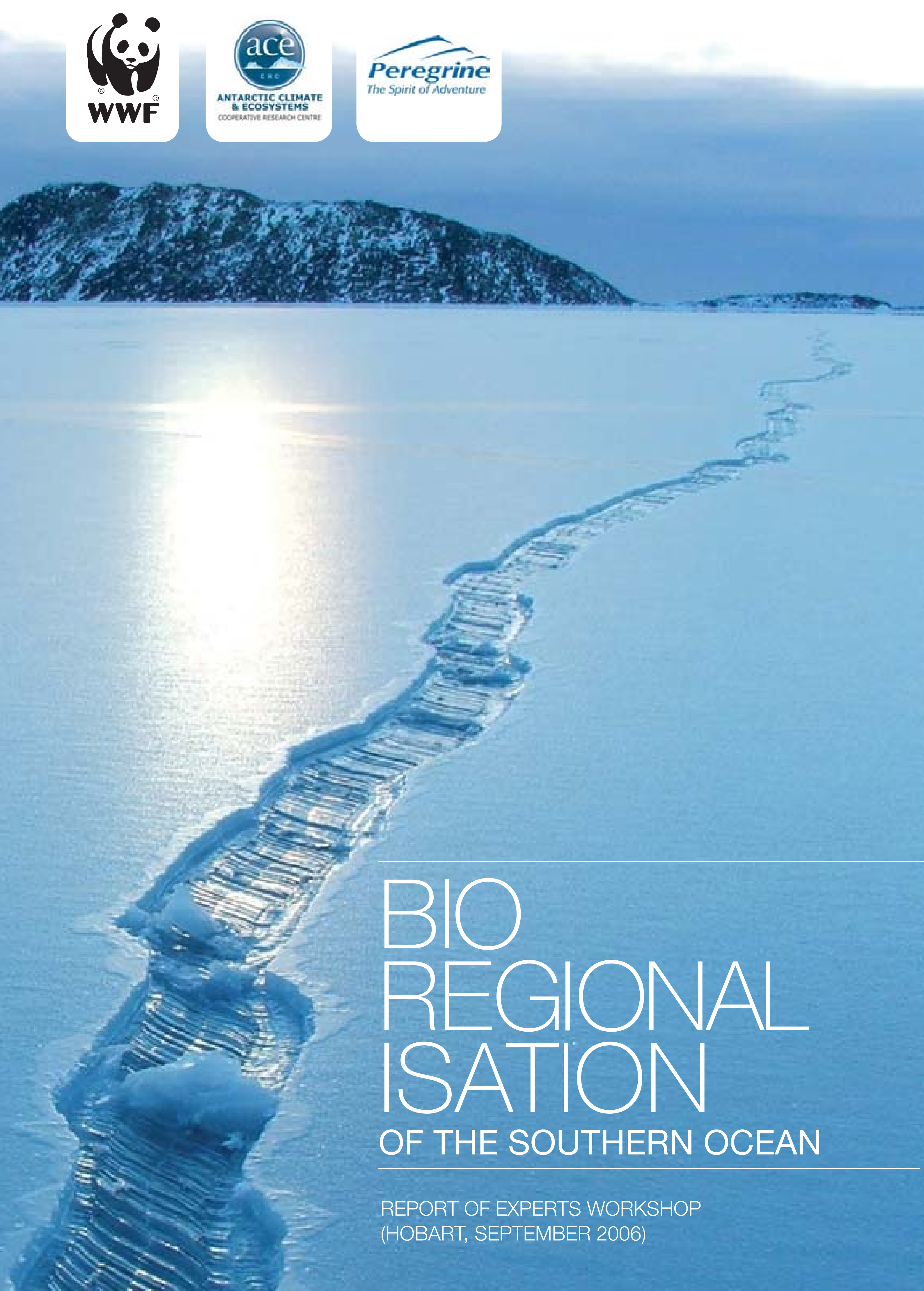

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ANTARCTIC CLIMATE & ECOSYSTEMS COOPERATIVE RESEARCH CENTRE

Peregrine
The Spirit of Adventure

BIOREGIONALISATION OF THE SOUTHERN OCEAN

REPORT OF EXPERTS WORKSHOP
(HOBART, SEPTEMBER 2006)


Wayne Papps, Australian Government Antarctic Division, © Commonwealth of Australia

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The CD attached to this report includes appendices, analysis tools, data and maps (including a GIS database) referred to in the report.

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Responsible Tourism is a fundamental platform of Peregrine's operations. In line with this principle of sustainability, Peregrine has funded this report in the belief that it provides a foundation for the understanding and long-term conservation of Antarctica's important habitats and wildlife.

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The authors wish to thank all of the participants in the 2006 Experts Workshop, whose expertise and thoughtful input provided the material and outcomes for this report, as well as reviews of the manuscript. A full list of participants can be found at the end of the report.

Cover photo: © Paul Dudley courtesy Australian Government Antarctic Division

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Acronyms and abbreviations

ACC	Antarctic Circumpolar Current
ATCM	Antarctic Treaty Consultative Meeting
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CEP	Committee for Environmental Protection
CPR	Continuous Plankton Recorder
LME	Large Marine Ecosystem
MPA	Marine Protected Area
PAR	Photosynthetically active radiation
PF	Polar Front
SACCF	Southern Antarctic Circumpolar Current Front
SAF	Subantarctic Front
SC-CAMLR	Scientific Committee for the Conservation of Antarctic Marine Living Resources
SSH	Sea surface height
SST	Sea surface temperature
STF	Subtropical Front

Table of Contents

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Executive Summary

In September 2006, twenty-three scientists from six countries attended an Experts Workshop on Bioregionalisation of the Southern Ocean held in Hobart, Australia. The workshop was hosted by the Antarctic Climate and Ecosystems Cooperative Research Centre, and WWF-Australia, and sponsored by Peregrine. The workshop was designed to assist with the development of methods that might be used to partition the Southern Ocean for the purposes of large-scale ecological modelling, ecosystem-based management, and consideration of marine protected areas. In 2005, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and its Scientific Committee (SC-CAMLR) considered that a bioregionalisation of the Southern Ocean was needed to underpin the development of a system of marine protected areas in the Convention area.

The aim of the workshop was to bring together scientific experts in their independent capacity to develop a ‘proof of concept’ for a broad-scale bioregionalisation of the Southern Ocean, using physical environmental data and satellite-measured chlorophyll concentration as the primary inputs. Work included presentation of background information, computer-based analysis undertaken in small groups, and plenary discussion on the methods, data and results. Workshop participants are listed at the end of this report.

At the conclusion of the workshop, a method had been agreed upon that could be used to take the bioregionalisation work forward. Consensus was achieved on a draft physical regionalisation, and progress was made in determining how to include additional (e.g. biological) data for a more complete bioregionalisation. This report outlines the key results of the workshop, and highlights some of the issues discussed.

An understanding of the spatial characteristics of large ecosystems such as the Southern Ocean is important for the achievement of a range of scientific, conservation and management objectives. Bioregionalisation is a process that aims to partition a broad spatial area into distinct spatial regions, using a range of environmental and biological information. The process results in a set of bioregions, each with relatively homogeneous and predictable ecosystem properties. The properties of a given bioregion should differ from those of other regions in terms of species composition as well as the attributes of its physical and ecological habitats.

Classification of regions based only on biological data is often impractical at larger scales because of insufficient geographic coverage, even though there may be sufficient data to subdivide smaller-scale portions of those regions. Physical and satellite-observed data generally have better spatial and temporal coverage and greater availability than biological data. These can be used to help characterise regions on the basis of environmental properties, physical processes, primary production, and habitat type.

Initial discussions during the workshop focused on defining the major physical processes in the Southern Ocean, and their relationships with ecological processes. A key aspect of undertaking an ecologically meaningful regionalisation is to understand how important ecological processes correspond to the physical and satellite-observed parameters, and whether these parameters are appropriate for use as proxies or surrogates. This may depend in part on the end-use application of the analysis, and the scale at which the analysis is being undertaken.

Environmental data used as the primary input for analysis during this workshop were chosen based on their spatial coverage across the Southern Ocean. The datasets considered included bathymetry, sea ice concentration and extent, sea surface temperature, sea surface height, chlorophyll *a* concentration, nutrient data (silicate, nitrate and phosphate), and insolation (photosynthetically active radiation - PAR).

A series of presentations on approaches to bioregionalisation that have been undertaken elsewhere (terrestrial Antarctica, Australia, New Zealand) allowed detailed consideration of the relative benefits of different methods. The analytical methods used by Lyne and Hayes (2005), Leathwick et al. (2006a) and Raymond & Constable (2006) were used as starting points for the analysis during the workshop. These methods were refined into a single methodology, In September 2006, twenty-three scientists from six countries attended an Experts Workshop on Bioregionalisation of the Southern Ocean held in Hobart, Australia. The workshop was hosted by the Antarctic Climate and Ecosystems Cooperative Research Centre, and WWF-Australia, and sponsored by Peregrine. The workshop was designed to assist with the development of methods that might be used to partition the Southern Ocean for the purposes of large-scale ecological modelling, ecosystem-based management, and consideration of marine protected areas.


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following workshop discussions and practical explorations of the methods.

Issues examined included the choice of data and extraction of relevant parameters to best capture ecological properties, the use of data appropriate for end-user applications, and the relative utility of taking a hierarchical, non-hierarchical, or mixed approach to regionalisation. The final method involved the use of a clustering procedure to classify individual sites into groups that are similar to one another within a group, and reasonably dissimilar from one group to the next, according to a selected set of parameters (e.g. depth, ice coverage, temperature). This approach shared strong similarities to several previous regionalisation methods, including Lyne and Hayes (2005) and Leathwick et al. (2006a).

The workshop established a proof of concept for bioregionalisation of the Southern Ocean, demonstrating that this analysis can delineate bioregions that agree with expert opinion at the broad scale. Consensus was reached on which of the trial bioregionalisations were the most ecologically and statistically meaningful according to expert opinion.

The workshop concluded that a statistical, hierarchical approach was the most useful in displaying the different levels of similarity and providing choices on the degree to which the region might be subdivided on the basis of the chosen datasets. The datasets were divided into primary and secondary datasets, reflecting

the primary properties of the region and the secondary environmental properties that might provide smaller-scale subdivisions to reflect the spatial heterogeneity of the Southern Ocean ecosystem.

The primary datasets used in this analysis were depth, sea surface temperature, silicate and nitrate. These highlighted the different environmental characteristics of large regions including the continental shelf and slope, frontal features (Subantarctic Front, Polar Front, Southern Antarctic Circumpolar Current Front), the deep ocean, banks and basins, island groups and gyre systems. Other primary datasets that could be usefully considered in future analyses were identified by the workshop, and included sea surface height and insolation.

The secondary datasets used in the analysis were ice concentration and mean chlorophyll *a* values. The addition of these datasets suggested smaller-scale spatial heterogeneity within the regions particularly in the continental shelf and slope areas, and the seasonal ice zone. These results highlighted the need for further analysis at the secondary level.

The final stages of the analysis included discussion on how well the defined regions corresponded to our present knowledge of the Southern Ocean. Experts provided information on the patterns and features that they would expect to see, according to current observations and understanding, and these largely concurred with the outcomes of the analysis.

Finally, workshop participants discussed priorities for future work, including the development of further methods to deal with uncertainty, understanding of inter- and intra-annual variation, validation of results, the incorporation of additional data (particularly biological datasets) and finer-scale analysis of particular areas of interest.

This workshop established a ‘proof of concept’ for bioregionalisation of the Southern Ocean. Continuation of this work will be an important contribution to the achievement of a range of scientific, management and conservation objectives, including large-scale ecological modelling, ecosystem-based management, and the development of an ecologically representative system of marine protected areas. ■

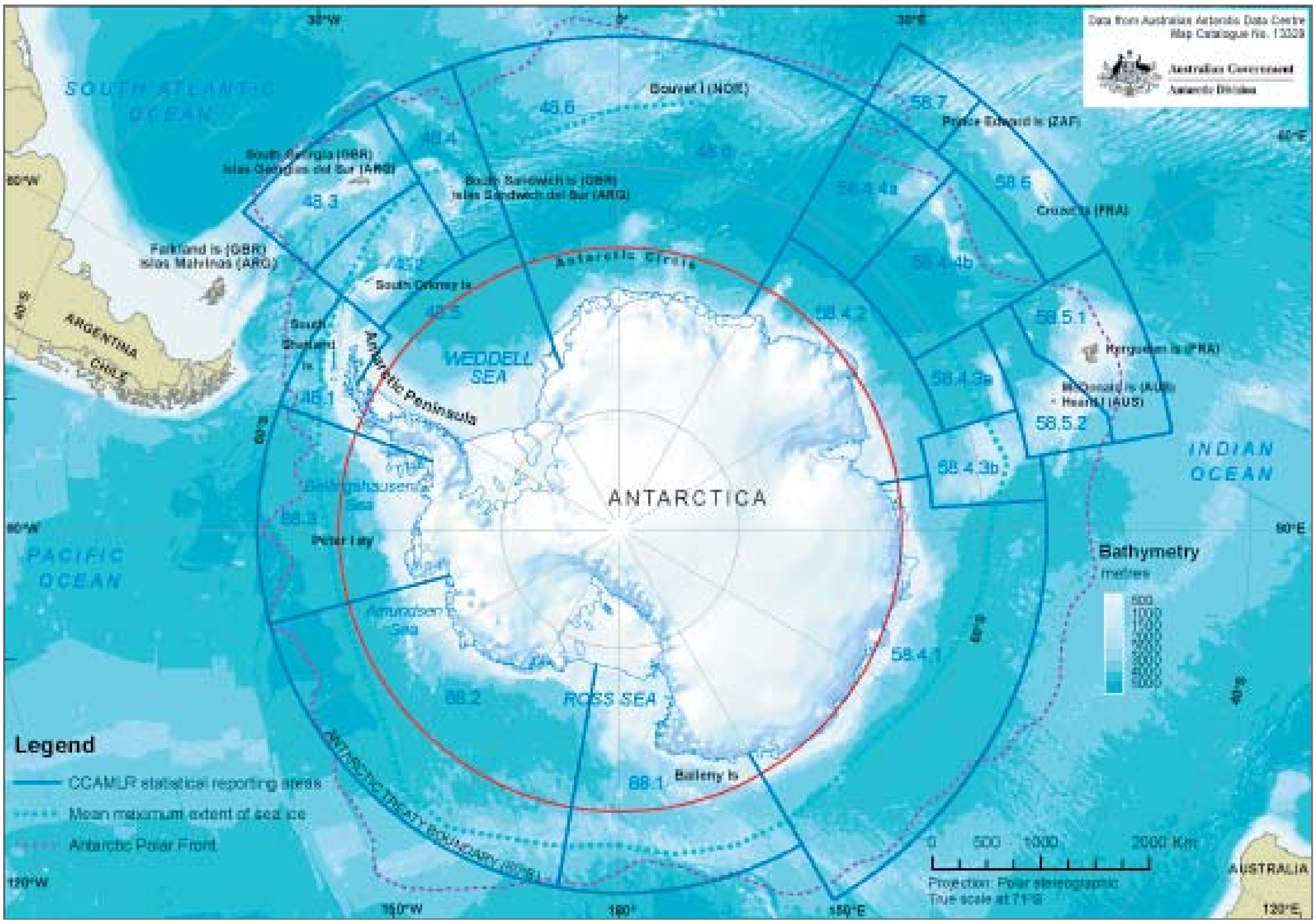

FIGURE 1: Map of Antarctica and the Southern Ocean. (Data from Australian Antarctic Data Centre)

1. Introduction

The Southern Ocean covers around 10% of the world's ocean surface, and includes some of the most productive marine regions on Earth. Although they are among the least-studied, the seas around Antarctica are a critical component of the global climate system and marine ecosystem.

An understanding of the spatial characteristics of large ecosystems such as the Southern Ocean is important for the achievement of a range of scientific, management and conservation objectives including ecological modelling, ecosystem-based management of living resources, and the establishment of an ecologically representative system of marine protected areas.

Bioregionalisation is a process that aims to partition a broad spatial area into distinct spatial regions, using a range of environmental and biological information. The process results in a set of bioregions, each with relatively homogeneous and predictable ecosystem properties. The properties of a given bioregion should differ from those of other regions in terms of species composition as well as the attributes of its physical and ecological habitats. Bioregionalisation can assist in providing information on the location and distribution of species and their habitats, and is an important foundation for efforts to further understand, conserve and manage activities in the marine environment.

Attempts to classify large ocean areas into meaningful management units have been carried out for coastal and shelf areas worldwide, for example in the definition of Large Marine Ecosystems (LMEs) (Sherman and Alexander, 1986; Sherman and Duda, 1999), Marine Ecoregions (Spalding et al., 2006), and the use of LMEs together with biogeochemical provinces (Platt and Sathyendranath, 1988; 1993; Longhurst, 1998) to define global regions for ecosystem-based fisheries management (Pauly et al., 2000).

In 2005, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and its Scientific Committee (SC-CAMLR) identified a series of key tasks to assist in developing a comprehensive and ecologically representative system of marine protected areas (MPAs) (SC-CAMLR-XXIV, 2005). A broad-scale bioregionalisation of the Southern Ocean was identified as an important first step in this process. CCAMLR agreed that this process will need to be undertaken in cooperation with the Committee for Environmental Protection (CEP), which reports to the Antarctic Treaty Consultative Meeting (ATCM).

In 2006, WWF initiated a project to undertake some of the initial work towards a broad-scale bioregionalisation, in partnership with the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC, Australia) and sponsored by Antarctic expedition cruise operator, Peregrine. The aim of this work has been to develop a 'proof of concept' for a broad-scale bioregionalisation of the Southern Ocean based on synoptic environmental data in the first instance.

As part of this work program, an Experts Workshop was held in Hobart, 4-8 September 2006, to review and expand upon the initial developmental work provided by Raymond and Constable (2006). This document provides a report of that workshop, detailing:

- background to the workshop and bioregionalisation in the Southern Ocean;
- an agreed approach to bioregionalisation;
- an example of a regionalisation for the Southern Ocean based on synoptic environmental data; and
- future work towards a bioregionalisation of the Southern Ocean.

An understanding of the spatial characteristics of large ecosystems such as the Southern Ocean is important for the achievement of a range of scientific, conservation and management objectives. Bioregionalisation is a process that aims to partition a broad spatial area into distinct spatial regions, using a range of environmental and biological information. The process results in a set of bioregions, each with relatively homogeneous and predictable ecosystem properties. The properties of a given bioregion should differ from those of other regions in terms of species composition as well as the attributes of its physical and ecological habitats.

1.1 What is bioregionalisation?

Large ecosystems can be partitioned at a range of spatial scales, according to their physical, environmental and biological characteristics. Variation in climate, topography and other physical factors forms different habitat types, which in turn support different species and communities. Biological diversity varies throughout this geographic space, and may be further influenced by factors such as the availability of nutrients and food, as well as human activities.

