air_temperature.html) accessed 23 October 2015.

Pape, R. and Löffler, J., 2012, 'Climate change, land use conflicts, predation and ecological degradation as challenges for reindeer husbandry in Northern Europe: What do we really know after half a century of research?', *AMBIO* 41(5), 421–434 (doi: 10.1007/s13280-012-0257-6).

Permanent Secretariat of the Alpine Convention (ed), 2011, *Sustainable rural development and innovation*, Report on the state of the Alps, Alpine Signals, Special edition 3, Permanent Secretariat of the Alpine Convention, Innsbruck; Bolzano.

Permanent Secretariat of the Alpine Convention (ed), 2015, *Demographic changes in the Alps*, Report on the State of the Alps, Alpine Signals, Special edition 5, Permanent Secretariat of the Alpine Convention, Innsbruck; Bolzano.

Petit, J. and Prudent, G. (eds), 2010, *Climate change and biodiversity in the European Union overseas entities*, Reprint, IUCN, Gland; Brussels.

Pons, M., López Moreno, J. I., Esteban, P., Macià, S., Gavaldà, J., García, C., Rosas-Casals, M. and Jover, E., 2014, 'Influencia del cambio climático en el turismo de nieve del Pirineo. Experiencia del proyecto de investigación NIVOPYR', *Pirineos* 169, e006 (doi: 10.3989/Pirineos.2014.169006).

Pons, M., López-Moreno, J. I., Rosas-Casals, M. and Jover, È., 2015, 'The vulnerability of Pyrenean ski resorts to climate-induced changes in the snowpack', *Climatic Change* 131(4), 591–605 (doi: 10.1007/s10584-015-1400-8).

Ponti, L., Gutierrez, A. P., Ruti, P. M. and Dell'Aquila, A., 2014, 'Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers', *Proceedings of the National Academy of Sciences* 111(15), 5 598–5 603 (doi: 10.1073/pnas.1314437111).

Radić, V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E. and Cogley, J. G., 2013, 'Regional and global projections of twenty-first century glacier mass changes in response to climate scenarios from global climate models', *Climate Dynamics* 42(1–2), 37–58 (doi: 10.1007/s00382-013-1719-7).

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., OgéE, J., Allard, V., Aubinet, M., Bernhofer, C., Buchmann, N., Carrara, A., GrüNwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W. et al., 2007, 'Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: A joint flux tower, remote sensing and modelling analysis', *Global Change Biology* 13(3), 634–651 (doi: 10.1111/j.1365-2486.2006.01224.x).

Rubio, J. L., Safriel, U., Daussa, R., Blum, W. and Pedrazzini, F. (eds), 2009, *Water scarcity, land degradation and desertification in the Mediterranean region*, NATO Science for Peace and Security Series C: Environmental Security, Springer Netherlands, Dordrecht.

Ruiz-Labourdette, D., Nogués-Bravo, D., Ollero, H. S., Schmitz, M. F. and Pineda, F. D., 2012, 'Forest composition in Mediterranean mountains is projected to shift along the entire elevational gradient under climate change: Forest dynamics under climate change', *Journal of Biogeography* 39(1), 162–176 (doi: 10.1111/j.1365-2699.2011.02592.x).

Saadi, S., Todorovic, M., Tanasijevic, L., Pereira, L. S., Pizzigalli, C. and Lionello, P., 2015, 'Climate change and Mediterranean agriculture: Impacts on winter wheat and tomato crop evapotranspiration, irrigation requirements and yield', *Agricultural Water Management* 147, 103–115 (doi: 10.1016/j.agwat.2014.05.008).

Santini, M., Caccamo, G., Laurenti, A., Noce, S. and Valentini, R., 2010, 'A multi-component GIS framework for desertification risk assessment by an integrated index', *Applied Geography* 30(3), 394–415 (doi: 10.1016/j.apgeog.2009.11.003).

Santini, M., Collalti, A. and Valentini, R., 2014, 'Climate change impacts on vegetation and water cycle in the Euro-Mediterranean region, studied by a likelihood approach', *Regional Environmental Change* 14(4), 1 405–1 418 (doi: 10.1007/s10113-013-0582-8).

Santini, M. and Valentini, R., 2011, 'Predicting hot-spots of land use changes in Italy by ensemble forecasting', *Regional Environmental Change* 11(3), 483–502 (doi: 10.1007/s10113-010-0157-x).

