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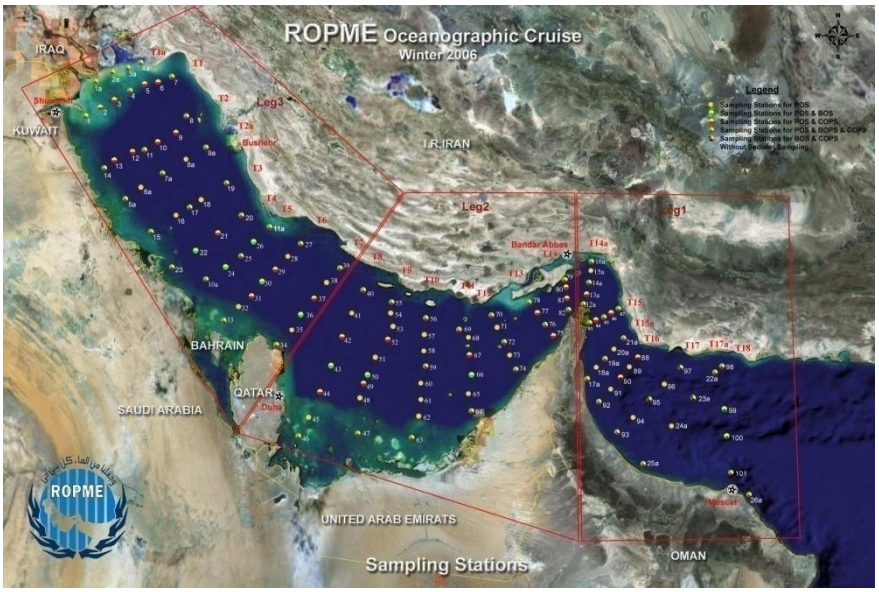
Regional Organization for the Protection of the Marine Environment

ROPME Oceanographic Cruise - Winter 2006



Technical Report Series

Technical Report : No. 4

Spatial Distribution of Chlorophyll-a in the ROPME Sea Area

January 2012

ROPME Oceanographic Cruise - Winter 2006

Technical Report Series:

1. Physical oceanography
2. Contaminants in Marine Sediments
3. Nutrients
4. Chlorophyll-*a*
5. Phytoplankton
6. Zooplankton
7. Ichthyoplankton
8. Meiobenthos
9. Macrobenthos

Disclaimer

This Report has been prepared by Kuwait Institute for Scientific Research, as the Principal Investigator on 'Chlorophyll' under a contract with ROPME. The Report is being separately subjected to peer review and linking with other relevant data and information, in order to develop an integrated understanding of the ROPME Sea Area. Meanwhile, in order to bestow the benefit of viewing the results in their preliminary form and promote a general level of understanding of the marine environment of the Region, notwithstanding the possible delay by peer review, this document is being brought out as part of a special Technical Report Series in the very form in which it was submitted by the Principal Investigator. Owing to this reason, ROPME shall not accept responsibility on the accuracy of data or interpretations contained in this Report. ROPME does not also subscribe to the inappropriate terms used to denote parts or full of the ROPME Sea Area inadvertently used by the Principal Investigator or provided in the published references and citations.

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Preface

In recognition of the importance of the oceanographic Cruises in the ROPME Sea Area to understand the state of the marine environment, ROPME Council has assigned high priority to the ROPME scientific Cruises. In pursuance of the Council Decision CM12/7, ROPME was mandated to coordinate a comprehensive oceanographic Cruise in Winter 2006. The Cruise was planned in such a way that the results and reports of the studies can find their way into the synthesis of ROPME State of the Marine Environment Report.

As a result of sustained efforts, cooperation of Member States, guidance of the designated scientific committee for the Cruise, encouragements from the Executive Committee of ROPME and the generous provisions made by the Council, the historic Winter Cruise was carried out successfully on board of M/V Ghods of I. R. Iran during 1st February and 11th March 2006.

Totally, 115 stations covering the RSA have been surveyed and 97 experts from ROPME Member States participated in the Cruise. The survey covered most of the main oceanographic disciplines.

The samples collected during the Cruise were distributed on a competitive basis to the competent laboratories in the Region and elsewhere for detailed analyses while sub-sample sets were kept in ROPME Marine Sample Bank to enable repetitive analyses in future, when required.