For example, forests, deserts and grasslands have different physical and environmental attributes, and contain different habitat types and communities of species. These different regions may occur adjacent to one another; however, each differs from the others in terms of physical and ecological characteristics. Some species may range across more than one region, whereas others will be more restricted in their range, according to their ability to live in particular habitat types or ecological conditions. For example, cacti are uniquely adapted to live only in desert conditions, while certain ubiquitous grasses are found in parts of the forest and the grassland, as well as the desert. Migrating birds may travel across all three regions, while deer inhabit the forest and the grassland but not the desert, and tree-dwelling mammals remain exclusively in the forest.

Boundaries between regions may be sharp, for example at the interface between a forest and adjacent alpine areas. Features such as the tree-line reflect the limit of tolerance by certain species to a particular set of physical conditions. However, boundaries may also be gradual, such as in the margins of a desert, where habitats and species from both the desert and the neighbouring grassland gradually blend across a wide transitional area. Transitional areas between adjacent ecosystems, regions or habitats are known as ecotones, and species may be found in decreasing numbers as they reach the edge of their range. Bioregionalisation provides a simplified interpretation of these physical and ecological boundaries. It endeavours to separate, say, desert, grassland and forest by drawing boundaries between them such that the attributes within each of the bounded areas are primarily desert, grassland and forest respectively.

This terrestrial analogy provides a simplified description of the bioregionalisation concept, and its utility in providing pragmatic solutions to complex ecological problems. Apart from the edges of rocky reefs, regional boundaries in the oceans are likely to be less sharp (or more ‘fuzzy’), and they may be more mobile or variable because of the fluid nature of the marine environment. Regionalisation of marine ecosystems is also more complex because of their three-dimensional nature. However, marine ecosystems can nevertheless be partitioned using the principles described above to provide a simplified interpretation spatial differences in their environmental characteristics, habitat types and ecological boundaries. ■

Defining regions

Regions are generally defined using a combination of qualitative (expert opinion, descriptive data) and quantitative statistical analyses. A range of data on physical, environmental and biological properties can be incorporated into a regionalisation analysis, according to data availability and coverage, and specific end-use applications. Statistical procedures for undertaking a regionalisation attempt to partition a broad spatial area into discrete regions, each with relatively homogeneous and predictable ecosystem properties, but sometimes occurring in more than one geographic location (Leathwick et al. 2003). The properties of a given region (both species composition as well as attributes of the physical and ecological habitats) should differ from those of adjacent regions.

Regions can be defined according to the range of species or communities that inhabit them. Indicator species may also be used, where individual species are known to exclusively inhabit a certain type of region. For example, certain species of desert snake, grassland lizard and forest frog might be used as indicators to define these regions.

Alternatively, physical and environmental information can be used to define regions using qualitative methods (e.g. Bailey, 1996). Topography, altitude, substratum and temperature are among the variables which influence the characteristics and structure of habitats and their associated species and communities. An understanding of the spatial extent of different environmental conditions and physical habitats can provide further information on the ecological properties likely to be found in each area, and thus the types of communities or species which might occur there. As a simplified example, the distribution of freshwater habitats may give some indication of where frogs are likely to be found. This is particularly useful where biological information is unavailable. Information on the distribution of frogs over a large area may be impractical to obtain, however freshwater ponds could

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be more easily identified using aerial photography.

Approaches to defining regions may also vary according to the particular application of a bioregionalisation analysis. For example, a manager interested in the conservation of reptiles may choose to define regions according specifically to the distribution of snakes and lizards, whereas an agricultural scientist might be more interested in the division of regions according to substratum type and topography.

Bioregions may also be defined at different spatial scales, according to the biological, physical or environmental characteristics of interest, and the scale of the data being used in the analysis (e.g. Bailey, 1996). The forest, grassland and desert may be encompassed within a much larger unit; for example all of these regions would be found in southern Africa. Within a particular region, there may also be finer-scale ecosystem divisions. For example, within a forest region, a mountain will support different vegetation with increasing altitude. Different forest communities may be found higher up the mountain, reflecting changes in topography and climatic conditions. At an even finer scale, features such as mountain streams, valleys and rocky outcrops may result in different forest communities occurring at the same altitude. Smaller scale ecosystems or regions can be seen as nested within ecosystems of a higher order, thus occurring within a hierarchical system.

Clearly, the final regionalisation will be dictated by the spatial detail required and the specific attributes needing to be captured in the subdivision. Nevertheless, a regionalisation needs to show generally how those attributes are nested within the larger scale heterogeneity of the system. This helps to appreciate whether areas with similar properties but separated in space may be influenced by different external environmental and ecological drivers at their boundaries.

Approaches to bioregionalisation in the marine environment have included the use of physical oceanographic parameters (e.g. ocean water masses, fronts, gyres and wave energy), geomorphology (e.g. depth, substratum, sediment characteristics and disturbance regimes), biological oceanography (e.g. primary and secondary production), fish stock distribution and abundance (e.g. areas of aggregation and fishing patterns), benthic communities (e.g. distribution and community structure) and marine mammals and birds (e.g. primary feeding and breeding locations).

Classification of regions based only on biological data is often impractical at larger scales because of insufficient geographic coverage, even though there may be sufficient data to subdivide smaller-scale portions of those regions (Belbin, 1993). Physical and satellite-observed data generally have better spatial and temporal coverage and greater availability than biological data. These can be used to help characterise regions on the basis of environmental properties, physical processes, primary production, and habitat type.

An important aspect of undertaking an ecologically meaningful regionalisation is therefore to understand how important ecological processes correspond to physical parameters, and whether those parameters are appropriate for use as proxies or surrogates. This may not require much ecological detail in the first instance, since physical and environmental data can provide an understanding of environmental heterogeneity which will inevitably affect the ecology of a region. ■


Photograph © Roger Kirkwood, courtesy Australian Government Antarctic Division

1.2 Bioregionalisation in the Antarctic context

Bioregionalisation of the Southern Ocean has relevance in a variety of applications within different scientific fields and for conservation and management across the Antarctic Treaty System. An understanding of spatial ecosystem characteristics is necessary to achieve a range of objectives in the Antarctic context, including:

- ecosystem modelling;
- ecosystem-based management of marine living resources;
- effective and systematic planning and management of other human activities;
- identification of biodiversity units and areas of high conservation value;
- establishment of a comprehensive and ecologically representative system of MPAs; and
- directing further research.

Recent discussions within the CCAMLR Scientific Committee (SC-CAMLR-XXIV) and the Committee for Environmental Protection (CEP IX) have agreed the importance of undertaking a bioregionalisation of the Southern Ocean, and highlighted the need to work together in achieving this common objective.

CCAMLR

The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) applies to all marine living resources within the area south of a line approximating to the Polar Front. The Convention Area is divided into three sectors corresponding to the adjacent Atlantic, Indian and Pacific oceans. These sectors are referred to as Statistical Areas 48, 58 and 88 respectively, and each is further divided into statistical subareas for catch reporting and management purposes (see Figure 1). Statistical subareas were defined on the basis of ocean characteristics, fish stock distributions and the location of fishing activities (Everson, 1977; Kock, 2000), thus providing one example of an existing bioregionalisation of the Southern Ocean. Subareas are used in catch reporting, and enable the implementation of conservation and management measures regionally or for individual stocks.

The primary objective of CCAMLR is the conservation of Antarctic marine living resources, where conservation includes rational use. CCAMLR has pioneered a precautionary, ecosystem approach to marine living resource management, and defines the Antarctic marine ecosystem as "the complex of relationships of Antarctic marine living resources with each other and with their physical environment".[1]

In 2005, the CCAMLR Workshop on MPAs considered the scientific work required for development of a system of protected areas to assist CCAMLR in achieving its conservation objectives. A broad-scale bioregionalisation of the Southern Ocean was identified as an important first step in this process (SC-CAMLR-XXIV, 2005).

CCAMLR has identified a series of key tasks to be undertaken towards bioregionalisation:

- collation of existing data, including benthic and pelagic features and processes;
- determination of statistical analyses required to facilitate a bioregionalisation, including use of empirical, model and expert data;
- development of a broad-scale bioregionalisation of the Southern Ocean, based on existing datasets; and
- delineation of fine-scale provinces within regions, where possible.

As part of this ongoing work, CCAMLR will hold a workshop in 2007 with the aim of providing advice on a bioregionalisation of the Southern Ocean, including, where possible, advice on smaller-scale delineation of provinces and potential areas for protection to further the conservation objective of CCAMLR. This workshop will involve members of both the CCAMLR Scientific Committee and the CEP, as well as external experts (SC-CAMLR-XXIV, 2005).

Committee for Environmental Protection

The Antarctic Treaty and its Protocol on Environmental Protection apply to the area south of 60°S, thus covering a smaller marine area than CCAMLR. The Environmental Protocol deals with environmental impact assessment, conservation of Antarctic flora and fauna, waste disposal and management, prevention of marine pollution, and area protection and management. The Committee for Environmental Protection (CEP) provides advice and recommendations to the ATCM in connection with the implementation of the Environmental Protocol.

Annex V of the Environmental Protocol states that Parties shall seek to identify a series of Antarctic Specially Protected Areas (ASPAs) (including marine and terrestrial areas) within a 'systematic environmental-geographic framework'[2]. This term has been defined as: "a method of classifying or organising subsets of environmental and geographic characteristics such as different types of ecosystems, habitat, geographic area, terrain, topography, climate, individual features and human presence into geographic regions. Each region would be distinctive or in some way different from other regions but some might have characteristics in common." (ATCM XXIV/WP012, 2001).

The bioregionalisation work proposed by CCAMLR corresponds closely to current efforts by the CEP to elaborate a systematic environmental-geographic framework, in particular through the terrestrial Antarctic Environmental Domains Analysis being undertaken by New Zealand for the Antarctic continent (Morgan et al., 2005).

In outlining the work programme for bioregionalisation, CCAMLR recognised the relative expertise of the CEP, and suggested that the CEP should be invited to undertake the initial work necessary to develop a bioregionalisation of the coastal provinces, as an extension of its terrestrial bioregionalisation work. At its meeting in 2006, the CEP undertook to engage fully with CCAMLR on this work, and agreed on the importance of such an analysis in contributing to its conservation and management objectives (CEP IX, 2006).

1.3 Antarctica and the Southern Ocean

Southern Ocean characteristics

The Southern Ocean extends across a total area of almost 35 million km^2, and consists of distinct provinces that differ physically and chemically (e.g. temperature, sea ice, nutrients and currents), as well as ecologically. It is characterised by deep basins, separated by large, mid-oceanic ridges and containing prominent plateaus and island groups.

Two major currents dominate the Southern Ocean system. The Antarctic Circumpolar Current (ACC) (or "West Wind Drift") flows eastwards around the continent, driven by the prevailing westerly winds. The ACC forms a unique link connecting all of the world's major oceans through an unbroken water mass surrounding the Antarctic continent, (Orsi et al., 1995). However, its path is influenced by topographic features such as the Kerguelen Plateau and the Scotia Arc, which deflect fronts and generate eddies. Closer to the continent, easterly winds form a series of clockwise gyres (the largest of these being in the Ross Sea and Weddell Sea) that combine to form the westward flowing Antarctic Coastal Current, also known as the "East Wind Drift".

The Subtropical Front (STF) marks the northernmost extent of the ACC, separating warmer, more saline subtropical waters from fresher, cooler subantarctic surface waters (Orsi et al., 1995). Further south, the majority of ACC water is transported in the Subantarctic Front (SAF), and also in the Polar Front, which marks the transition to very cold and relatively fresh Antarctic

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[1] CCAMLR, Article 1

[2] Protocol on Environmental Protection, Annex V, Article 3(2)

Surface Water, and separates Southern Ocean waters from the Atlantic, Pacific and Indian oceans to the north. The Polar Front also marks the northerly limit of many non-migrating Antarctic species (Knox, 1994), including Antarctic krill (*Euphausia superba*), the staple food of many of the Southern Ocean's seabirds, marine mammals and fish. Closer to the Antarctic continent, upwelling of very dense, cold abyssal waters occurs at the southern boundary of the ACC.

The Southern Ocean plays an important role in the global ocean circulation system. Figure 2 shows the relationships between the frontal systems and the greater patterns of ocean circulation. Of note are the extremely cold winds blowing off the Antarctic Ice Sheet which cool the coastal waters. In certain recurrent locations (coastal polynyas), these create high rates of sea ice formation. This in turn leads to the formation of cold, dense saline water that sinks to form Antarctic Bottom Water. This complex system also sees a continual surface expression in the Southern Ocean of the global ocean's normally deep nutrient layer, which is the primary reason for the sustained high productivity in the region. In the tropics, this nutrient layer only reaches the surface through upwelling.

The continental shelf surrounding Antarctica is unusually deep compared to elsewhere in the world, as a result of scouring by ice shelves and crustal depression caused by the weight of continental ice (Clarke, 1996). The continental shelf is generally narrow, except in large embayments such as the Ross Sea and Weddell Sea.

The Southern Ocean is covered by a band of largely seasonal sea ice that extends from a maximum southerly extent of ~75°S northwards as far as ~55°S at its maximum extent. The width of this band is highly variable, ranging from a few hundred kilometres in the Indian Ocean sector to ~1600 km in the Weddell Sea. Given the relatively narrow width of the continental shelf surrounding the Antarctic continent, a large proportion of the Antarctic ice cover occurs over deep ocean, where it is exposed to a zone of strong cyclone activity and ocean waves and swell. The latter create a well-developed circumpolar marginal ice zone, which effectively protects the inner pack from incoming ocean wave energy.

The coastal zone is complex, with sea ice distribution and characteristics (of both pack and fast ice) being affected by coastal configuration and the presence of grounded icebergs, which are in turn closely linked to bathymetry (Massom et al., 2001). Coastal polynyas (large areas of open water) occur around the continent (Arrigo and van Dijken, 2003), and there are also two deep water polynyas in the Weddell and Cosmonaut seas (Morales Maqueda et al., 2004). Polynyas constitute major regional sea ice "factories", sites of major water-mass modification and, in places, enhanced biological activity.

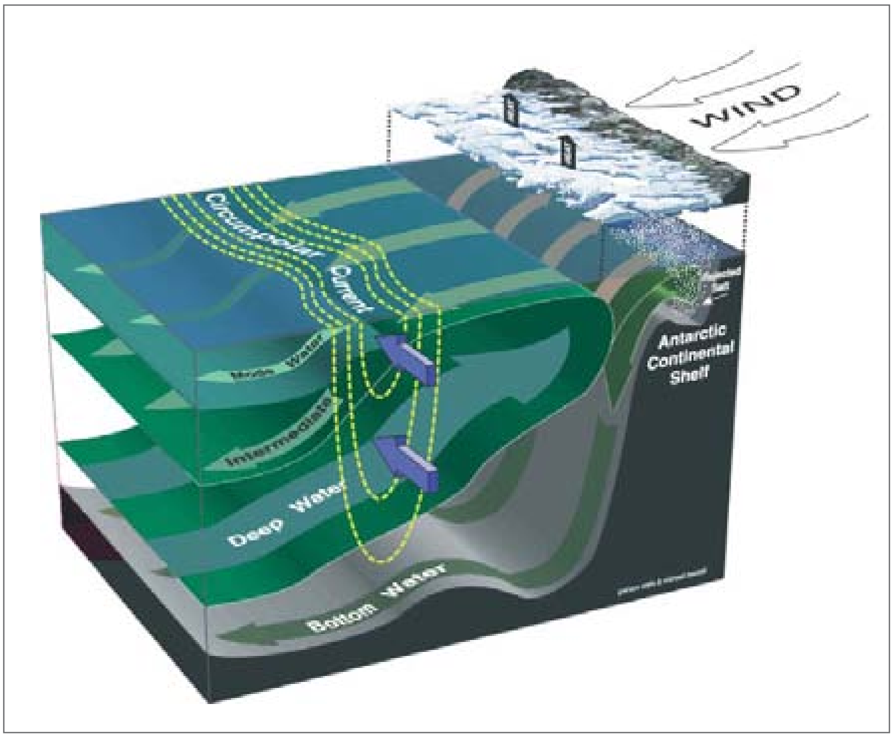

FIGURE 2: Three-dimensional structure of water masses, showing relationship between the ACC and deep water (Figure reprinted with permission from: Rintoul, 2000).

The seasonal cycle of sea ice advance and retreat is one of the major drivers of physical and ecological processes in the Southern Ocean. On the hemispheric scale, the sea ice cover in winter interacts with key oceanic and biological boundaries such as the continental shelf break, the southern boundary of the Antarctic Circumpolar Current (Tynan, 1998) and the Antarctic Divergence, the latter being an important zone of upwelling. The areal extent of Antarctic sea ice varies annually by a factor of ~5, from a maximum of 18-20 x 10^6 km^2 in September-October to 3-4 x 10^6 km^2 each February. As such, it is predominantly a seasonal sea ice zone, although large regions of perennial ice persist in the western Weddell Sea, Amundsen Sea and Ross Sea and southwest Pacific Ocean though summer (Gloersen et al., 1992).

The major features driving the dynamics of sea ice are shown in Figure 3.

The Antarctic Peninsula region is the only Antarctic sector to have experienced a rapid warming trend over the past 50 years, of ~0.5°C per decade (Vaughan et al., 2001). Moreover, the West Antarctic Peninsula (WAP) region is the only Antarctic sector to have experienced a statistically significant decreasing trend in sea ice areal extent since 1978 (see inset in Figure 3, from Kwok and Comiso, 2002). Recent results imply that this change may result from changes in dynamic (i.e., wind-driven) forcing (Massom et al., 2006). These factors, combined with the profound impact of the Antarctic Peninsula as a meridional blocking feature that extends to low latitudes and oceanic characteristics, suggest that the WAP region should be treated as a separate regime.

Forming an important habitat for a wide range of organisms specifically adapted to its presence, sea ice plays a dominant defining role in structuring high-latitude marine ecosystems (Ackley and Sullivan, 1994; Brierley and Thomas, 2002; Eicken, 1992; Lizotte and Arrigo, 1998; Nicol and Allison, 1997), and on a variety of scales. The most productive areas of the Southern Ocean lie in the Seasonal Ice Zone, between the maximum northern extents of sea ice in winter and summer. Here in particular, Antarctic krill and other planktonic organisms support an abundance of fish, birds, seals and whales. In addition, the ice edge is typically a region of enhanced biological activity during the melt season in particular (Nicol and Allison, 1997; Smith and Nelson, 1986; Smith et al., 1988; Sullivan et al., 1993).