Schöner, W., Böhm, R., Haslinger, K., Blöschl, G., Merz, R., Blaschke, A. P., Viglione, A., Parajka, J., Kroiß, H. and Kreuzinger, N., 2010, *Anpassungsstrategien an den Klimawandel für Österreichs Wasserwirtschaft*, Im Auftrag des BMLFUW und der Länder, ZAMG, TU-Wien, Wien.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C. and Vonk, J. E., 2015, ‚Climate change and the permafrost carbon feedback', *Nature* 520(7546), 171–179 (doi: 10.1038/nature14338).

Screen, J. A. and Simmonds, I., 2010, 'The central role of diminishing sea ice in recent Arctic temperature amplification', *Nature* 464(7293), 1 334–1 337 (doi: 10.1038/nature09051).

Senatore, A., Mendicino, G., Smiatek, G. and Kunstmann, H., 2011, 'Regional climate change projections and hydrological impact analysis for a Mediterranean basin in Southern Italy', *Journal of Hydrology* 399(1–2), 70–92 (doi: 10.1016/j.jhydrol.2010.12.035).

SOGREAH, 2011, *Stratégies territoriales d'adaptationau changement climatique dans le Grand Sud-Ouest*, Etude MEDCIE Grand Sud-oues Rapport de la Phase 1, Artelia.

Stepien, A., Koivurova, T., Gremsperger, A. and Niemi, H., 2014, 'Arctic indigenous peoples and the challenge of climate change', in: Tedsen, E., Cavalieri, S., and Kraemer, R. A. (eds), *Arctic marine governance*, Springer Berlin Heidelberg, Berlin; Heidelberg, pp. 71–99.

Tamme, O., 2012, *Klimawandel im österreichischen Berggebiet: Ursachen, Auswirkungen und Anpassungsmaßnahmen*, Forschungsbericht No 65, Bundesanstalt für Bergbauernfragen, Wien.

Tanasijevic, L., Todorovic, M., Pereira, L. S., Pizzigalli, C. and Lionello, P., 2014, 'Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region', *Agricultural Water Management* 144, 54–68 (doi: 10.1016/j.agwat.2014.05.019).

The BACC II Author Team, 2015, *Second assessment of climate change for the Baltic Sea basin*, Springer International Publishing, Cham, Heidelberg, New York, Dordrecht, London.

Umweltbundesamt, 2007, ‚Wald und Waldnutzung', in: *Umweltsituation in Österreich: Achter Umweltkontrollbericht des Umweltbundesamtes*, Umweltbundesamt GmbH, Wien, pp. 95–104.

Umweltbundesamt, 2013, ‚Landwirtschaft und Wald', in: *Umweltsituation in Österreich: Zehnter Umweltkontrollbericht des Umweltbundesamtes*, Umweltbundesamt GmbH, Wien, pp. 95–115.

UNESCO, 2009, *Climate change and Arctic sustainable development: Scientific, social, cultural and educational challenges*, UNESCO, Paris.

Vennetier, M., Vilà, B., Liang, E., Guibal, F., Taahbet, A. and Gadbin-Henry, C., 2007, 'Impact of climate change on pines forest productivity and on the shift of a bioclimatic limit in Mediterranean area.', in: Leone, V. and Lovreglio, R. (eds), *Proceedings of the international workshop MEDPINE 3: Conservation, regeneration and restoration of Mediterranean pines and their ecosystems*, Proceedings of the International Workshop, 2005/09/26-30, CIHEAM, Bari, pp. 189–197.

Werners, S., Szalai, S., Kőpataki, E., Csaba Kondor, A., Musco, E., Koch, E., Zsuffa, I., Trombik, J., Kuras, K., Koeck, M., Lakatos, M., Peters, R., Lambert, S., Hlásny, T. and Adriaenssens, V., 2014, *Future imperfect: Climate change and adaptation in the Carpathians*, GRID-Arendal, Arendal.

Wisz, M. S., Broennimann, O., Grønkjær, P., Møller, P. R., Olsen, S. M., Swingedouw, D., Hedeholm, R. B., Nielsen, E. E., Guisan, A. and Pellissier, L., 2015, 'Arctic warming will promote Atlantic-Pacific fish interchange', *Nature Climate Change* 5(3), 261–265 (doi: 10.1038/nclimate2500).