To enhance benefits from the reproduced results of the Cruise among Regional scientific community towards a better understanding of the marine environment in the RSA and to enable furtherance of marine researches, ROPME Secretariat decided on the publication of the results in a series of Technical Reports as follows:

1. Physical oceanography
2. Contaminants in Marine Sediments
3. Nutrients
4. Chlorophyll-*a*
5. Phytoplankton
6. Zooplankton
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8. Meiobenthos
9. Macrobenthos

The present Technical Report is devoted to the spatial distribution of chlorophyll-*a* in the RSA. The analyses of chlorophyll samples and reporting have been conducted by a team of scientists led by Dr. Faiza Y. Al-Yamani at Kuwait Institute for Scientific Research (KISR) under a contract with ROPME.

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1. Introduction

The Regional Organization for the Protection of the Marine Environment (ROPME) plays a major role in the protection of the Marine Environment and prevention of its degradation, and provides technical co-ordination and assistance for its eight Member States (Bahrain, I.R. Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates) in the implementation of the Kuwait Regional Convention (Kuwait Action Plan/KAP) and its Protocols. ROPME has been initiating and supporting a number of projects, covering environmental assessment and environmental management, as well as supporting public awareness and training programs.

The term "ROPME Sea Area" (RSA) was coined by Plenipotentiaries of the Member States to achieve unanimity in denoting the area covered by the Kuwait Regional Convention of 1978. According to Article II of the Kuwait Regional Convention, the ROPME Sea Area (RSA) is defined as extending between the following geographic latitudes and longitudes, respectively: 16°39'N, 53°3'30"E; 16°00'N, 53°25'E; 17°00'N, 56°30'E; 20°30'N, 60°00'E; 25°04'N, 61°25'E. RSA covers Inner RSA, Sea of Oman, and a part of the Arabian Sea (Fig. 1).

The Inner RSA (refers to the waters west of the Straits of Hormuz), is a shallow semi-enclosed body of water located in a climatically arid region. It has an average depth of 35 m with a maximum depth of 107 m at the Strait of Hormuz. Seasonally, it is supplied with freshwater from Shatt Al-Arab and its associated systems in the north. Its mean salinity is about 41 psu. The Sea of Oman and the Arabian Sea are much deeper (2000 m) than the Inner RSA with mean salinity of 37 psu.

Plankton studies were conducted by several investigators in the RSA. Though those studies were limited in space and time, they provide valuable background information on the productivity and biodiversity of phytoplankton, zooplankton and ichthyoplankton populations in the RSA. Phytoplankton studies are important because they represent the first step of the food web in the marine ecosystem. Chlorophyll-*a* is an indicator of the amount of plant growth in water and a proxy of the phytoplankton biomass. Information on chlorophyll-*a* provides insights into the dynamics of the ecosystem, on the food availability for upper trophic levels, and on the overall environmental quality and dynamics of the marine ecosystem.