Although in the past characterised as simple, the Antarctic food web involves complex relationships between primary producers and higher predators, as well as abiotic factors. The Antarctic ecosystem is characterised by

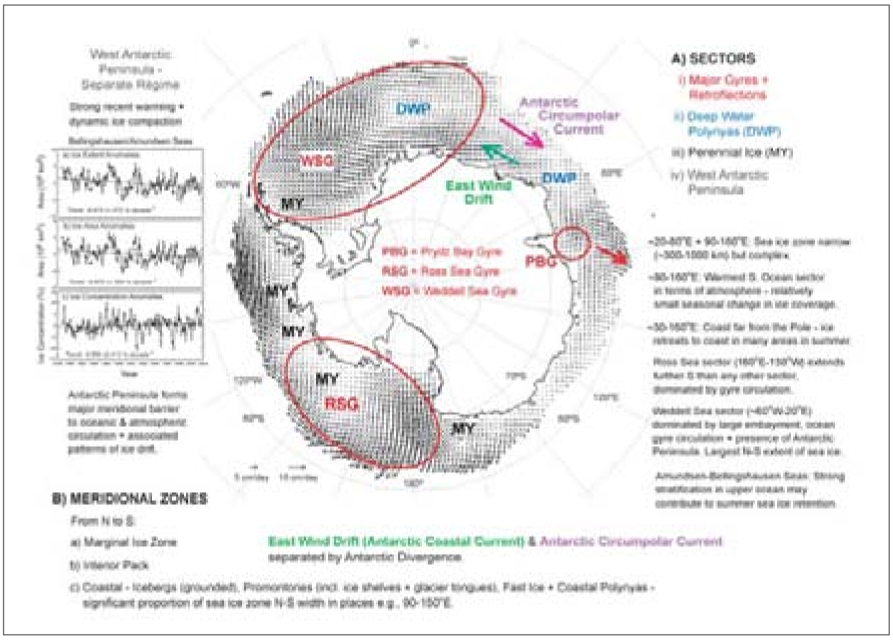

FIGURE 3: Map of climatological (mean) satellite-derived sea ice motion for 1997 (courtesy US National Snow and Ice Data Center; Fowler, 2003), with broad-scale sea ice sectors superimposed. Explanations are provided in the figure. The motion vectors are projected to a 25 x 25 km resolution grid. Dominant features in the climatological ice drift pattern are 3 major ocean gyre systems, the westward-drifting Antarctic Coastal Current and eastward flowing Antarctic Circumpolar Current, with regions of retroflection associated with the ocean bathymetry i.e., ocean bathymetric "steering". Figure by R. Massom.

strong seasonal cycles and major food-web differences that are intimately related to the annual sea ice growth-decay cycle and sea ice conditions, as well as associated ocean dynamics (mixing), water density and nutrient availability (Garrison and Mathot, 1996; Legendre et al., 1992; Lizotte, 2001).

Existing regionalisations for the Southern Ocean

The Southern Ocean has been divided into large-scale regions before, primarily based on physical characteristics such as frontal features (Orsi et al., 1995; Longhurst, 1998) and ice dynamics (Tréguer and Jacques, 1992). Information on the distribution of species has been used in biogeographic classifications of benthic fauna (Ekman, 1953; Hedgpeth, 1970; Dell, 1972), and also by CCAMLR in the definition of statistical subareas on the basis of fish stock distribution (Everson, 1977) (see Figure 1).

In the southern Indian Ocean, some smaller scale regionalisations have been attempted in the development of a bioregionalisation in Australian waters to assist in regional marine planning (Lyne et al. 2005), the designation of marine reserves (Meyer et al. 2000), and benthic habitat mapping (Beaman and Harris, 2005).

Early biogeographic classifications for the Southern Ocean delineated large-scale provinces according to the distribution of benthic fauna (Hedgpeth, 1970; Dell, 1972). More recent studies have largely confirmed these broad-scale patterns regions, although there are now thought to be significant differences between the benthic faunas of East and West Antarctica (Clarke and Johnston, 2003). A recent study on the biodiversity and biogeography of subantarctic mollusca (Linse et al., 2006), using species from the continental shelf areas (0-1000 m), identified the following distinct sub-regions in the Southern Ocean: Antarctic Peninsula, Weddell Sea, Dronning Maud Land, Enderby Land, Wilkes Land, Ross Sea, and the independent Scotia arc and subAntarctic islands (Figure 4). These divisions have also been used by WWF and The Nature Conservancy (TNC) in a study to synthesise existing classifications into a system of Marine Ecoregions of the World (Spalding et al., 2006).

Tréguer and Jacques (1992) defined five functional units south of the Polar Front on the basis of ice and nutrient dynamics. This work demonstrated the role of ice dynamics in controlling phytoplankton initiation and growth, and the nutrient regimes that discriminate each of these units. Defined units include the Polar Front Zone, located between approximately 60°S and 55°S, and the Permanently Open Ocean Zone which lies between the Polar Front and the maximum northern extent of winter sea ice. The Seasonal Ice Zone is located between the northern limits of the pack-ice in winter and in summer, while the Coastal and Continental Shelf Zone is adjacent to the Antarctic continent. The Permanent Ice Zone incorporates ocean areas under ice shelves.

Orsi et al. (1995) described large-scale frontal features of the ACC, based on historical hydrographic data. Gradients in ocean surface properties were used to define three major fronts within the ACC which separate water masses and flow characteristics. These are shown in Figure 5.

Longhurst (1998) proposed a global system of ocean classification based on a simple set of environmental variables (sea surface temperature, mixed layer depth, nutrient dynamics and circulation) together with planktonic algal ecology. In this classification scheme (Figure 6) the Southern Ocean includes two provinces in the Westerly Winds Biome between approximately 40°S and 50°S (South Subtropical Convergence Province and SubAntarctic Water Ring Province) and two in the Antarctic Polar Biome between 50°S and the continental coast (Antarctic Province and Austral Polar Province).

The LME classification system defines the Southern Ocean as a single unit (Sherman and Duda, 1999), while several other classifications define only a small number of concentric rings around the continent. However, the Southern Ocean has a variety of distinct provinces within these larger regions which differ in their chemical, physical and ecological characteristics, and which show considerable longitudinal, as well as latitudinal variation. Improved data coverage and availability through satellite imaging, and improved understanding of ocean characteristics through ecosystem modelling makes it now possible to elaborate on these previous regionalisations using a wider range and broader coverage of data. ■

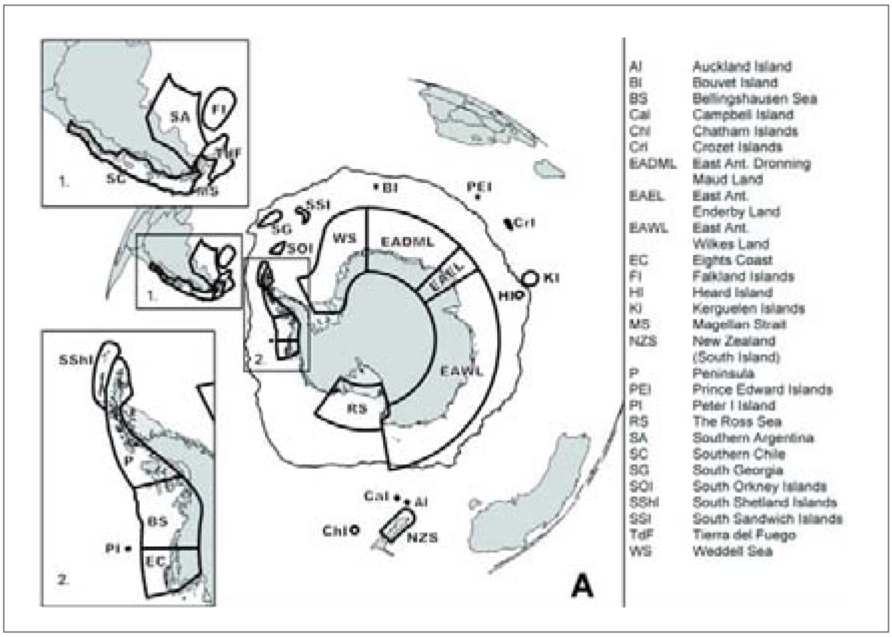

FIGURE 4: Biogeographic areas of the Southern Ocean defined by Linse et al. (2006), using distribution records for shelf (0-1000 m) species of shelled gastropods and bivalves
(Figure reprinted with permission from: Linse *et al*, 2006)

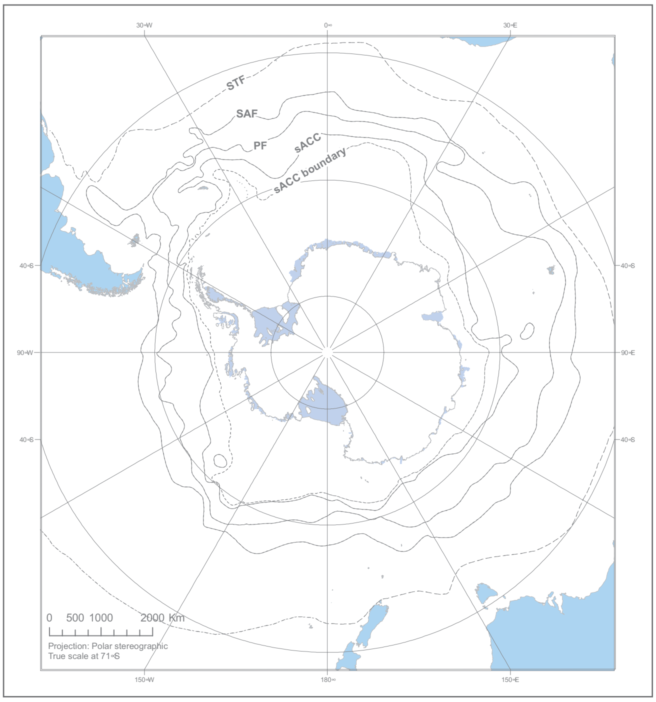

FIGURE 5: Fronts of the Southern Ocean, as defined by Orsi et al. (1995)

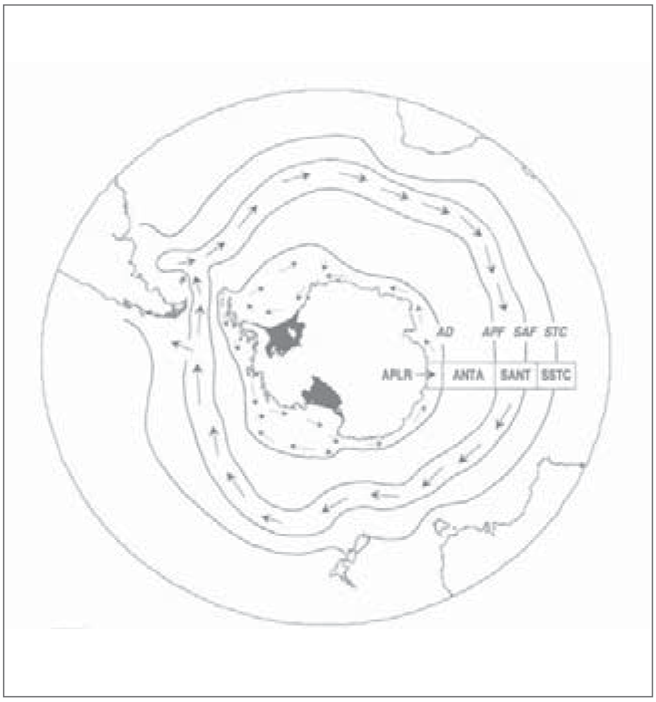

FIGURE 6: Classification of the Southern Ocean, Longhurst (1998)
(Reprinted from: Ecological Geography of the Sea, A.R. Longhurst. Copyright (1998), with permission from Elsevier)

1.4 Experts Workshop

The aim of the Experts Workshop was to review the methods for identifying major provinces, collate available synoptic datasets, and to gain input and recommendations from experts on the process and the results. In particular, the workshop aimed to develop a "proof of concept" for a broad-scale bioregionalisation of the Southern Ocean, using physical and environmental data as the primary input.

A list of the workshop participants is provided at the end of this report.

Specific objectives of the workshop were to:

- review and assess the processes developed to date and the proposed methods;
- discuss and make recommendations on data types to be included in a broad-scale bioregionalisation;
- collate appropriate datasets;
- apply the approved method(s) to the Southern Ocean using available datasets, to test and validate the process and produce a 'proof of concept' including maps of the defined broad-scale provinces;
- assess preliminary results and broad-scale provinces, given present knowledge of the Southern Ocean.
- provide recommendations on products to be developed, including the final report, maps, illustrations, datasets and a GIS (or other) database; and
- provide recommendations on datasets and/or method(s) that might be used to develop further fine-scale bioregionalisations.

The workshop was held over five days, and included background presentations, plenary discussion, and computer-based analysis in small groups.

At the start of the workshop, background presentations were given on some of the major physical processes in the Southern Ocean, and initial discussion focused on the relationships between physical and ecological processes. A series of presentations were also given on approaches to bioregionalisation that have been undertaken elsewhere, which allowed detailed consideration of the application of different methods.

Participants then investigated different aspects of data analysis and refinement of methods in small groups, focusing initially on their regions of particular expertise (e.g. South Atlantic, East Antarctica, Ross Sea) and later looking at the Southern Ocean as a whole. Selected physical datasets were provided for use in the initial analysis, and others were made available by participants during the week. The analytical methods used by Lyne and Hayes (2005), Leathwick et al. (2006a) and Raymond and Constable (2006) were used as starting points for the analysis during the workshop. These methods were refined into a single methodology, following workshop discussions and practical explorations of the methods. Appendix I gives further details on the background and technical aspects of each of these methods.

The final stages of the workshop included discussion on how well the defined regions corresponded to our present knowledge of the Southern Ocean. Priorities were identified for further work on issues including uncertainty, understanding of inter- and intra-annual variation, validation of results, the use of additional data (particularly biological datasets) and finer-scale analysis of particular areas of interest.

The Southern Ocean covers around 10% of the world's ocean surface, and includes some of the most productive marine regions on Earth. Although they are among the least-studied, the seas around Antarctica are a critical component of the global climate system and marine ecosystem.


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2. Approach to bioregionalisation

This section describes the approach to bioregionalisation that was used as a starting point for the workshop discussions and analysis. Descriptions of each step are presented here, together with background information on issues that must be considered. Further technical detail is provided in Appendix II. A summary of the final method adopted is presented in Section 3.

The regionalisation process can be partitioned into the following steps:

1. Identify the ecological patterns and processes that have relevance to the end-use application of the regionalisation
2. Identify the major environmental drivers or properties that control these patterns and processes, and extract relevant parameters describing those properties
3. Pre-process the data (e.g. normalise, transform, smooth)
4. Compile a data matrix of individual sites (rows) by properties (columns)
5. Apply a clustering procedure to group sites with similar properties
6. Post-process the clusters to meet any application-specific constraints on the regions (e.g. minimum size)
7. Expert review of the regions to ensure suitability for the application.

This process can be iterative. Ideally, the initial process will establish the mechanisms by which new data and/or knowledge could be incorporated into revisions of the bioregionalisation, although this would be expected to assist more in establishing or revising smaller scale subdivisions rather than altering the higher level bioregionalisation.

Figure 7 is a schematic representation of the bioregionalisation process, illustrating how data selected to reflect ecological processes can be used to define bioregions. ■

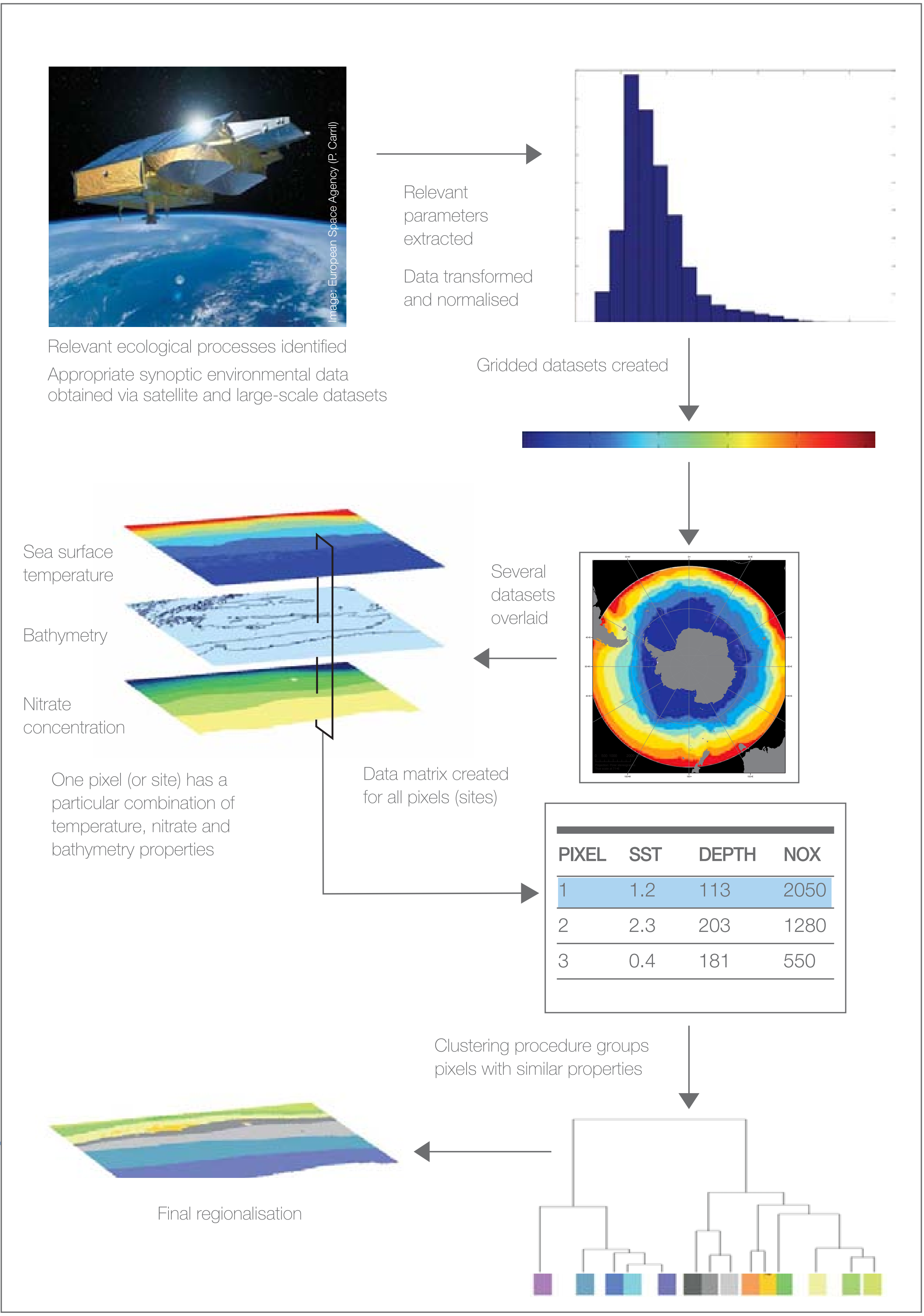
Image: European Space Agency (P. Carril)

PIXEL	SST	DEPTH	NOX
1	1.2	113	2050
2	2.3	203	1280
3	0.4	181	550

FIGURE 7: Schematic representation of the bioregionalisation process

2.1 Identifying properties to be captured

An important first step in the bioregionalisation analysis is to identify distinct ecological processes and their defining properties. The identification of ecological processes to be captured in the regionalisation is likely to be driven by the requirements of a particular end-use application.