Zemp, M., Paul, F., Hoelzle, M. and Haeberli, W., 2008, 'Glacier fluctuations in the European Alps, 1850-2000: An overview and a spatiotemporal analysis of available data', in: Orlove, B. S., Wiegandt, E., and Luckman, B. H. (eds), *Darkening peaks: Glacier retreat, science, and society*, University of California Press, Los Angeles, pp. 152–167.

Section 6.6: Vulnerability to climate change in urban regions

Adger, W. N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D. R., Naess, L. O., Wolf, J. and Wreford, A., 2008, 'Are there social limits to adaptation to climate change?', *Climatic Change* 93(3–4), 335–354 (doi: 10.1007/s10584-008-9520-z).

Bassi, S. and Kettunen, M., 2008, *Forest fires: Causes and contributing factors in Europe*, IP/A/ENVI/ST/2007-2015/, Policy Department A: Economic and Scientific Policy, European Parliament, Brussels.

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M. and Pullin, A. S., 2010, 'A systematic review of evidence for the added benefits to health of exposure to natural environments', *BMC Public Health* 10(1), 456 (doi: 10.1186/1471-2458-10-456).

Brooks, N., Neil Adger, W. and Mick Kelly, P., 2005, 'The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation', *Global Environmental Change* 15(2), 151–163 (doi: 10.1016/j.gloenvcha.2004.12.006).

Camia, A., Amatulli, G. and San-Miguel-Ayanz, J., 2008, *Past and future trends of fire danger in Europe*, EUR 23427 EN, JRC 46533, JRC, Ispra.

EC, 2014, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions — The urban dimension of EU policies: Key features of an EU Urban Agenda, COM (2014) 490 final of 18 July 2014, Brussels.

EEA, 2012, *Urban adaptation to climate change in Europe: Challenges and opportunities for cities together with supportive national and European policies*, EEA Report No 2/2012, European Environment Agency.

EEA, 2014, 'Climate-ADAPT case study: Room for the River Waal — Protecting the city of Nijmegen' (http://climate-adapt.eea.europa.eu/viewmeasure?ace_measure_id=4401) accessed 3 November 2015.

EEA, 2015, 'Urban vulnerability to climate change in Europe — A map book' (http://climate-adapt.eea.europa.eu/tools/urban-adaptation/introduction) accessed 30 August 2016.

EEA, 2016, *Urban adaptation to climate change in Europe 2016 — Transforming cities in a changing climate*, EEA Report No 12/2016, European Environment Agency.

EEA, ETC CCA and ETC SIA, 2015, Map book urban vulnerability to climate change — Factsheets, European Environment Agency.

Fernandez, L., S., Byard, D., Lin, C.-C., Benson, S. and Barbera, J. A., 2002, 'Frail elderly as disaster victims: Emergency management strategies', *Prehospital and Disaster Medicine* 15(2), 67–74.

Fischer, E. M. and Schär, C., 2010, 'Consistent geographical patterns of changes in high-impact European heatwaves', *Nature Geoscience* 3(6), 398–403 (doi: 10.1038/ngeo866).

Grinze, L., Huss, A., Thommen, O., Schindler, C. and Braun-Fahrländer, C., 2005, 'Heat wave 2003 and mortality in Switzerland', *Swiss Medical Weekly* 135, 200–205.

van Hove, L. W. A., Jacobs, C. M. J., Heusinkveld, B. G., Elbers, J. A., van Driel, B. L. and Holtslag, A. A. M., 2015, 'Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration', *Building and Environment* 83, 91–103 (doi: 10.1016/j.buildenv.2014.08.029).

Huynen, M. M. T. E., Martens, P., Schram, D., Weijenberg, M. P. and Kunst, A. E., 2001, 'The impact of heat waves and cold spells on mortality rates in the Dutch population', *Environmental Health Perspectives* 109(5), 463–470 (doi: 10.1289/ehp.01109463).

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., Kinney, P., Bowman, D. M. J. S. and Brauer, M., 2012, 'Estimated global mortality attributable to smoke from landscape fires', *Environmental Health Perspectives* 120(5), 695–701 (doi: 10.1289/ehp.1104422).

JRC, 2015, 'Rapid damage assessment — EFFIS-RDA' (http://forest.jrc.ec.europa.eu/effis/about-effis/technical-background/rapid-damage-assessment) accessed 10 December 2015.