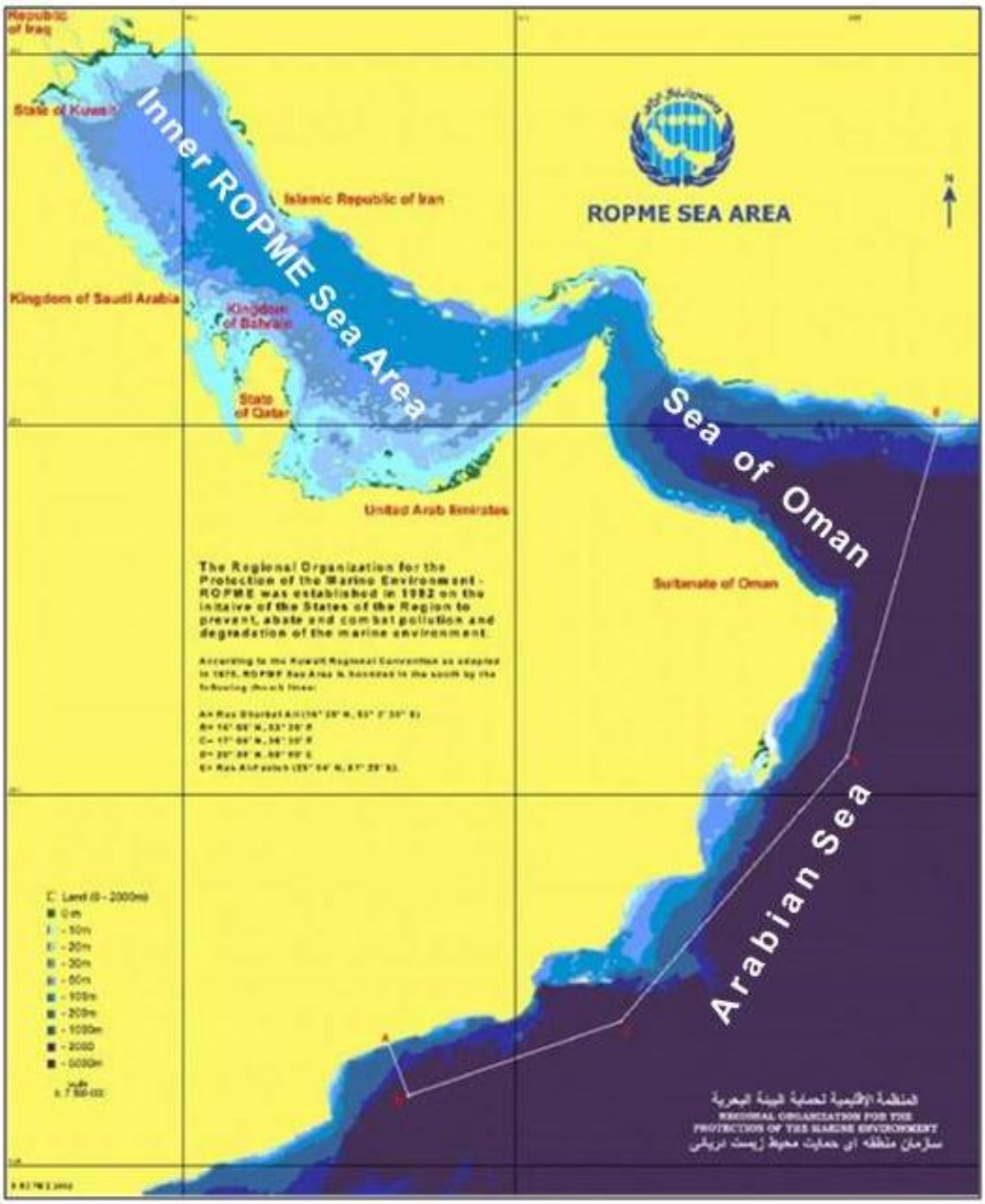

Fig. 1. ROPME Sea Area (RSA).

Satellite imagery of chlorophyll-*a* (Fig. 2) shows that mean chlorophyll concentrations were high in certain parts of the Inner RSA and in the Sea of Oman waters. It is evident from Figure 2 that the RSA includes areas of medium chlorophyll concentration, with concentrations of ~1 mg/m^3 in surface waters, while other areas have high and very high concentrations of ≥10 mg/m^3.