Ideally, a bioregionalisation would delineate units that, depending on the scale, clearly separate habitats, communities and ecosystems. In this ideal world, populations would reside wholly within these areas. In reality, there is considerable complexity that needs to be addressed because of the different relationships that species have with the environment and other biota (Andrewartha & Birch 1984). A bioregionalisation aims to capture the properties of the important relationships rather than, necessarily, simply trying to circumscribe the distributions of whole populations of species.

This concept is illustrated in Figure 8. Some species will be found closely aligned with environmental gradients. Other species will appear in areas with high levels of perturbation, such that environmental factors are mixed and ever changing in their relative distributions. Yet others will exploit the diversity of patches in fringing habitats and ecotones. For mobile species, some taxa will be found across most areas but only some areas will be important to them as feeding or reproductive areas. An important step in the process is to determine how to accommodate environmental gradients and overlaps in the regionalisation.

The marine environment comprises three dimensions – geographic space and depth. Distribution of biota in the pelagic environment is mostly determined by the potential productivity in the water masses and the movement of those water masses in space and depth. The benthic environment has additional features reflecting variation in the depth, substratum types and roughness of the seafloor, and the degree to which this promotes interaction with the pelagic realm. These features are often considered to the primary drivers of environmental heterogeneity. Secondary drivers are more ephemeral or changing over time. In the Antarctic, they would also include other features of the environment such as the annual cycle of advance and retreat of the sea ice zone.

A bioregionalisation would generally try to represent the heterogeneity in ecosystem structure and function, which primarily would subdivide areas according to the magnitude of productivity and its predictability in time. Further subdivision would relate to the diversity of habitats and the relationships of species and food-webs to those habitats. The process will need to differentiate between areas with relatively constant features from those that are highly variable, even though they may have similar mean values. This is because a region with a large amount of disturbance can accommodate different assemblages involving opportunistic species as well as those that require long-term stability. Some areas in a bioregionalisation may need to represent large areas of habitat discontinuity or disturbance, which could be important regions in themselves. As a result of these considerations, a goal for a bioregionalisation is to capture not only the differences in diversity and the suite of ecosystem relationships, but also the potential differences in environmental stability.

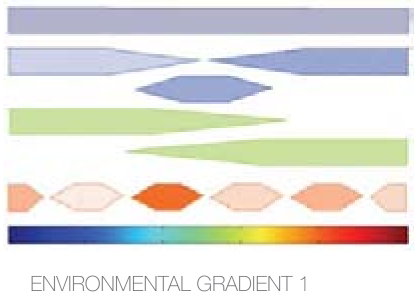

FIGURE 8(a): distribution of species with respect to a single environmental gradient, say temperature. Each polygon represents a different taxon, colours represent similar taxa. Width of bars represents relative abundance for a taxon.

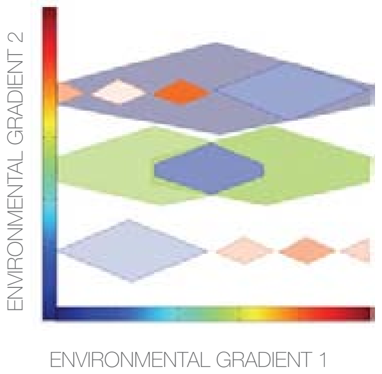

FIGURE 8(b): as for (a) but with distributions relative to two environmental gradients - distributions on gradient 1 are as in (a). A general discontinuity between species distributions in (a) might be roughly at the midpoint (green on the environmental gradient). In (b) the separation between groups of taxa becomes clearer on the second gradient.

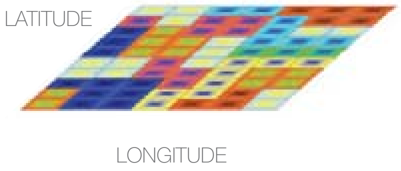

FIGURE 8(c): The environmental conditions form a patchwork in geographic space which can result in regions of similar environmental conditions being separated geographically. Here, parallelograms represent spatial areas with colours representing two environmental parameters (outer colour is from environmental gradient 1 and inner colour is from gradient 2). Each area is expected to have a species composition consistent with that composition at the intersection of two respective environmental gradient colours in (b).

FIGURE 8: Conceptual diagram illustrating potential relationships between species along gradients of environmental parameters.


Photograph by Brian Ball, Australian Government Antarctic Division © Commonwealth of Australia

2.2 Classification method

The intent of a regionalisation is to partition the study area into a set of discrete spatial regions, each with relatively homogeneous ecosystem properties. In the bioregionalisation analysis, regions are selected by grouping sites with particular characteristics. In some cases there may be specific, known characteristics that can be used to delineate region boundaries, such as water temperature changes across oceanic fronts. Another example is to separate the continental shelf from the continental slope by choosing an appropriate bathymetric contour, say 1000 m. Generally, however, the expectation is that the regions will reflect a natural clustering of the environmental or biotic data.

Clustering algorithms are well suited to bioregionalisation analysis, as they are designed to partition a large data set into a number of subsets, each with relatively similar properties that differ from those of the other subsets. In the context of a regionalisation, the clustering process takes sites (or cells) from a grid in geographic space. Each site has associated ecological properties (physical and/or biotic data) and this information is used to group together sites with relatively similar ecological properties. Those groupings (which are calculated in 'environmental space', i.e. based only on environmental properties, and ignoring spatial information) are then projected back into geographic space in order to find the spatial extents of the resulting regions. Thus, the regions are discrete in environmental space, but may be scattered or fragmented in geographical space (i.e. there may be several regions with the same properties located in different geographic areas).

Choosing clustering algorithms

There are a large number of clustering algorithms that could potentially be used, all of which have assumptions or limitations that may preclude their use in particular circumstances or with particular types of data. Thus, the outcomes of the bioregionalisation could be influenced by the choice of the algorithm. The aim is to develop a clustering process that is consistent with the data and for which the results are likely not to change much with alternative clustering algorithms. Consideration will need to be given, inter alia, to algorithm assumptions, complexity, and accuracy.

It is important to make the distinction between the clusters that are produced by a clustering algorithm, and the regions that are formed from those clusters. A cluster is a group of sites that are considered to have similar environmental properties. However, because the clustering process is based on environmental similarity (and not spatial information), a single cluster may contain sites that are spatially separated. A region is thus considered to be a group of sites that belong to the same cluster, but which also form a contiguous spatial area. A single cluster may produce a number of regions, each of which have the same general properties, but which are spatially distinct.

Clustering algorithms are often based around the concept of a dissimilarity metric, which (in the context of a regionalisation) is used to calculate how dissimilar two sites are, given their ecosystem properties (physical or biological data). The clustering of sites into regions is carried out in such a way that the intra-region dissimilarity of sites is low (i.e. sites within a region are similar to each other) relative to inter-region dissimilarities. Dissimilarity-based clustering methods can be broadly divided into hierarchical or non-hierarchical schemes. Further information on these schemes, and the issues related to selecting clustering algorithms, is provided in Appendix II. ■

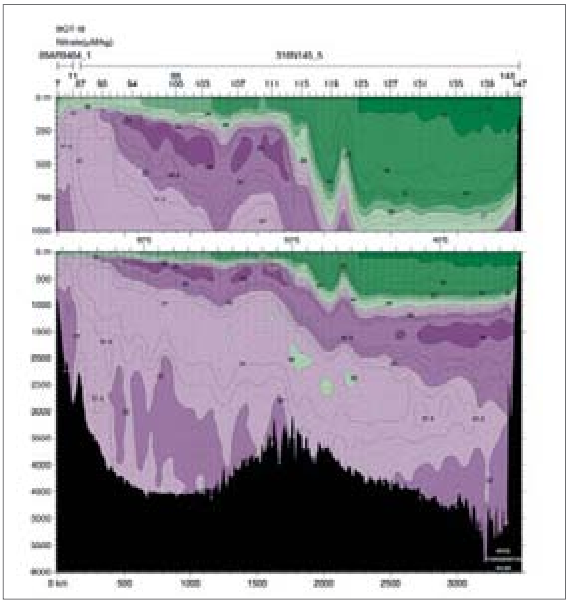

FIGURE 9: Water mass profile of nitrate concentration from Antarctica to the tropics, showing surface expression of the nutrient layer in the Southern Ocean. (Figure from http://woceSOatlas.tamu.edu. Orsi and Whitworth, 2005)

2.3 Variables that capture properties

Once the relevant physical properties have been identified, appropriate data must be selected to be included in the analysis. The data that are used in the clustering method should be matched to the ecological patterns and processes and spatial and temporal scales that are important to the end-use application. However, there is considerable latitude for choice within this broad guideline. Importantly, the data used in the clustering procedure will not necessarily be the raw observations from field sampling. The data may be transformed or be analysed within a model (processing algorithm) to provide the necessary inputs to clustering. For example, ice concentration maps can be routinely obtained from satellite passive microwave data (since 1978). However, daily ice concentration or mean concentration over time might not alone be indicative of the ecological processes of importance. The amount of time an area is free of significant concentrations of sea ice over the course of a year may be more important in terms of productivity in an area or the amount of time the area might be open to feeding activity of birds, seals and whales. Data availability and the choices of subsequent processing algorithms may impose some constraints on the types of data that can be used.

Figure 9 demonstrates how a particular variable (nitrate concentration) can capture environmental properties (surface expression of nutrients) across a broad spatial area.

Once relevant data have been collated, the study area is divided into a grid of sites (or interpolated from point observations), at a sufficiently fine spatial scale to enable appropriate resolution of the final areas. Descriptive statistics – such as means, variances, and other ecologically relevant information, including rates of change of parameters – are computed from the input data at a site level. Site data may be further processed if necessary. This might include spatial or temporal smoothing of the data in order to ensure that the data provides information at an appropriate scale for the regionalisation. The algorithms for selecting areas often also require data to be normalised so that variables with different measurement units can be statistically combined.

Variables of comparable type but measured on different scales are often normalised to a similar scale, say 0 to 1, while preserving the rates of change between different levels of the variable that need to be maintained in the analysis. Alternatively variables might be transformed where biological changes are greater in one part of the gradient, e.g., a log transformation might be used with ocean depth, given that rates of biological turnover are rapid near the ocean surface, but decrease with progression to deeper waters. Care needs to be taken to ensure that the properties of the variables and their relationships to other variables are not altered in the process. Variables that influence multiple ecological processes will reflect different aspects of those processes depending on how they are incorporated into the analyses.

The spatial and temporal scales of the data should be appropriate to the desired scale of the areas. Data with fine-scale spatial or temporal structure may need to be smoothed for use in broad-scale regionalisations. For pelagic applications, the selection of spatial regions is complicated by the depth structure of the water column and temporal variability at seasonal and longer timescales. A hierarchical approach is often used to assist in resolving problems of scale. The levels of the hierarchy can represent either spatial scales, or different ecological processes. A process-oriented hierarchy often has an approximate spatial structure due to the spatial scales of the processes.

To illustrate the concept of temporal variability at seasonal timescales, Figure 10 shows the mean monthly chlorophyll *a* concentrations for each month during summer (December to March). The seasonal variability of this property must be taken into account when using such data to capture ecological processes. Nevertheless, Figure 10 shows that certain areas maintain high levels of chlorophyll *a* concentration throughout this period, and thus a summer mean value may be appropriate for use in a bioregionalisation analysis.

Further information on scaling and weighting of variables is provided in Appendix II. ■

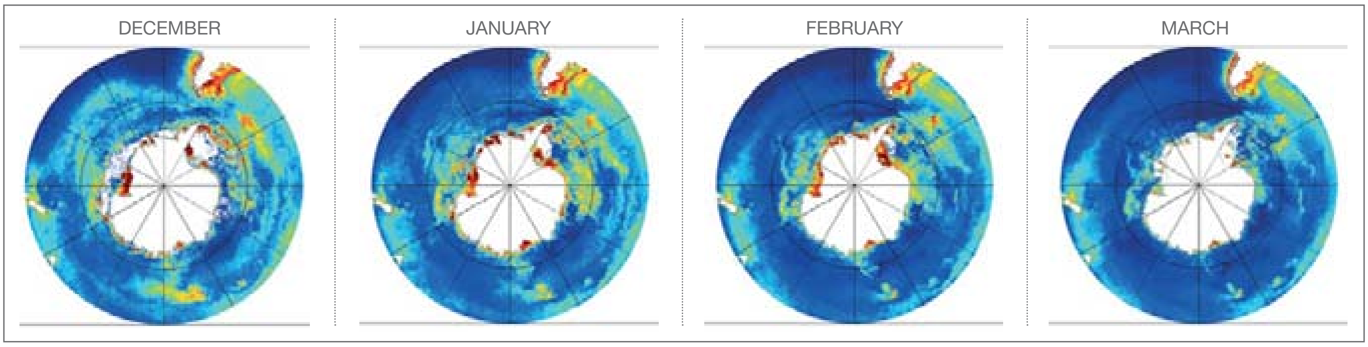

FIGURE 10: Mean monthly chlorophyll *a* concentrations for each month during summer (Dec-Mar) (Images provided by the SeaWiFS Project, NASA/Goddard Space Flight Center and ORBIMAGE)

2.4 Uncertainty

A regionalisation requires an assessment of the uncertainties in the locations of the boundaries between areas. In addition, as assessment should be made of whether the heterogeneity within an area is not sufficiently great that the area should not be differentiated from one or more of its neighbours.

Here, the term “uncertainty” is used to describe the effects of a number of different processes, including imprecision in data (for example measurement error, and bias due to incomplete or unbalanced observations), model uncertainty (uncertainty within models that have been used to derive one variable from others, such as climatologies or primary productivity models), and epistemic uncertainty (lack of knowledge of how to go about the regionalisation process; Raymond and Constable 2006). Each of these can affect the resulting region boundaries. Note that stochastic, seasonal, or other temporal or spatial variability in data represents the temporal or spatial variability of the underlying ecosystem processes, and is not treated as uncertainty. However, if it is not clear how this variability should be incorporated into the regionalisation (e.g. should summer or annual means be used?) then this would, in turn, be a source of uncertainty.

A key output of an uncertainty analysis would be an assessment of the uncertainty in region boundary locations. This would indicate to end-users where they might expect the region boundaries to change if the data or analysis methods were to be updated or changed. ■

Photograph by John Kelly, Australian Government Antarctic Division © Commonwealth of Australia

Photograph by Grant Dixon, Australian Government Antarctic Division © Commonwealth of Australia

3. Physical regionalisation

3.1 Summary of adopted method

The classification method adopted during the workshop was a mixed non-hierarchical and hierarchical approach. The classifications were performed on a 1/8th degree grid, covering the marine area from 80°S to 40°S. The full set of 720,835 grid cells was subjected to a non-hierarchical clustering to produce 40 clusters. The mean data values for each of the 40 clusters was calculated and a hierarchical classification was then performed to produce a dendrogram and the final clustering.

Sites with missing data were excluded from the analyses. These were principally sites shallower than 200 m depth, for which the chosen nutrient data did not apply. These excluded sites are shown in the maps as white. Future work will need to fill in these missing cells, for example by considering their other attributes.

Primary regionalisation

The primary regionalisation used the following datasets:

- bathymetry (log10 transformed)
- sea surface temperature (SST)
- nitrate (NOx) concentration
- silicate (Si) concentration

Descriptions of each of these datasets are provided in Appendix III.

The workshop agreed that the ocean water masses combined with topography of the ocean floor were likely to define the primary features of the Southern Ocean and coastal Antarctic systems. Sea surface temperature was included as a proxy for the different water masses of the Southern Ocean (Figure 11). Topography (captured by bathymetric data) was included because of the clear ecological differentiation of the shelf, slope and abyssal regions as well as its influence on upwelling, eddying and as a potential source of iron. Bathymetry (Figure 12) was transformed (log10) to give most weight to the shallower areas less than 2500 m with a greater opportunity to differentiate the shelf break and slope.

Silicate and nitrate concentrations (Figures 13 and 14) were included to provide information on nutrient characteristics. Silicate concentration also provides a measure of actual primary production (particularly in diatom-dominated areas), since silicate is taken up during photosynthesis in the production of diatom shells. The silicate layer was found to be particularly useful for accurately differentiating water masses reflecting plankton communities in deeper water and along the various fronts. The nitrate and silicate climatologies at the 200 m depth layer were used rather than the surface layer as this is a better indicator of available nutrients, whereas surface nutrients are likely to be depleted in areas of nutrient-limited productivity. However, the use of the 200 m depth layer resulted in missing data in the shelf areas of less than 200 m depth.

Sea surface height (SSH) and insolation (mean summer climatology of photosynthetically-active radiation (PAR) at the ocean surface) were considered as additional primary variables that would have utility in defining frontal systems and productivity respectively, however they were not used at this stage because of insufficient time, and because the currently available datasets were incomplete. These datasets should be considered in future analyses.

Physical environmental data used as the input for analysis during the workshop were chosen based on their spatial coverage across the Southern Ocean. The datasets considered included bathymetry, sea ice concentration and extent, sea surface temperature, sea surface height, chlorophyll *a* concentration, nutrient data (silicate, nitrate and phosphate), and insolation (photosynthetically active radiation - PAR).