Kaźmierczak, A. and Cavan, G., 2011, 'Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure', *Landscape and Urban Planning* 103(2), 185–197 (doi: 10.1016/j.landurbplan.2011.07.008).

Kovats, R. S. and Hajat, S., 2008, 'Heat stress and public health: A critical review', *Annual Review of Public Health* 29, 41–55 (doi: 10.1146/annurev.publhealth.29.020907.090843).

KPSA, 2014, 'Climate adaptation atlas' (http://www.ruimtelijkeadaptatie.nl/en/climate-adaptation-atlas) accessed 21 October 2015.

Mabey, N., Cook, R., Schulz, S. and Schwartzkoppff, J., 2014, *Underfunded, underprepared, underwater? Cities at risk*, E3G, London.

Oke, T., 1987, *Boundary layer climates*, 2nd ed, Methuen, London; New York.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. and Solecki, W., 2015, 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change* (doi: 10.1016/j.gloenvcha.2015.01.004).

Prokop, G., Jobstmann, H., Schönbauer, A., European Commission and Directorate-General for the Environment, 2011, *Overview of best practices for limiting soil sealing or mitigating its effects in EU-27 final report*, Publications Office, Luxembourg.

Rahman, M., Armson, D. and Ennos, R., 2013, 'A comparison of the shading effectiveness of five different street tree species in Manchester, UK', *Journal of Arboriculture* 39(4), 157–164.

Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D. C. and Solecki, W., 2014, 'Urban areas', in: Field, C. B., Barros, V. R., Dokken, D. J., et al. (eds), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York, pp. 535–612.

Rojas, R., Feyen, L., Bianchi, A. and Dosio, A., 2012, 'Assessment of future flood hazard in Europe using a large ensemble of bias corrected regional climate simulations', *Journal of Geophysical Research* 117, D17109 (doi: 10.1029/2012JD017461).

Rojas, R., Feyen, L. and Watkiss, P., 2013, 'Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation', *Global Environmental Change* 23(6), 1 737–1 751 (doi: 10.1016/j.gloenvcha.2013.08.006).

Ruimte voor de Rivier, no date, 'Room for the River' (https://www.ruimtevoorderivier.nl/english) accessed 3 November 2015.

Steeneveld, G. J., Koopmans, S., Heusinkveld, B. G., van Hove, L. W. A. and Holtslag, A. A. M., 2011, 'Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in the Netherlands', *Journal of Geophysical Research: Atmospheres* 116(D20), D20129 (doi: 10.1029/2011JD015988).

Tapia, C., Guerreiro, S., Mendizabal, M., Kilsby, C., Feliu, E., Glenis, V., Dawson, R. and Eluwa, C., 2015, *High level quantified assessment of key vulnerabilities and priority risks for urban areas in the EU*, RAMSES-D3.1, Tecnalia R&I, Newcastle University, Newcastle.

UN-HABITAT (ed), 2011, *Cities and climate change: Policy directions — Global report on human settlements 2011*, Global Report on Human Settlements, Earthscan, Washington, DC.

Zhou, B., Rybski, D. and Kropp, J. P., 2013, 'On the statistics of urban heat island intensity', *Geophysical Research Letters* 40(20), 5 486–5 491 (doi: 10.1002/2013GL057320).

Chapter 7: Strengthening the knowledge base

Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A. and Zemp, M., 2014, 'The concept of essential climate variables in support of climate research, applications, and policy', *Bulletin of the American Meteorological Society* 95(9), 1 431–1 443 (doi: 10.1175/BAMS-D-13-00047.1).

Ciscar, J. C., Feyen, L., Soria, A., Lavalle, C., Raes, F., Perry, M., Nemry, F., Demirel, H., Rozsai, M., Dosio, A., Donatelli, M., Srivastava, A., Fumagalli, D., Niemeyer, S., Shrestha, S., Ciaian, P., Himics, M., Van Doorslaer, B., Barrios, S. et al., 2014, *Climate impacts in Europe: The JRC PESETA II Project*, JRC Scientific and Policy Reports EUR 26586 EN, JRC87011, European Commission — Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability, Seville.

EC, 2008, Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), OJ L 164, 25.6.2008, pp. 19–40.

EEA, 2014, *National adaptation policy processes across European countries — 2014*, EEA Report No 4/2014, European Environment Agency.

EEA, 2015a, *National monitoring, reporting and evaluation of climate change adaptation in Europe*, EEA Technical report No 20/2015, European Environment Agency.