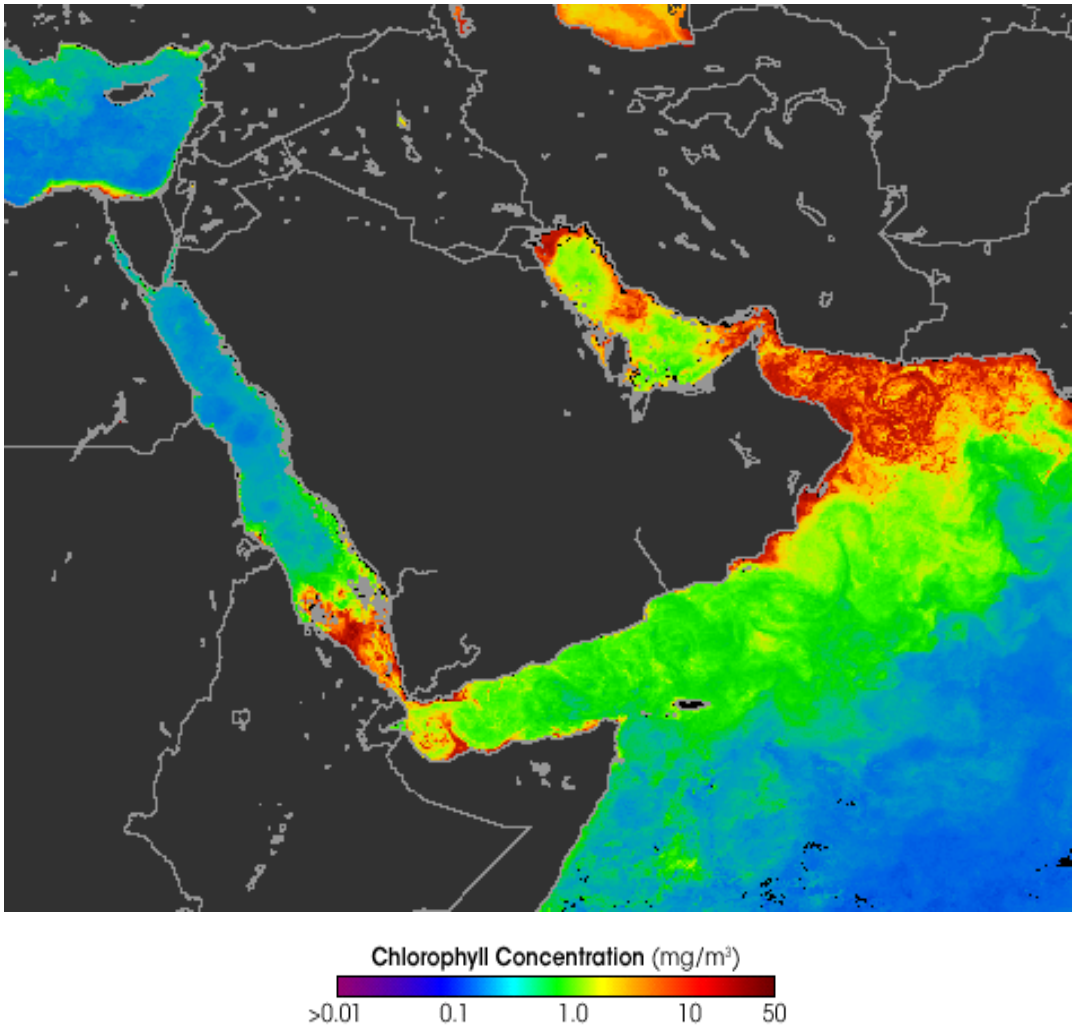

Fig. 2. Mean surface chlorophyll concentration (mg/m^3 = μg/l) in the ROPME Sea Area and adjacent waters during March 2006. Data are derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) using the standard OC3 chlorophyll algorithm (O'Reilly *et al.*, 2000). Blue color denotes very low chlorophyll concentration (<0.8 mg/m^3), green and yellow is medium (from 1 to 3 mg/m^3), and red is high concentration (>8 mg/m^3 and more). (Source: http://earthobservatory.nasa.gov/Observatory/Datasets/chlor.seawifs.html).

This significant spatial variability in chlorophyll probably results from differences in the physical and chemical properties of the upper water column that influence the distribution and growth of phytoplankton, which needs to be studied in details using ship surveys. The ROPME Sea Cruise of Winter 2006 provided an opportunity to look at the spatial variability in chlorophyll distribution during the winter season.

Previous published field results of chlorophyll's spatial variability in the RSA are based on data collected episodically or at coarse spatial resolution by specific programs providing general overviews (e.g., Grashoff, 1976; Al-Yamani, 1989) or at higher spatial resolution targeting specific regions, time periods and/or processes (e.g., Subba Rao and Al-Yamani, 1999; Al-Yamani *et al*., 2006). Results of several surveys in the RSA either provide non-synoptic, coarse resolution realizations of overall phytoplankton patterns or detailed but time and site specific views of localized features and processes. Direct comparisons, relationships and possible interactions between sub-regions within the RSA, as well as the relative timing and nature of response to seasonal and inter-annual forcing remain poorly quantified. Studies in the RSA cannot be compared with studies conducted in the Arabian Sea, which is well-studied and surveyed by many international and national cruises. Systematic analyses of synoptic spatial/temporal variability of phytoplankton in the Inner RSA have awaited the availability of a consistent satellite time series together with detailed analyses of the results, obtained during ROPME research cruises.

The aim of this study was to describe the spatial distribution of phytoplankton biomass in the RSA during Winter 2006. Our hypotheses include the following:

1. There is spatial distribution in the physico-chemical values and the chlorophyll concentrations in the RSA
2. The chlorophyll concentration results obtained from the analysis of the Winter 2006 samples are comparable to previous published results for chlorophyll.
3. There is a difference between the spatial chlorophyll distributions in Winter 2006 compared to Summer 2001.

This report focuses on spatial distributional aspects related to the concentration of phytoplankton chlorophyll-*a* pigment (phytoplankton biomass), and phaeophytin in the Inner RSA and Sea of Oman water column during winter season of 2006. In addition, related parameters such as concentrations of nutrients, turbidity and dissolved oxygen concentrations, as well as physical parameters (salinity, temperature and water density) were measured. These results are discussed in this report together with some satellite-derived data. Brief comparison of the winter distribution of chlorophyll-*a* with that of Summer 2001 is included.