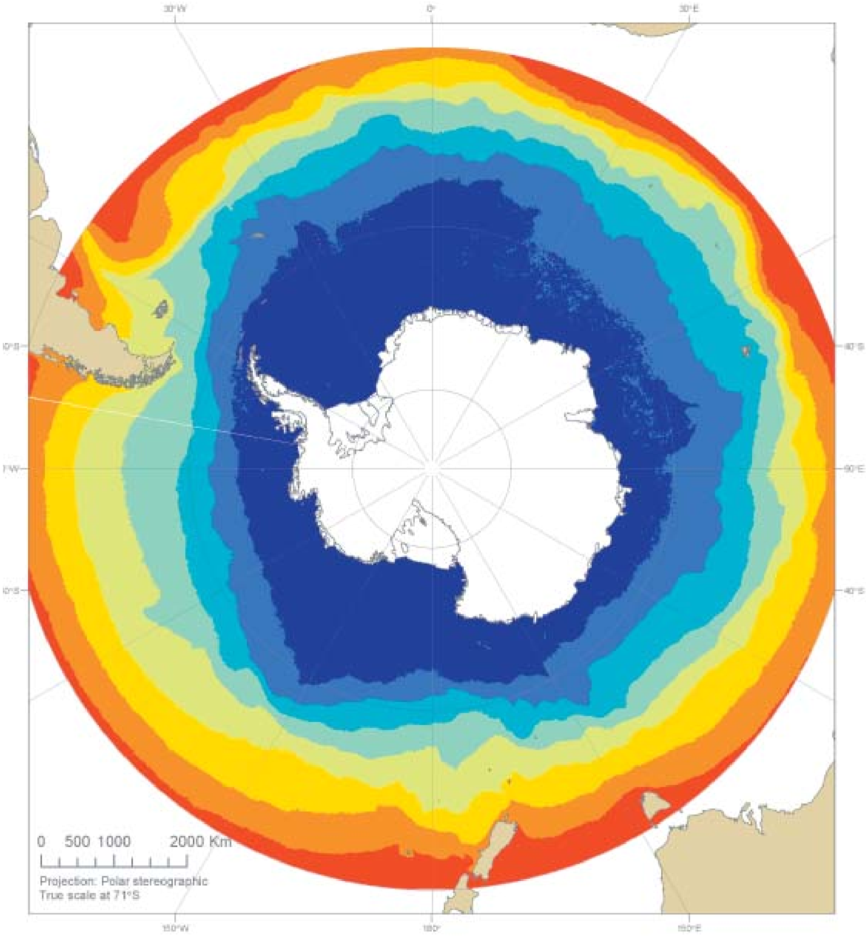

FIGURE 11: Mean annual sea surface temperature (SST). Monthly values from NOAA Pathfinder satellite annual climatology, averaged over the period 1985-1997 (Casey and Cornillon 1999)

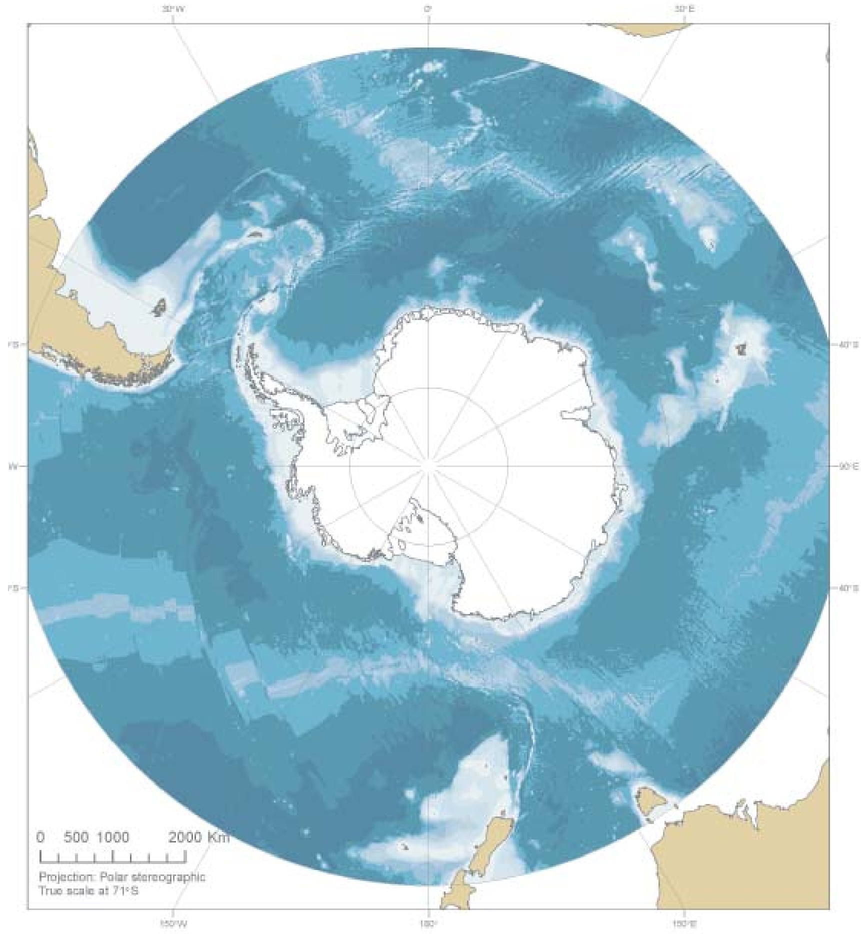

FIGURE 12: Bathymetry of the Southern Ocean. Depth data from the GEBCO digital atlas (IOC, IHO and BODC, 2003).

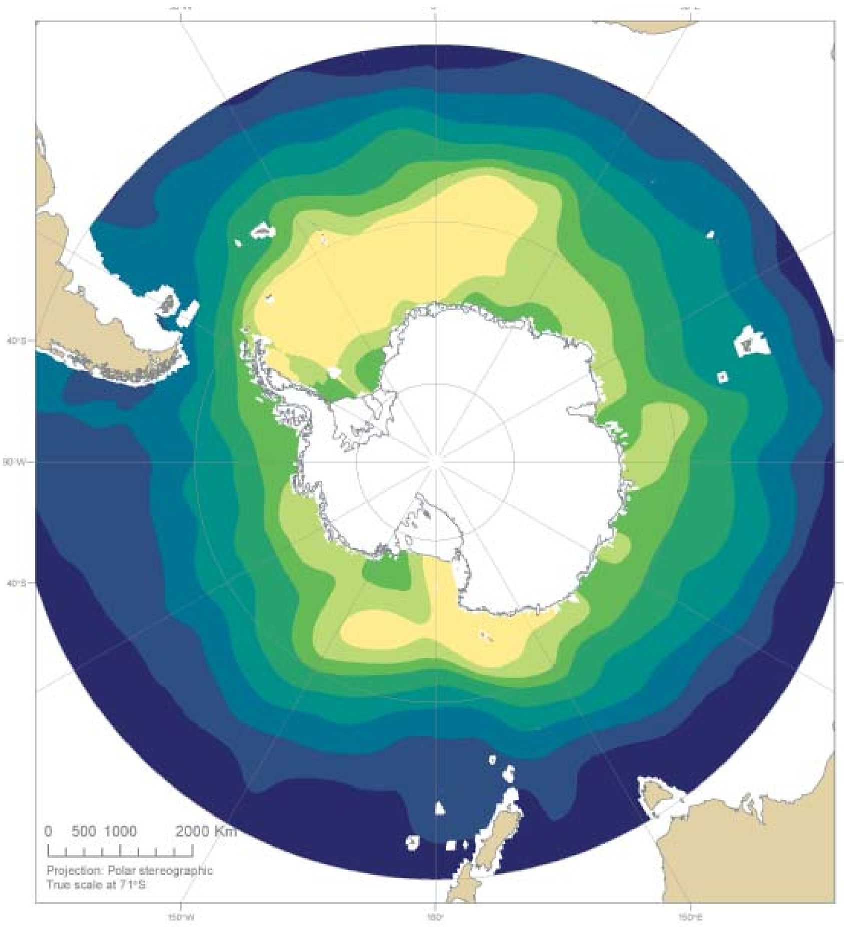

FIGURE 13: Silicate concentration (at 200 m depth). Climatology from the WOCE global hydrographic climatology (Gouretski and Koltermann, 2004)

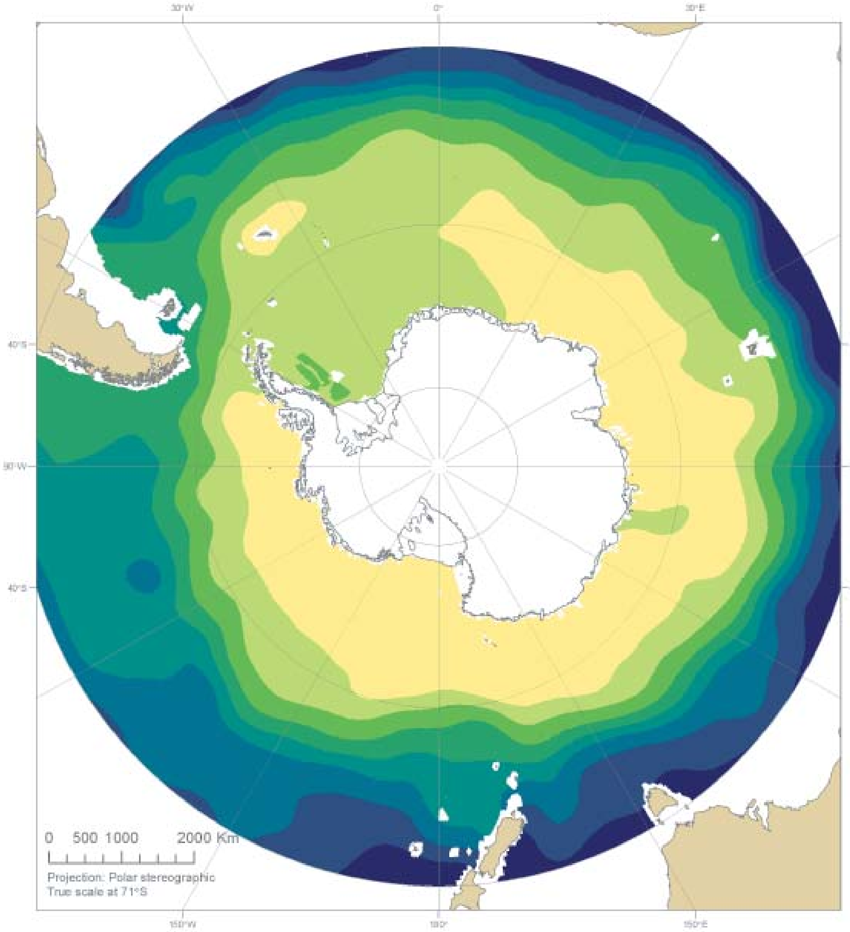

FIGURE 14: Nitrate concentration (at 200 m depth). Climatology from the WOCE global hydrographic climatology (Gouretski and Koltermann, 2004)


Photographer: John van den Hoff, Australian Government Antarctic Division, © Commonwealth of Australia

Secondary regionalisation

The Workshop agreed that the bioregionalisation should ideally differentiate first between the main divisions of coastal Antarctica (shelf and slope areas), sea ice zone and northern open ocean waters before further subdividing according to secondary features. Nevertheless, two potential components of a secondary classification were explored to determine if there is sufficient spatial heterogeneity to warrant a further subdivision.

Sea ice was considered to modify the pelagic environment both in terms of the potential for primary production as well its influence on the distribution of marine mammals and birds. The impact of sea ice on the environment was explored using a data layer comprising the number of days an area was covered by at least 15% concentration of sea ice (Figure 15).

The concentration of satellite-observed sea surface chlorophyll was explored using a data layer comprising log transformed chlorophyll *a* densities (Figure 16). The chlorophyll distribution was truncated at 10 mg.m^{-3} (where all values greater than 10 were made equal to 10), because the variability in higher order productivity most likely results from variability in the range from 0-10 mg.m^{-3}. While chlorophyll *a* concentration may not reflect primary production absolutely, it was considered to be a suitable proxy for the purposes of exploring spatial heterogeneity in primary production at the large scale.

Descriptions of each of these datasets are provided in Appendix III. ■

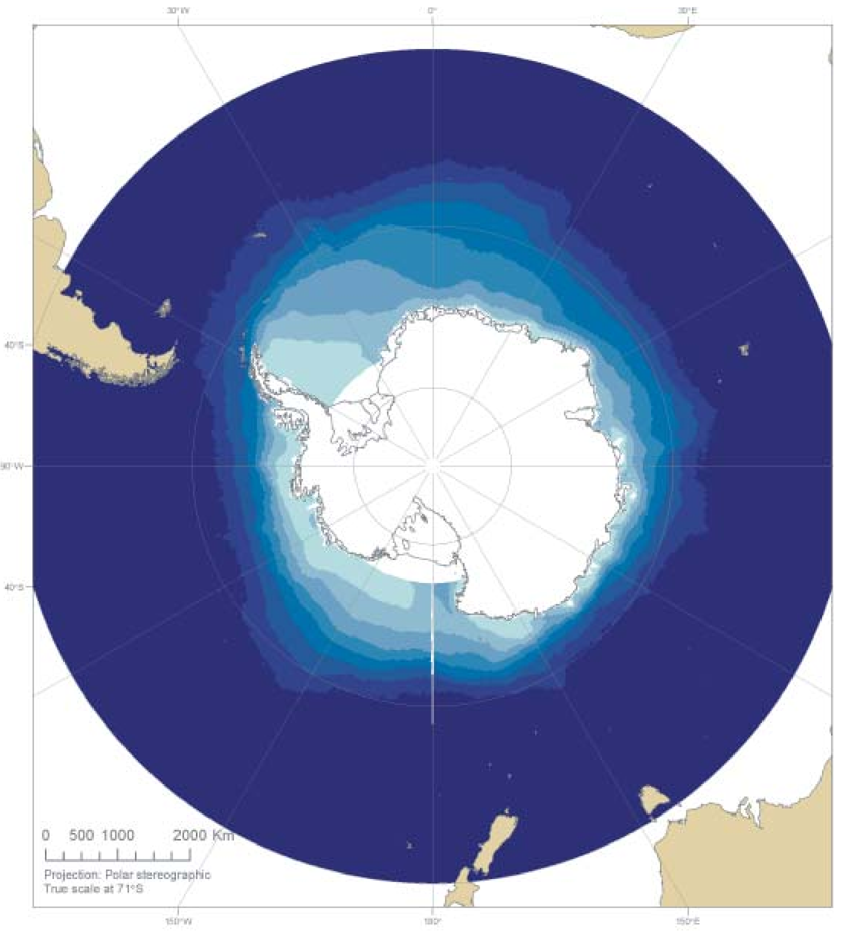

FIGURE 15: Proportion (0-1) of the year for which the ocean is covered by at least 15% sea ice. Calculated from satellite-derived estimates of sea ice concentration spanning 1979–2003. (Comiso, 1999

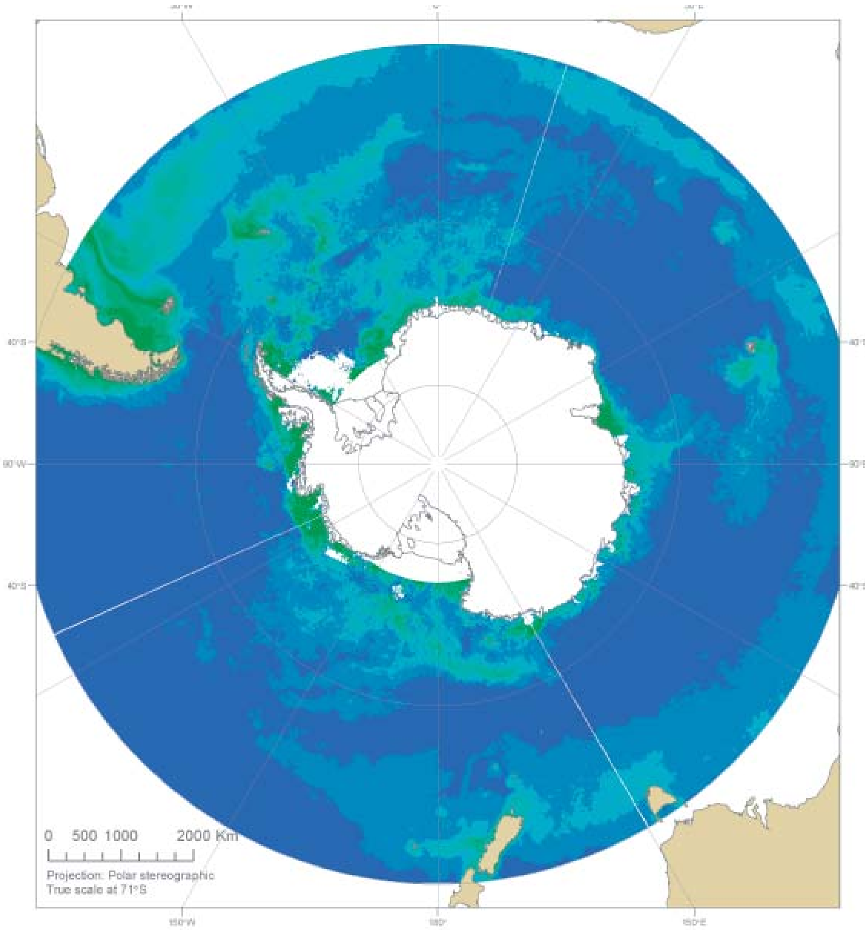

FIGURE 16: Mean summer (DEC-FEB) surface chlorophyll-*a* concentrations. Summer means (1998-2004) from SeaWiFS.

Photograph by Nick Gales, Australian Government Antarctic Division © Commonwealth of Australia

3.2 Results of Southern Ocean bioregionalisation

Primary regionalisation

The results of the primary regionalisation are shown in Figures 17 (dendrogram) and 18 (map). The physical properties of each region are shown in Table 1. This regionalisation clearly differentiates, at the highest levels, between coastal Antarctica (including embayments), the sea ice zone and the northern open ocean waters. The analysis highlights the different environmental characteristics of large regions including the continental shelf and slope, frontal features (Subantarctic Front, Polar Front, Southern Antarctic Circumpolar Current Front), the deep ocean, banks and basins, island groups, and gyre systems. ■

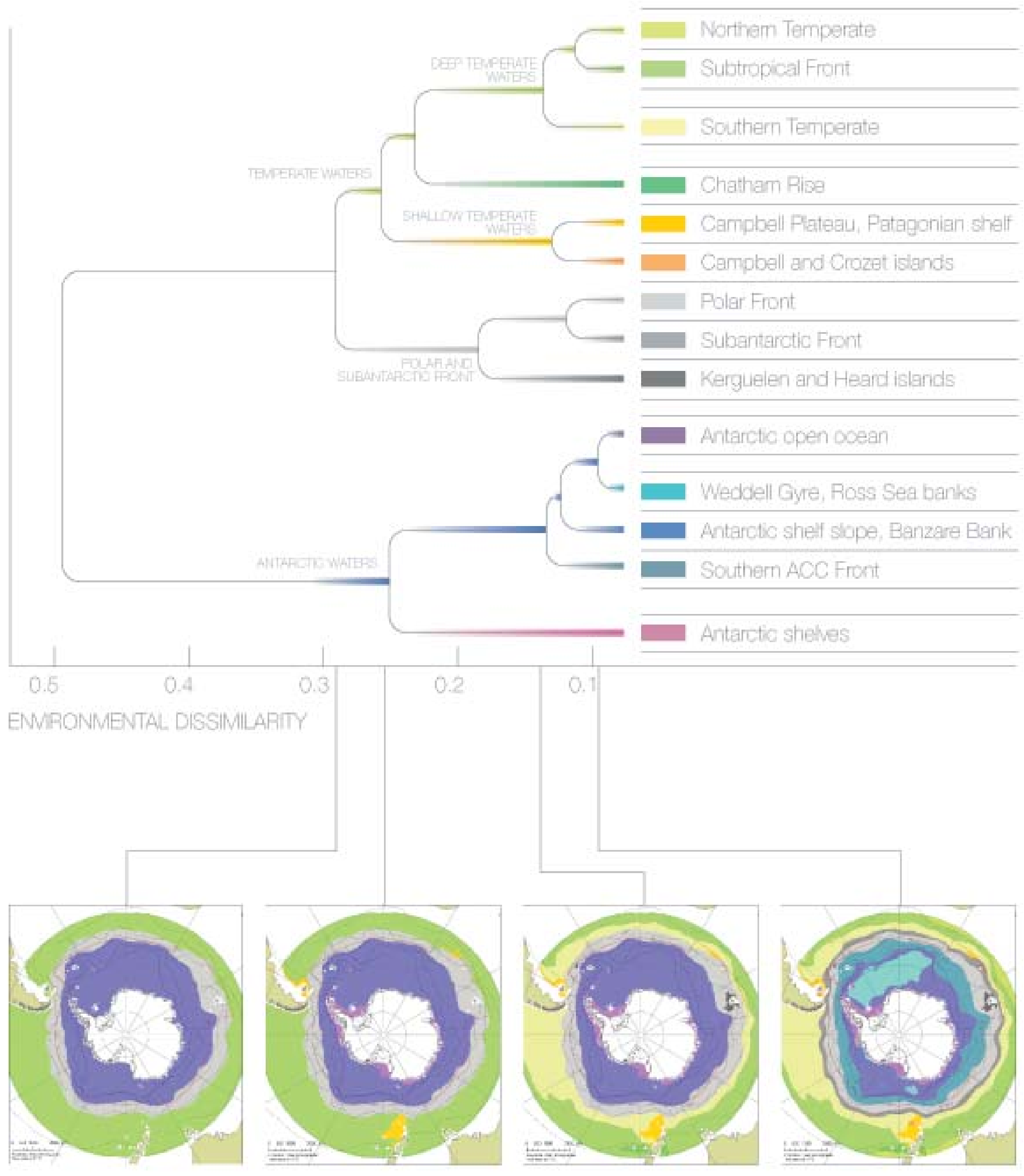

FIGURE 17: Dendrogram for primary (14-cluster) regionalisation, with thumbnail maps showing regionalisations at different stages of the hierarchy