EEA, 2015b, *Overview of climate change adaptation platforms in Europe*, EEA Technical report No 5/2015, European Environment Agency.

EEA, 2016a, *Flood risks and environmental vulnerability — Exploring the synergies between floodplain restoration, water policies and thematic policies*, EEA Report No 1/2016, European Environment Agency.

EEA, 2016b, 'Use of freshwater resources' (http://www.eea.europa.eu/data-and-maps/indicators/use-of-freshwater-resources-2/assessment-1) accessed 15 March 2016.

EU, 2011, Regulation (EU) No 691/2011 of the European Parliament and of the Council of 6 July 2011 on European environmental economic accounts, OJ L 192, 22.7.2011, pp. 1–16.

EU, 2013a, Decision No 1313/2013/EU of the European Parliament and of the Council of 17 December 2013 on a Union Civil Protection Mechanism, OJ L 347, 20.12.2013, pp. 924–947.

EU, 2013b, Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet', OJ L 354, 28.12.2013, pp. 171–200.

EU, 2014a, Commission implementing decision of 19 March 2014 on the adoption of the LIFE multiannual work programme for 2014-17, 2014/203/EU, OJ L 116, 17.4.2014, pp. 1–56.

EU, 2014b, Regulation (EU) No 282/2014 of the European Parliament and of the Council of 11 March 2014 on the establishment of a third Programme for the Union's action in the field of health (2014-2020) and repealing Decision No 1350/2007/EC, OJ L 86, 21.3.2014, pp. 1–13.

EU, 2014c, Regulation (EU) No 377/2014 of the European Parliament and of the Council of 3 April 2014 establishing the Copernicus Programme and repealing Regulation (EU) No 911/2010, OJ L 122, 24.4.2014, pp. 44–66.

Eurostat, 2015, *Smarter, greener, more inclusive? Indicators to support the Europe 2020 strategy. 2015 edition*, eurostat Statistical books.

FAO, 2016, *Global forest resources assessment 2015. How are the world's forests changing?*, Second edition, Food and Agriculture Organization of the United Nations, Rome.

GCOS, 2010a, GCOS: Ensuring the availability of global observations for climate change, World Meteorological Organization, Geneva.

GCOS, 2010b, *Implementation plan for the global observing system for climate in support of the UNFCCC (2010 update)*, GCOS-138, World Meteorological Organization, Geneva.

GCOS, 2015, *Status of the global observing system for climate. Full report*, GCOS-195, World Meteorological Organization, Geneva.

IAEG-SDG, 2015, Summary of comments (25 September 2015) and list of indicator proposals (11 August 2015), United Nations Statistics Division.

IPCC, 2014, *Climate change 2014: Impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge; New York.

PreventionWeb, 2016, 'Open-Ended Intergovernmental Expert Working Group: Indicators. Background Documents in Support of the Development of Indicators.' (http://www.preventionweb.net/drr-framework/open-ended-working-group) accessed 1 September 2016.

PROVIA, 2013, *PROVIA guidance on assessing vulnerability, impacts and adaptation to climate change*, Consultation Document, United Nations Environment Programme, Nairobi.

Street, R., Parry, M., Scott, J., Jacob, D., Runge, T., European Commission and Directorate-General for Research and Innovation, 2015, *A European research and innovation roadmap for climate services*, Publications Office, Luxembourg.

UN, 2015, Sendai Framework for Disaster Risk Reduction 2015–2030, A/RES/69/283, General Assembly, 69th session.

UNECE, 2014, *Conference of European Statisticians Recommendations on Climate Change-Related Statistics*, United Nations Economic Commission for Europe, Geneva.

UNECE, 2015, *Terms of reference of a task force on measuring extreme events and disasters*, United Nations Economic Commission for Europe, Conference of European Statisticians, Geneva.

UNECE and FAO, 2015, 'Forests in the ECE region: Trends and challenges in achieving the global objectives on forests' (http://www.unece.org/forests/forests-in-the-ece-region-2015.html) accessed 4 August 2015.

European Environment Agency

Climate change, impacts and vulnerability in Europe 2016
An indicator-based report

2017 — 419 pp. — 21 x 29.7 cm

ISBN 978-92-9213-835-6
doi:10.2800/534806

TH-AL-17-001-EN-N
doi:10.2800/534806

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Publications Office

European Environment Agency