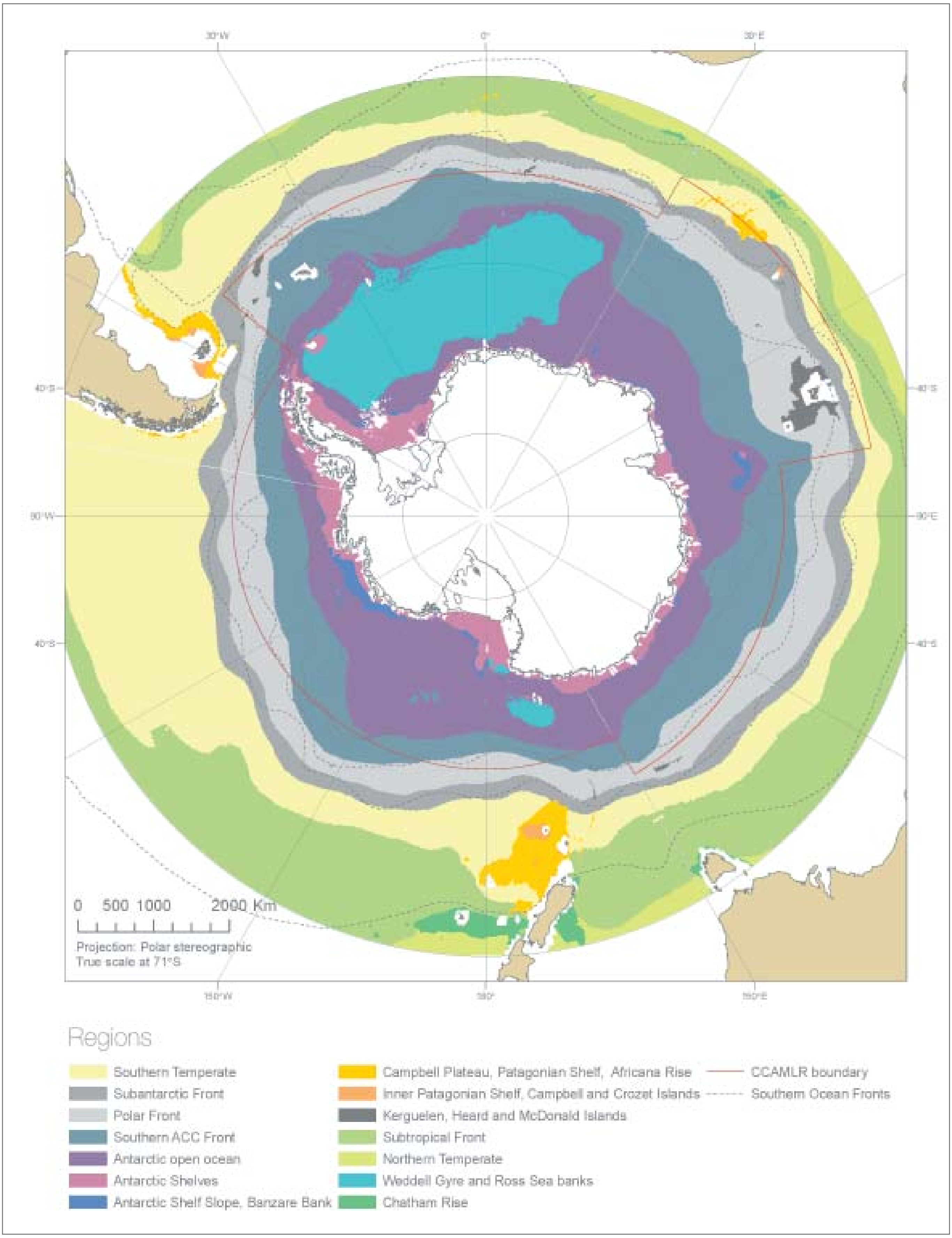

FIGURE 18: Primary regionalisation of the Southern Ocean based on: depth, sea surface temperature (SST), silicate (Si) and nitrate (NOx) concentrations (14 cluster groups) (white areas represent cells with missing data that were not classified in these analyses).

TABLE 1: Physical properties (mean and standard deviation of data values) of regions shown in Figure 18 (14 cluster groups based on primary datasets)

REGION NAME	Number of grid cells	Depth mean (m)	Depth SD	SST mean (°C)	SST SD	Si mean (µmol/kg)	Si SD	NOx mean (µmol/kg)	NOx SD
Southern Temperate	110567	-4119.952	821.342	8.681	1.854	7.998	2.402	20.919	1.616
Subantarctic Front	40180	-3917.738	921.884	5.840	0.791	15.231	2.582	25.158	1.052
Polar Front	83006	-4134.095	732.582	3.539	0.999	28.382	6.492	29.236	1.815
Southern ACC Front	108053	-4109.261	818.366	0.945	0.872	56.089	9.814	32.370	1.503
Antarctic Open Ocean	136360	-3612.533	897.680	-0.682	0.535	79.593	5.804	33.169	1.374
Antarctic Shelves	30767	-520.048	213.352	-1.149	0.380	82.044	9.211	32.356	1.821
Antarctic Shelf Slope, BANZARE Bank	6508	-1455.466	389.636	-1.227	0.434	79.961	2.946	33.599	1.343
Campbell Plateau, Patagonian Shelf, Africana Rise	7451	-1034.451	427.437	8.453	1.129	7.876	2.582	20.898	1.735
Inner Patagonian Shelf, Campbell & Crozet islands	913	-343.482	109.436	7.742	0.827	8.084	2.233	20.857	1.427
Kerguelen, Heard & McDonald Islands	2294	-1270.202	734.782	3.360	0.818	25.846	4.024	29.279	1.318
Subtropical Front	94234	-4461.472	788.887	11.804	1.511	4.607	1.235	15.257	2.062
Northern Temperate	9946	-4163.621	951.003	15.496	0.774	4.336	0.727	10.154	1.667
Weddell Gyre & Ross Sea banks	52905	-4466.641	762.290	-0.680	0.333	98.163	5.615	31.965	0.553
Chatham Rise	3025	-1568.439	858.953	14.361	0.802	4.112	0.610	12.061	1.453

Uncertainty

The time available to the workshop did not permit a rigorous analysis of uncertainty. However, a limited analysis was undertaken to investigate the uncertainty associated with the clustering algorithm. Figure 19 illustrates this uncertainty. Uncertainty was computed by first calculating the difference between the environmental characteristics of a grid cell and the average environmental characteristics of the cluster to which it was assigned. (Each grid cell is assigned to the cluster to which it is most environmentally similar). A second difference was then computed, this time between the environmental characteristics of a grid cell and the average environmental characteristics of the next-most similar cluster. The first difference value was then divided by the second. Thus, high uncertainty values (red, close to 1) indicate that a grid cell lies on the environmental boundary between two different clusters, and so its allocation to one or the other is less certain than for a grid cell that is strongly typical of the cluster to which is has been allocated. Note that this uncertainty analysis considers only a specific subset of the possible sources of uncertainty in the regionalisation (specifically, to do with the allocation of grid cells to particular clusters).

Secondary regionalisation

The secondary regionalisation incorporated two additional datasets to reflect properties that further modify the marine environment. The impact of sea ice on the environment was explored using a data layer comprising the proportion of the year (0-1) that an area was covered by at least 15% concentration of sea ice. The concentration of satellite-observed sea surface chlorophyll was explored using a data layer comprising log transformed chlorophyll densities.

The ice and chlorophyll data were incorporated both separately and in a single classification, and the results of these analyses are displayed in Appendix IV. The preliminary results of this analysis using a large number of clusters, based on both ice and chlorophyll, are presented in Section 3.3 for three sectors of the Southern Ocean. This exploratory classification is of use in illustrating the heterogeneity arising from these properties at a smaller scale than that of the primary regionalisation, however further work is needed to identify the appropriate level of regional separation using these secondary datasets, and to determine whether other datasets could be used to assist this process.

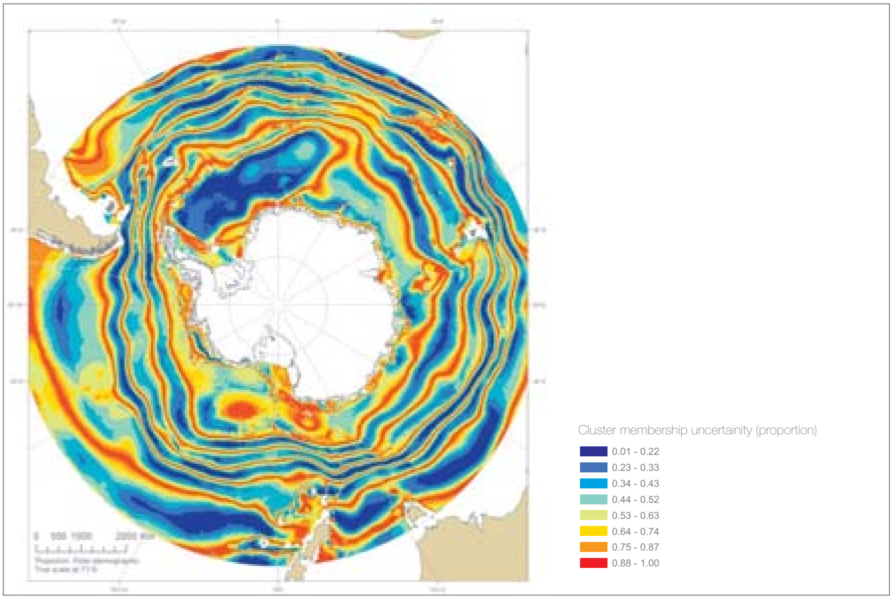

FIGURE 19: Map showing scaled uncertainty for the primary (14-cluster) classification

3.3 Expert review of bioregionalisation results

An assessment of the final results was carried out by expert review to determine if the defined regions were consistent with present knowledge of the ecosystem. The following sections describe the defined regions in further detail, focusing separately on the Atlantic, Indian and Pacific ocean sectors (CCAMLR Statistical Areas 48, 58 and 88, respectively). For each sector, a map of the regions defined by the primary regionalisation is overlain with information on known large-scale physical and ecological features such as fronts, gyres, seamounts and maximum sea ice extent. In addition, maps showing an example of a secondary regionalisation (using ice and chlorophyll data to define 40 clusters for the Southern Ocean) illustrate the high degree of smaller-scale heterogeneity arising from patchiness in chlorophyll and sea ice concentrations, particularly in shelf areas and the seasonal ice zone.

South Atlantic (Area 48)

The Atlantic sector is characterised by the narrowing of the ACC as it passes through Drake Passage between South America and the Antarctic Peninsula. In the west, strong currents, eddies and mixing associated with the ACC and the Weddell-Scotia Confluence (WSC) occur in the vicinity of the Scotia Arc. In the central and eastern areas, there is a greater contribution of the Weddell gyre and a broadening of the ACC. A large continental shelf area is present in the great embayment of the Weddell Sea, along with a number of ice shelves. These features are captured well in the primary regionalisation. The Atlantic sector is also dominated by strong seasonal cycles, manifest by changing irradiance and seasonal sea-ice cover. The bathymetry of the southwest Atlantic steers the flow of the ACC northwards, carrying polar waters to more northerly latitudes than elsewhere in the Southern Ocean. This transport is critical to the local marine systems around some of the more northerly SubAntarctic island groups where large colonies of many land-based predators breed.

The southwest Atlantic is possibly the most studied of all the areas in the Southern Ocean. It has higher productivity than other areas. Extensive summer phytoplankton blooms, particularly around some of the island chains, probably result from the mixing of micronutrients with surface waters through the flow of the ACC and the WSC as they pass over the Scotia Arc. A range of zooplankton species including Antarctic krill (*Euphausia superba*), consume this primary production. In turn, these taxa are consumed by numerous species of nekton, seabirds and marine mammals. The resulting biodiversity is possibly higher than elsewhere in the Southern Ocean.

Zooplankton community structure in the southwest Atlantic appears to be dependent upon the timing of the seasonal sea-ice retreat (Ward et al., 2003). Sea-ice influences the timing of reproduction; a late retreat delays reproduction and reduces population sizes of a number of zooplankton species. During years of normal sea-ice retreat copepods are more advanced, and there are also higher abundances of krill larvae. This implies that the seasonal environment critically influences the biogeography of zooplankton communities in the southwest Atlantic. As a consequence, multi-year datasets that encompass years of differing environmental

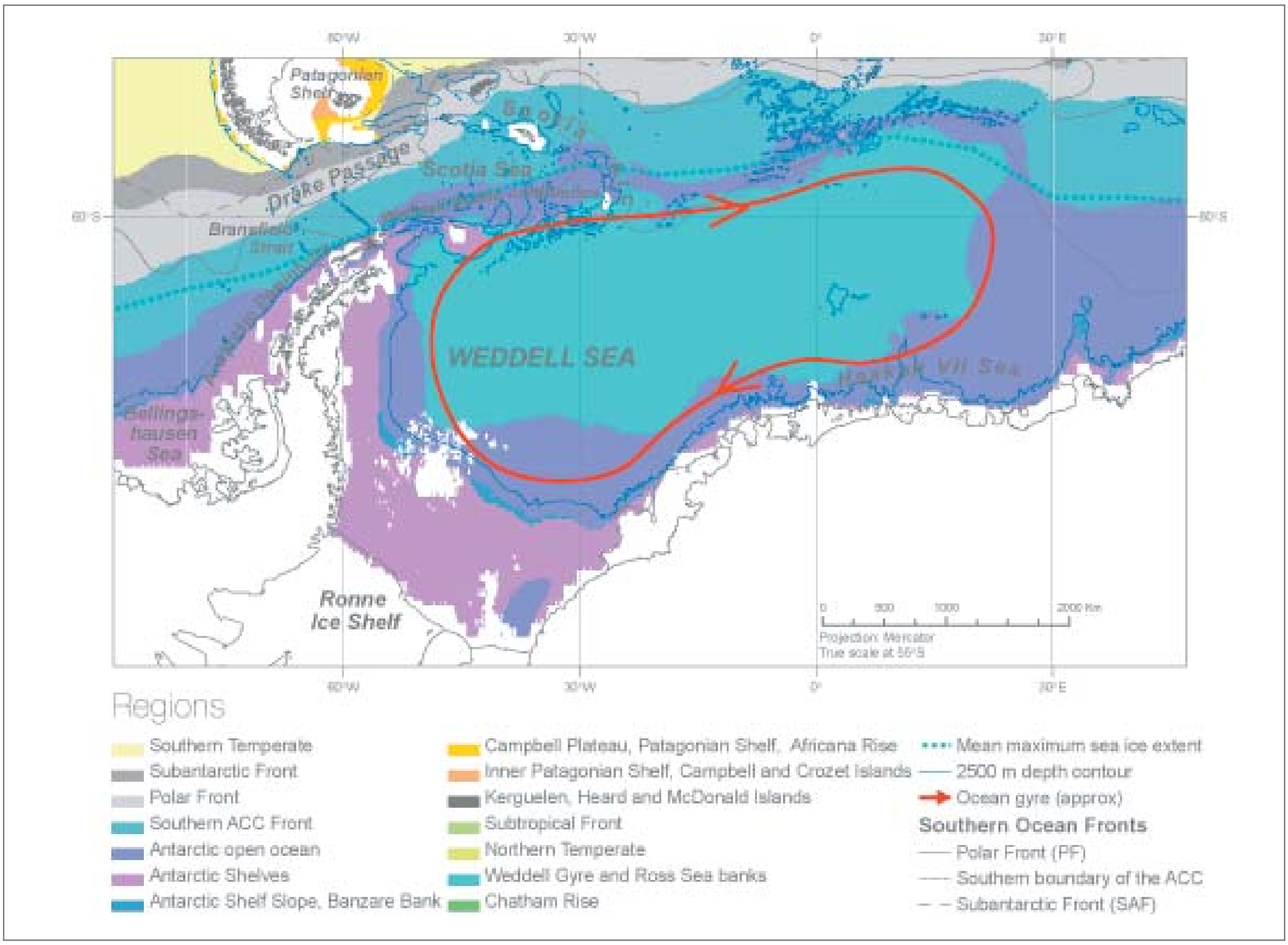

FIGURE 20: Map showing primary regionalisation for the South Atlantic sector (Area 48), with major physical features

conditions are likely to provide broader and more generic descriptions of community structure in the southwest Atlantic than do single year synoptic surveys.

A number of such analyses are now available, which reveal that (multi-year) sampling of zooplankton species across the ACC to the northwest of South Georgia form four community groupings, and that these are geographically consistent with the different water masses identified on the basis of temperature and salinity properties. Copepods are the largest contributors to total abundance within these groupings. All groups can be characterised by varying proportions of a relatively small subset of species, many of which are present throughout the region. Other species are characteristic of particular groups. The close physical and biological coupling observed across the ACC confirms that frontal zones, and particularly the Polar Front, are features across which community properties change in the Atlantic sector.

Small and mesopelagic zooplankton species also play a major role in the southwest Atlantic. Small copepods form approximately 75% of total copepod abundance in the upper ocean layers across all major oceanographic zones. These species show a continuum of temperature ranges, and there is no evidence that the Polar Front is a major biogeographic boundary to their distribution. Indeed, several important species reach maximum numbers in this area. Total copepod abundance is thus higher in the vicinity of the Polar Front than in any other region (Atkinson and Sinclair, 2000).

Larger zooplankton species such as Antarctic krill and salps (mainly *Salpa thompsoni*) are also major grazers in the Southern Ocean and particularly in the productive southwest Atlantic sector where krill biomass forms more than 50% of Southern Ocean krill stocks. Spatially, summer krill density correlates positively with chlorophyll *a* concentrations. Temporally, within the southwest Atlantic, summer krill densities correlate positively with sea-ice extent the previous winter. Summer food and the extent of winter sea ice are thus key factors in the high krill densities observed in the southwest Atlantic Ocean. Salps, by contrast, occupy the extensive lower-productivity regions of the Southern Ocean and tolerate warmer waters than krill (Atkinson et al., 2004).

The secondary regionalisation shows the patchiness in primary production and ice cover around the coastal region as well as the patchiness in primary production in the oceanic areas and around the islands of the Scotia Arc. The pattern of clusters from Antarctic Peninsula area to South Sandwich Island area matches well with the spatial distribution of krill length composition cluster groups observed during CCAMLR-2000 survey (Figure 5 of Sigel et al. 2004). Also, the influence of the Weddell Gyre on the productivity and water properties of the Bransfield Strait (Amos, 2001) is apparent.

Figures 20 and 21 show the primary and secondary regionalisations for the South Atlantic sector. (Note that the colours used in the secondary regionalisation do not relate to those in the primary regionalisation).

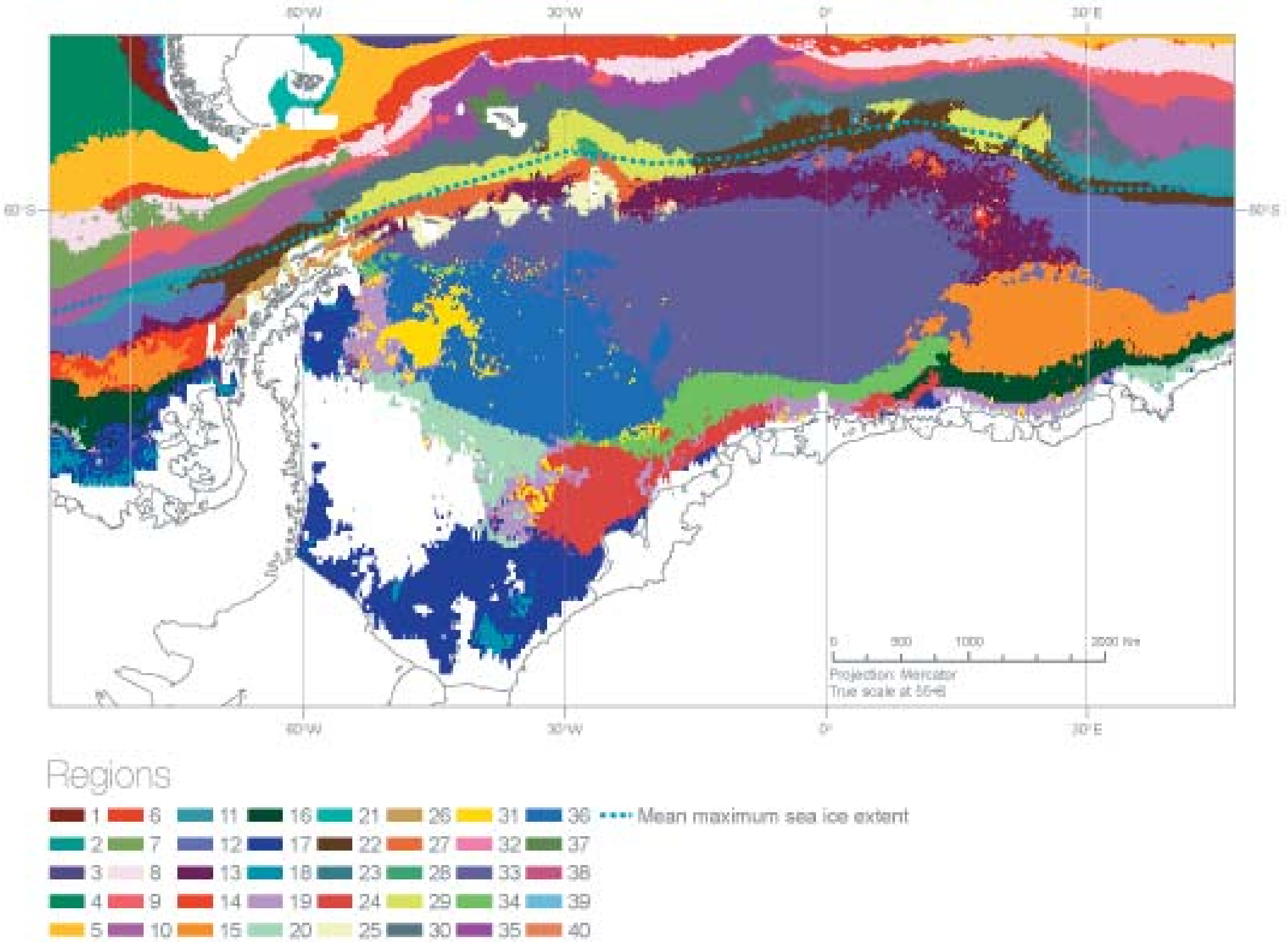

FIGURE 21: Map showing secondary regionalisation for the South Atlantic sector (Area 48)

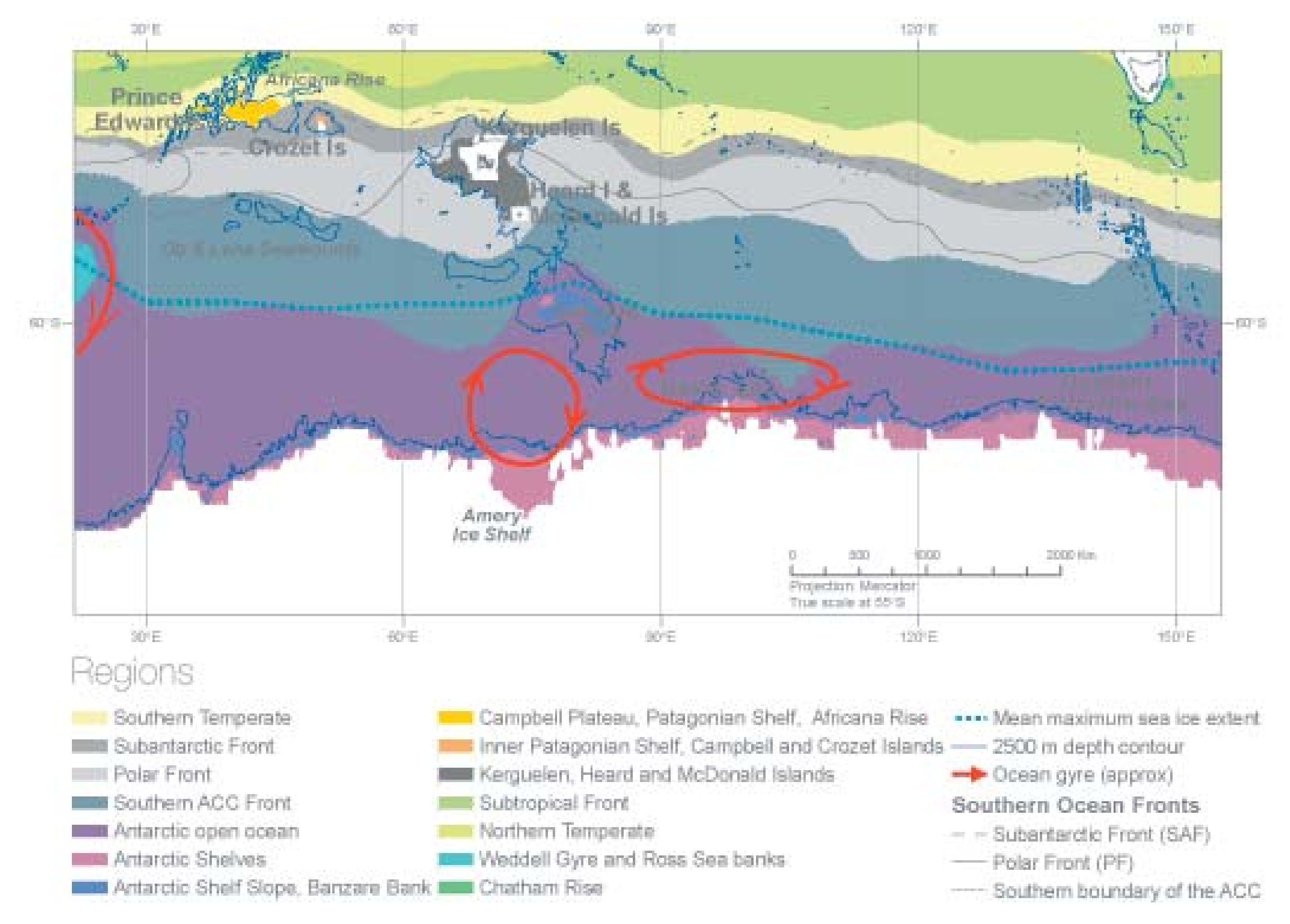

FIGURE 22: Map showing primary regionalisation for the Indian Ocean sector (Area 58), with major physical features

Indian Ocean (Area 58)

The Indian Ocean sector extends in the west from the eastern margins of the Weddell Gyre across the Indian Ocean with a gradual movement of the Polar Front from the north to the south. The flow of the ACC is disrupted by the greater Kergeulen Plateau, including BANZARE Bank, causing formation of many branches of the fronts. A set of subantarctic islands and banks are found in the western part of the sector between 45°S and 55°S. Gyres are present close to the small embayment of Prydz Bay, and also east of BANZARE Bank. These general features are evident in the primary classification.

Ice shelves are present along the coastal margins, including in Prydz Bay. Also, a number of polynyas occur along the coast (Arrigo and van Dijken, 2003; Massom et al., 1998), some of which are substantial contributors to production of sea ice and deep water formation. The annual progression and retreat of sea ice is uninterrupted in this region, extending to 60°S, although the winter sea ice extent is greater in the west than in the east.

Most research has occurred to the west of 60°E, although a recent survey of krill and associated environmental parameters (Jan-March 2006 - 30°E to 80°E) completed synoptic coverage of the coastal region from 30°E to 150°E (Nicol et al., 2000; 2006). These surveys suggest that productivity is higher and, along with Antarctic krill, *Euphausia superba*, extends further to the north in the area to the west of approximately 115°E (south of 60°S) compared to east of this longitude. Salps are found to the north of this krill distribution. This is evident in the secondary classification with a greater diversity of regions in the area of higher productivity between 115°E and Prydz Bay. This is also coincident with the evidence for an eastern gyre hypothesised by Nicol et al. (2000). The pattern of clusters around 30-80°E (south of 60°S) matches well the spatial pattern of krill length composition cluster groups found in recent surveys (Figure 12 of Nicol et al., 2006). These surveys also identified the higher densities of Antarctic krill, *Euphausia superba*, associated with the shelf break. This region also is indicated well in the secondary classification. The neritic community over the continental shelf is dominated by the crystal krill *Euphausia crystallorophias*, which are never found as adults to the north of the shelf break.

A number of studies have characterised the zooplankton assemblages in the Southern Indian Ocean and their association with fronts (e.g. Hosie 1994a; 1994b; Hosie et al., 1997; Chiba et al. 1999; 2001; Hoddell et al., 2000; Hosie et al., 2000; Hunt and Hosie, 2003; 2005; 2006a; 2006b). Continuous Plankton recorder (CPR) monitoring, primarily between 60 and 160°E from spring to autumn, have identified a number of breaks in the distribution of zooplankton taxa with fronts identified by Orsi et al. (1995). The SAF is a major biogeographic boundary for plankton with separate communities north and south of the front (Hunt and Hosie, 2003). Some changes in composition occur at the Polar Front, in particular the northern branch of the PF. A number of distinct zooplankton assemblages can also be defined south of the PF-N. These assemblages are identified more by subtle variation in the abundance or proportion of species rather than changes in species

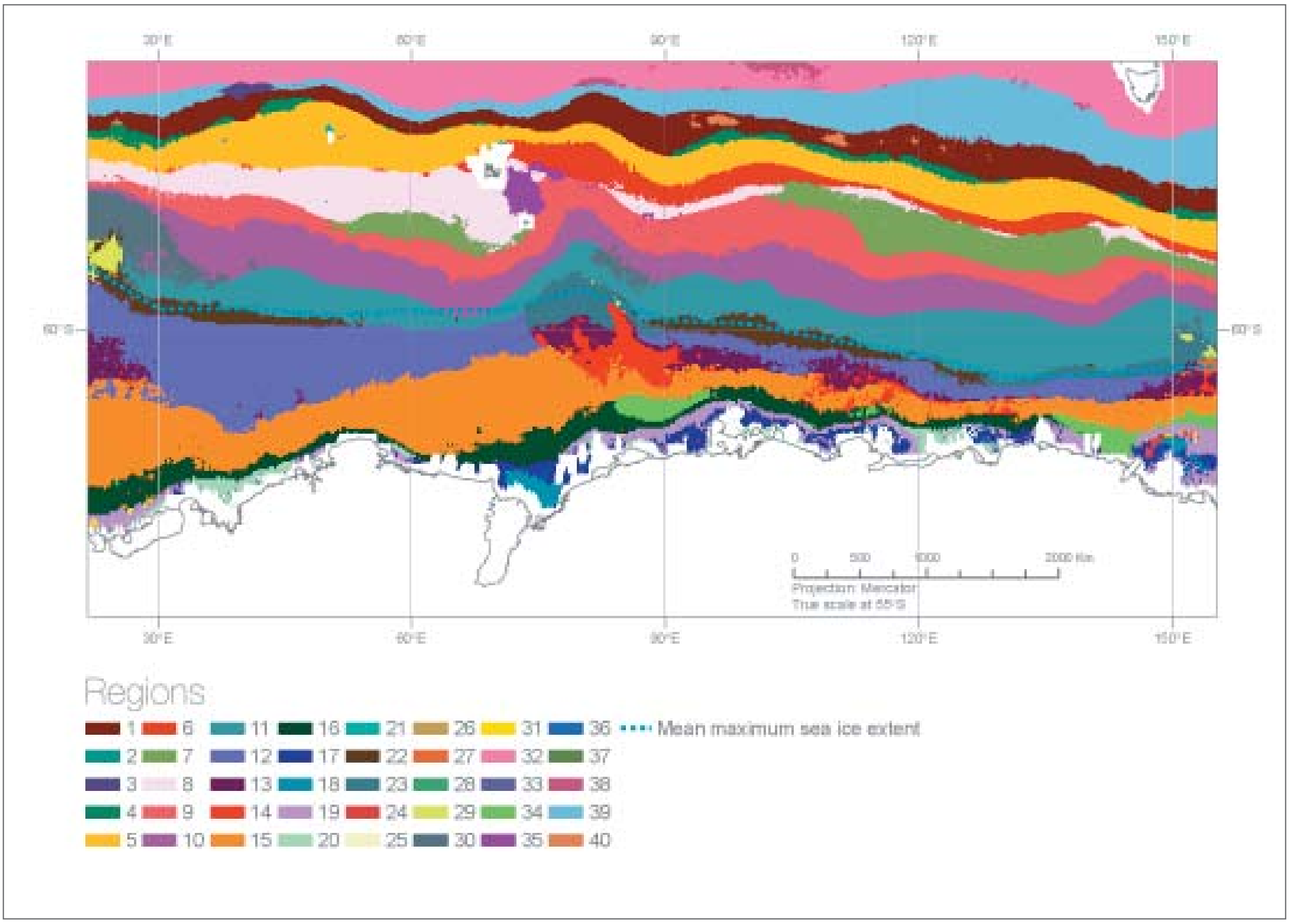

FIGURE 23: Map showing secondary regionalisation for the Indian Ocean sector (Area 58)

composition (Hunt and Hosie, 2005). The Polar Fontal Zone (SAF and PF) is often reported as an area of elevated primary production which then declines south of the PF. This is probably true for phytoplankton, and certainly many vertebrate predators forage in this area. However, the CPR survey has consistently shown that zooplankton abundance increases substantially south across the SAF and remain high though the Southern Ocean to a point between 60 to 62°S where zooplankton abundance declines suddenly (Hosie et al., 2003). The upper 20 m of the water column in the area further south usually remains almost devoid of zooplankton. This decline approximates the position of the SACCF (Orsi et al., 1995) although a link is yet to be established. Overall, the patterns displayed in the secondary classification correspond to the patterns of zooplankton described here.

Figures 22 and 23 show the primary and secondary regionalisations for the Indian Ocean sector. (Note that the colours used in the secondary regionalisation do not relate to those in the primary regionalisation).

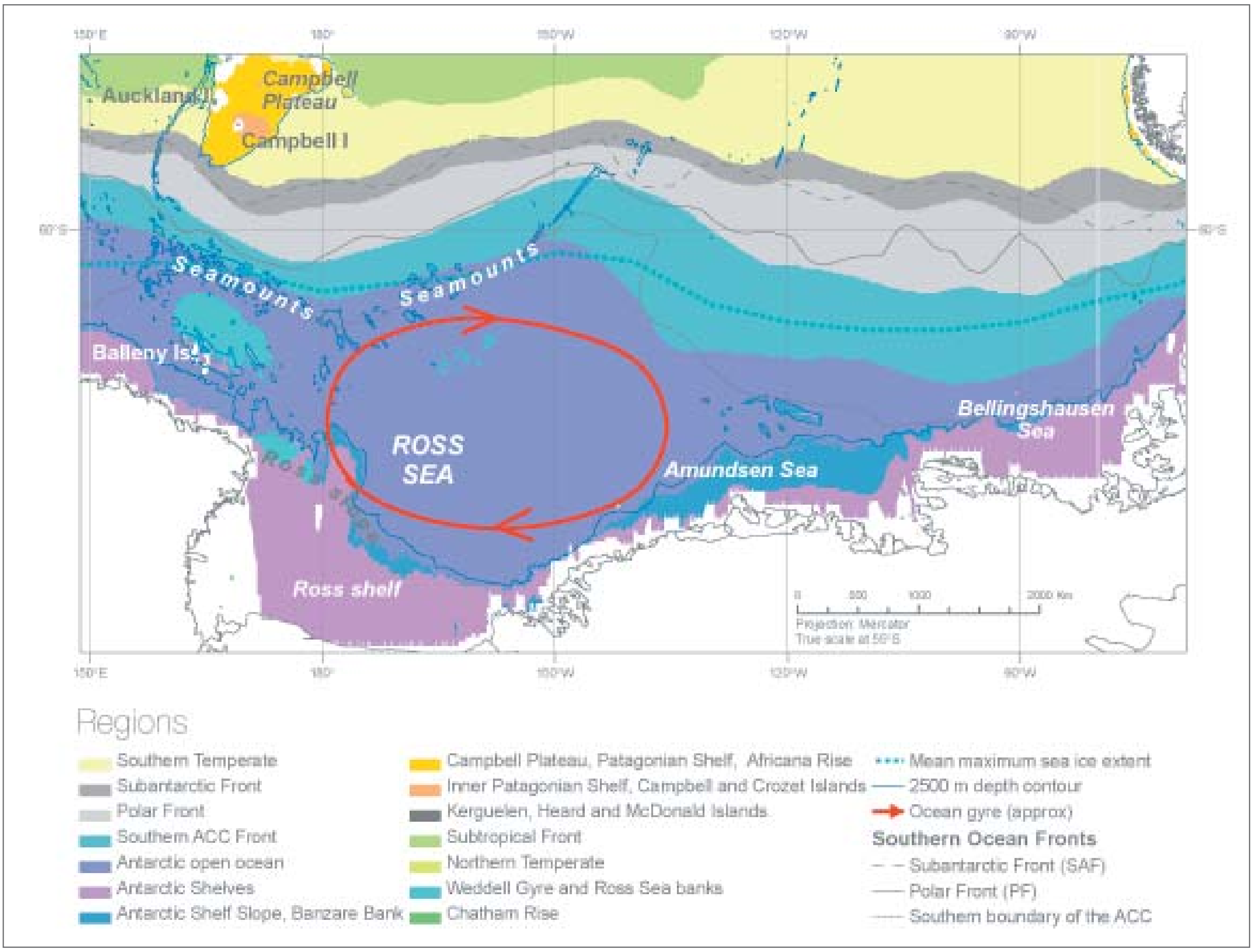

FIGURE 24: Map showing primary regionalisation for the Pacific Ocean sector (Area 88), with major physical features

Pacific Ocean (Area 88)

The Pacific sector is similar in ocean characteristics to the Indian Ocean sector except for the interaction with Ross Sea and its associated gyre. The inner Ross Sea over the continental shelf has characteristics distinct from those of the ACC. The western part of the Ross Sea has a complex shelf and slope area along with the Balleny Islands and ridges of seamounts extending to the north (the Macquarie Ridge extending to the Campbell Plateau) and to the east. A clockwise current flows within the area shallower than the 500 m isobath, and the East Wind Drift current flows in the opposite direction along the continental shelf break. Upwelling of Circumpolar Deep Water also occurs along this shelf break (Ainley, 2002). Seasonal polynyas in the western shelf area play an important role in the distribution of phytoplankton, zooplankton, fish, birds and seals. The concentration of top predators in the Ross Sea coincides with the marginal ice zone that rings the Ross Sea Polynya. This area is dominated by diatoms, while the central, open water portion of the polynya is dominated by Phaeocystis (Ainley et al., 2006). The primary classification identifies the Ross Sea shelf and slope areas. Features such as the Ross Sea polynya are not captured in the primary classification, but these may be reflected in the heterogeneity of the secondary classification.

Further to the east in the Pacific Sector is a narrowing of the ACC towards the Drake Passage. Also, the seasonal sea ice zone narrows in the eastern part of the Bellingshausen Sea. The primary classification captures the major ocean and coastal features, although it does not reflect the ocean ridges in the eastern part of the sector.

The separation of subtropical and subantarctic waters as well as distinguishing the Campbell Plateau from the ocean environment is supported by research on productivity of the region (Boyd et al. 1999; Murphy et al. 2001) and fish assemblages (Bradford-Grieve et al. 2003). Although these general differences are retained in the secondary classification, the wider Campbell Plateau is not differentiated from the southern temperate waters. This may be because of the lack of differentiation in the chlorophyll data used here.

The secondary classification does identify the heterogeneity of the environment associated with the island and ridge system in the eastern part of the sector. It also identifies the expected complexity in the Ross Sea Gyre and its relationship to the coastal system. These results reflect studies documenting the variation in diversity and ecological processes in the region (Bradford-Grieve and Fenwick 2001; Pinkerton et al., 2006; Sharp, 2006). For example, *Euphuasia superba* is found to the north of the shelf break while the neritic fauna is dominated by *Euphausia crystallorphias* and *Pleuragramma antarcticum*.

Figures 24 and 25 show the primary and secondary regionalisations for the Pacific Ocean sector. (Note that the colours used in the secondary regionalisation do not relate to those in the primary regionalisation). ■

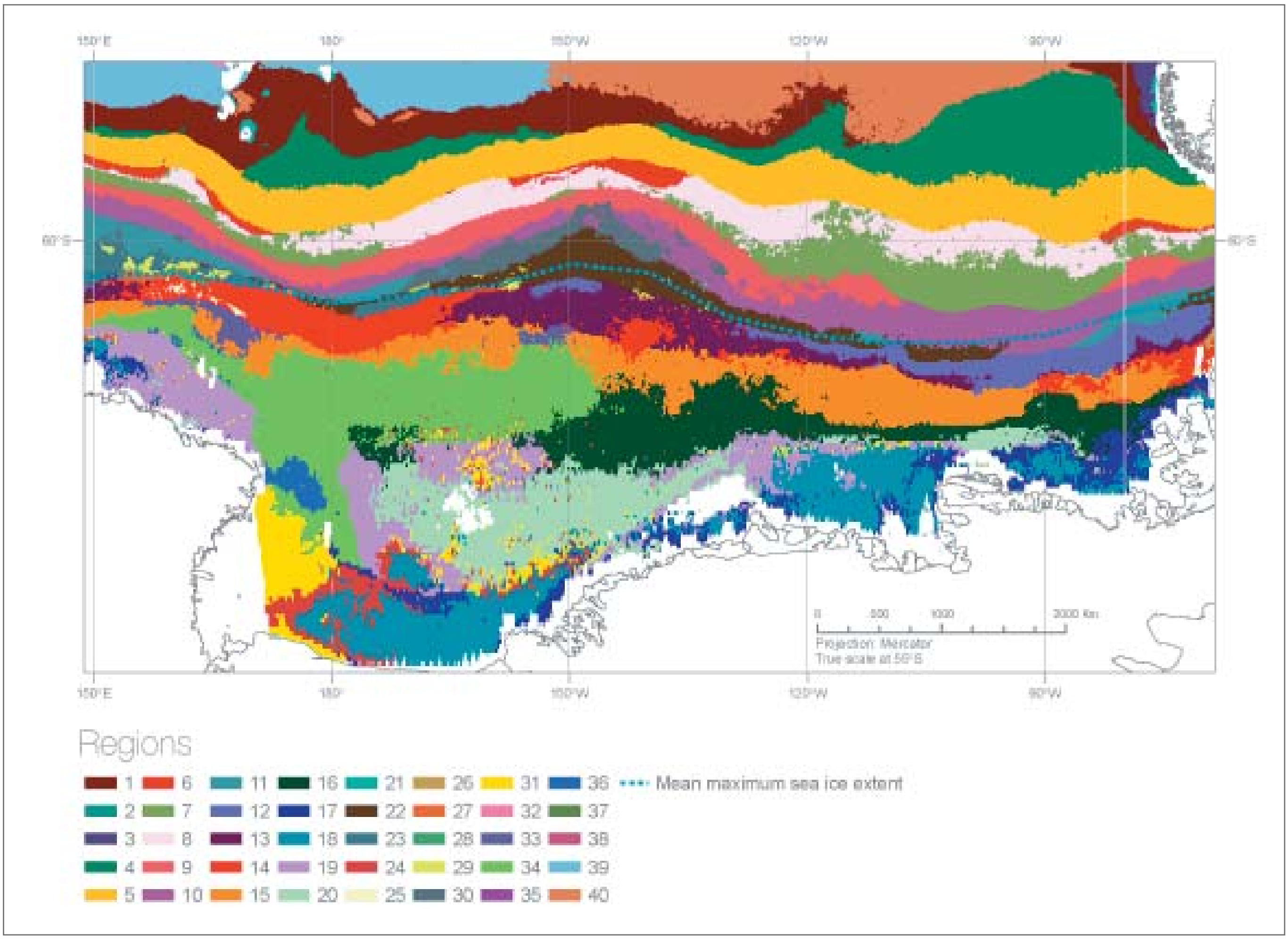

FIGURE 25: Map showing secondary regionalisation for the Pacific Ocean sector (Area 58)

The primary regionalisation of the Southern Ocean highlights the different environmental characteristics of large regions including the continental shelf and slope, frontal features (Subantarctic Front, Polar Front, Southern Antarctic Circumpolar Current Front), the deep ocean, banks and basins, island groups and gyre systems. The addition of secondary datasets suggests smaller-scale spatial heterogeneity within the regions, particularly in the continental shelf and slope areas, and the seasonal ice zone.

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4. Future work

The workshop identified a range of areas in which future work might be directed in order to produce a final bioregionalisation for the Southern Ocean. Priorities included the incorporation of additional (particularly biological) datasets, and finer-scale analysis of particular areas of interest. It also identified that the statistical methods might be refined further. However, the workshop was satisfied that the proof of concept developed is sufficient to undertake the tasks identified by CCAMLR and the CEP.

Further data could be used to update or refine the draft broad-scale primary regionalisation (for example using additional datasets such as insolation (PAR) and sea surface height). Datasets used in this analysis might also be refined, for example using derived datasets such as a 'silicate depletion' data layer (reflective of primary production) derived by subtracting silicate at the surface from silicate at 200 m depth.The remotely-sensed PAR data are confounded by the inability to distinguish ice cover from cloud cover, however they might be transformed to represent biologically relevant variation in available light, by combining PAR data and ice data.

The addition of sea ice and chlorophyll *a* datasets in the exploratory secondary classifications illustrated the high level of heterogeneity arising from these parameters. Refinement of the analysis and data used at the secondary classification level is needed to identify the appropriate level of regional separation at a smaller scale using these secondary datasets, and to identify whether other datasets could be used to assist this process. In particular, sea ice is a major driver of ecosystem processes in the Southern Ocean (see Section 1.3), and the inclusion of variables representing sea ice dynamics will be important in finer-scale regionalisation analyses.

The draft regionalisation presented in this report is pelagic, however it may also be necessary to undertake a benthic regionalisation. Further consideration should be given to the relationships between the benthic and pelagic systems, and the utility of separating the two systems in the context of bioregionalisation analysis.

A range of potential biological datasets (for use in future analyses) were identified during the workshop (see Appendix V), but it will be necessary to identify which of these would be of most value. Data 'compendia' may be of assistance in providing information on inter-annual and seasonal variability, which can then be further analysed according to the defined objectives. Indicator species might also be investigated for their potential utility in providing further input to the analysis. In the longer term, the compilation of comprehensive biological data sets may allow the use of more sophisticated analytical approaches such as Generalised Dissimilarity Modelling (GDM – Ferrier et al. in press). This performs an integrated statistical analysis of biological and environmental data, using information on species turnover rates to identify the optimal weighting and transformation of environmental variables to be used in defining the classification.

It may be important to consider stochastic, temporal or spatial variability in defining bioregions in order to ensure that the outcome is robust to uncertainties and variability. Further work towards understanding (and, where possible, reducing) different types of uncertainty in the data, models or methods will help the classification process.

A bioregionalisation will inevitably be based on the best scientific evidence available at the time. Further refinement could be achieved by adding biological and environmental data as it becomes available, thereby reducing uncertainties. One source of refinement will be to add more biological data to test the relationship between physical and environmental surrogates and the ecological processes they are thought to represent. This is likely to be needed at finer-scale resolution of the bioregionalisation.

The most important avenue for further work will be to undertake a finer-scale regionalisation than that presented here. This might initially be focused in areas where more data is available, such as in the southwest Atlantic. The addition of datasets on chlorophyll *a* and sea ice extent illustrated the complexity of the coastal, shelf and seasonal ice areas, in relation to these parameters. These regions are likely to have additional complexity corresponding to other ecological processes and species distributions, and should be a priority for further research. ■

5. Conclusions

This workshop established a 'proof of concept' for bioregionalisation of the Southern Ocean. Further work within the frameworks of CCAMLR and the CEP will be an important contribution to the achievement of a range of scientific, management and conservation objectives, including large-scale ecological modelling, ecosystem-based management of human activities in the marine environment, and the development of ecologically representative protected area systems. Continuing work on this topic also has the potential to inform and contribute to the further development of bioregionalisation analysis as a tool for conservation and management in the global context.

List of Appendices (provided on CD)

APPENDIX I: Approaches to bioregionalisation – examples presented during the workshop

- Antarctic Environmental Domains Analysis (Harry Keys and Fraser Morgan, Department of Conservation, New Zealand)
- CCAMLR Small-Scale Management Units for the fishery on Antarctic krill in the Southwest Atlantic (Roger Hewitt, NOAA, USA)
- Australian National Bioregionalisation: Pelagic Regionalisation (Vincent Lyne and Donna Hayes, Department of the Environment and Heritage and CSIRO)
- Selecting Marine Protected Areas in New Zealand's EEZ (John Leathwick, NIWA, New Zealand)

APPENDIX II: Technical information on approach to bioregionalisation

APPENDIX III: Descriptions of datasets used in the analysis

APPENDIX IV: Results of secondary regionalisation using ice and chlorophyll data

APPENDIX V: Biological datasets of potential use in further bioregionalisation work

APPENDIX VI: Details of datasets, Matlab code and ArcGIS shapefiles included on the CD

List of workshop participants

PARTICIPANT	EXPERTISE	AFFILIATION
Dr. Ian Ball	Mathematical modelling, MPA selection	ACE CRC, AGAD, Australia
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Dr. Andrew Constable	Chair, ecosystem ecology and modelling, marine protected areas, CCAMLR	ACE CRC, AGAD, Australia
Dr. Susan Doust	Support, CCAMLR	AGAD, Australia
Dr. Susie Grant	Support, marine protected areas, CCAMLR, CEP	UK
Dr. Roger Hewitt	Krill biology, ecosystem ecology	SW Fisheries Centre, NOAA, USA
Dr. Graham Hosie	Zooplankton ecology; CPR program	AGAD, Australia SCAR representative
Dr. So Kawaguchi	Krill biology, ecosystem ecology	ACE CRC, AGAD, Australia
Dr. Harry Keys	Bioregionalisation, Antarctic regional classification	DOC, NZ
Dr. John Leathwick	Statistical modelling, bioregionalisation, MPA selection	NIWA, Hamilton, NZ
Dr. Gilly Llewellyn	Support, classification, regionalisation, marine protected areas	WWF-Australia
Dr. Vincent Lynne	Statistician, bioregionalisation	CSIRO MAR, Hobart, Australia
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Mr. Ewan McIvor	Environmental policy	AGAD, Australia
Dr. Denzil Miller	Observer	CCAMLR Secretariat
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Dr. Steve Nicol	Krill biology, ecosystem ecology	ACE CRC, AGAD, Australia
Dr. Matt Pinkerton	Ecosystem modelling, remote sensing	NIWA, NZ
Dr. Ben Raymond	Modelling, data visualisation	ACE CRC, AGAD, Australia
Dr. Steve Rintoul	Physical oceanography, remote sensing	ACE CRC, Australia
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Dr. Sergei Sokolov	Physical oceanography, remote sensing	ACE CRC, Australia
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Dr. Pete Strutton	Primary production, remote sensing	Oregon State University, USA
Dr. Phil Trathan	Ecosystem and predator ecology, CCAMLR	BAS, UK

Glossary of terms

Bioregionalisation (or Regionalisation)

A process that aims to partition a broad spatial area into distinct spatial regions, using a range of environmental and biological information. The process results in a set of bioregions, each with relatively homogeneous and predictable ecosystem properties. The properties of a given bioregion should differ from those of adjacent regions in terms of species composition as well as the attributes of its physical and ecological habitats. The term regionalisation may be used interchangeably (or sometimes to refer to an analysis undertaken using only physical data).

Bioregion (or Region)

A spatial compartment defined on the basis of its biological and/or physical properties. Each bioregion (or region) reflects a unifying set of major environmental influences which shape the occurrence of biota and their interaction with the physical environment. The term region may be used interchangeably (or sometimes to refer to spatial compartments which have been defined using only physical data).

Classification

The process of partitioning a broad spatial area into distinct regions. Also used to refer to the specific step within that process during which the actual allocation of sites to regions occurs, usually through a statistical process such as cluster analysis

Ecological process

In the context of this report, an ecological process is any process that affects the dynamics of a species

Hierarchy (spatial and statistical)

In the context of bioregionalisation, this term may be used to refer to spatial or ecological hierarchy, or statistical hierarchy.

Spatial or ecological hierarchy refers to the different levels of scale or ecological processes within a large area. A hierarchy may be nested, whereby smaller scale units or processes are nested within large scale units.

Statistical hierarchy has relevance in dissimilarity-based clustering methods, where an iterative approach is undertaken to group sites together into regions. All sites are initially allocated to their own regions. At each iteration of the process (or each step down the hierarchy), the two most similar regions are merged together, until at the end of the process there is only one region, which contains all of the sites. This is often displayed in dendograms.

Parameter

Information extracted from data. For example, sea ice concentration is a variable from which the parameters of ‘proportion of year when the ocean is covered by at least 15% ice’ or ‘areas with greater than 50% ice coverage’ can be extracted.

Property

This term is used here to describe the defining characteristics or attributes of a particular ecological process, or of a given region.

Proxy

A parameter that can be used to provide similar information or patterns to another parameter or variable, usually used when desired data (e.g. the distribution of species) are unavailable, or where one parameter can be used in the place of several others in order to simplify the analysis.

Site

In the context of bioregionalisation analysis, a site is the smallest unit of analysis. The study area is divided into a grid of sites, at sufficiently fine scale to enable appropriate resolution of the final areas. Each site will have a particular set of parameters, according to the input data.

Synoptic

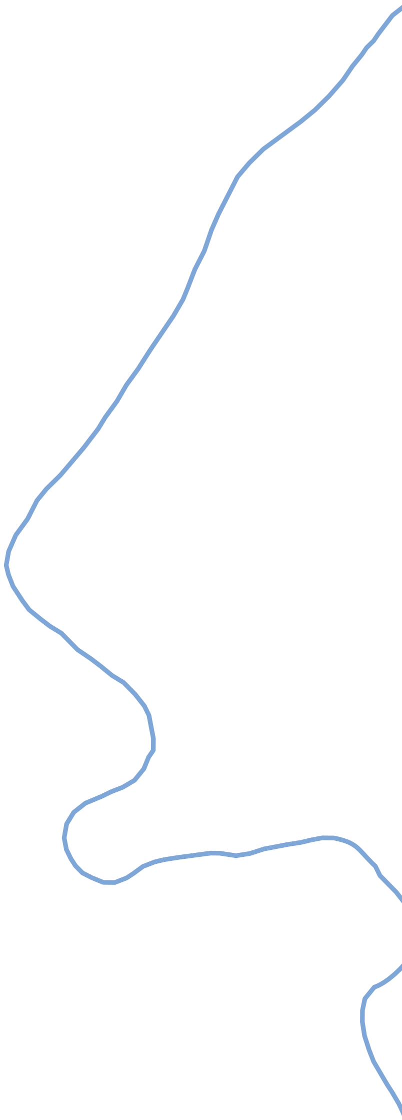
This term is used to describe data that have broad and continuous spatial coverage (e.g. across the entire Southern Ocean). Here, synoptic data may also refer to summaries of the observed conditions over time (e.g. mean monthly values averaged to obtain an annual mean). Synoptic data may be obtained through satellite remote-sensing, or through model climatologies generated from observed values.

Uncertainty

In the context of bioregionalisation analysis, uncertainty refers to the effects of imprecision in data (e.g. measurement error), uncertainty within models used to derive variables (e.g. climatology models), and epistemic uncertainty (potential errors in the chosen method). Each of these types of uncertainty can affect the resulting region boundaries.

Variable

Variables are physical or environmental data from which specific parameters can be extracted. For example, sea ice concentration is a variable from which the parameters of ‘proportion of year when the ocean is covered by at least 15% ice’ or ‘areas with greater than 50% ice coverage’ can be extracted.



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