2. Materials and Methods

ROPME's Winter Cruise of 2006 covered the Inner RSA and Sea of Oman (Fig. 3). The cruise was divided into three legs and 23 transects. Water samples were collected from 03 February to 09 March 2006. At each station, three depths were sampled, and two replicates per depth (at most stations) were filtered. For one station, only 500 ml of water was filtered, while at all other stations 1 liter of sea water was used for filtration.

The Winter 2006 Cruise was conducted by the Al-Quds vessel. Water samples were collected by Niskin bottle for nutrients and chlorophyll measurements from 104 stations, from surface, middle and bottom layers (Fig. 3). In addition, *in situ* measurements were obtained from a submersible CTD profiler Ocean Seven 316 (IDRONAUT, Italy) with fluorometer, turbidity meter, pH and oxygen sensors.

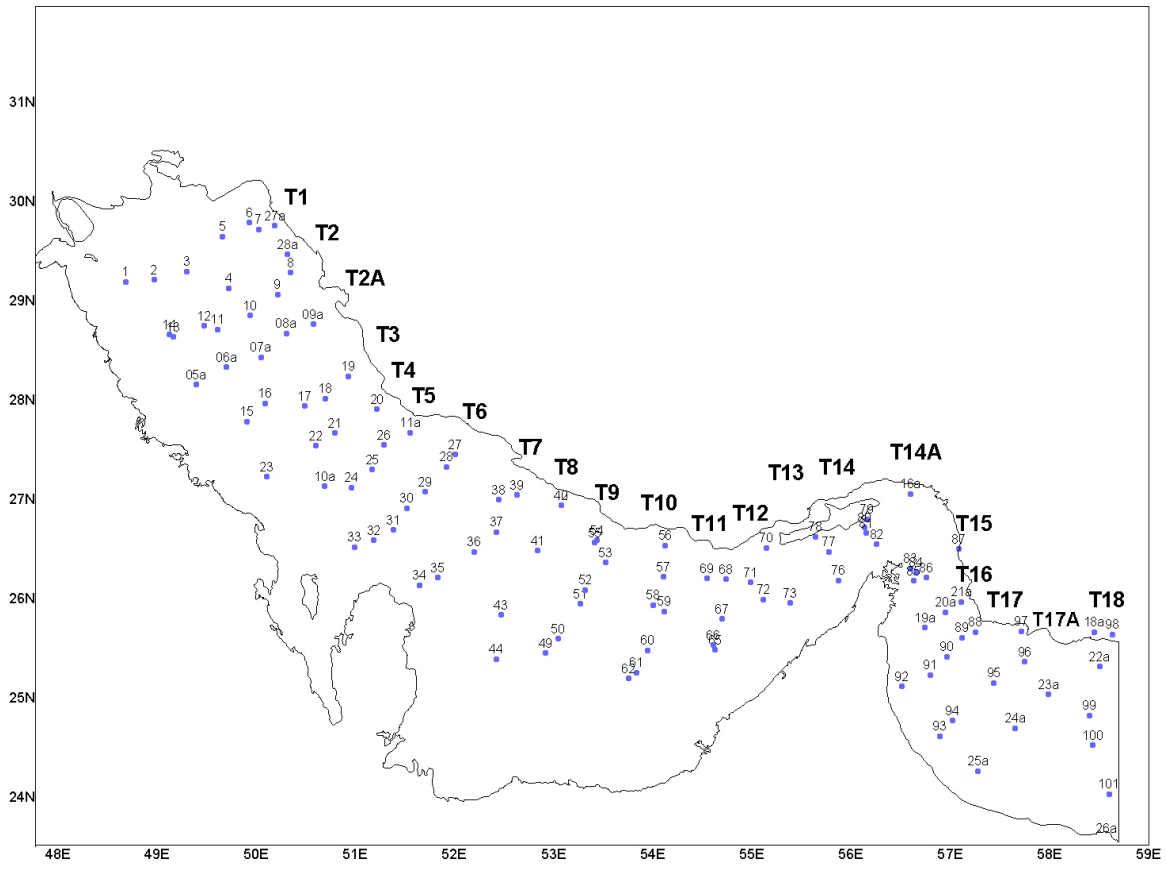

Fig. 3. Sampling station locations occupied during Winter 2006 cruise.

Satellite data, obtained from *Terra* (EOS AM-1) and *Aqua* (EOS PM-1), equipped by MODIS sensors (Moderate-resolution Imaging Spectroradiometer) and *OrbView-2* (equipped by SeaWiFS - Sea-viewing Wide Field-of-view Sensor) spacecrafts were processed at the Mariculture, Fisheries and the Marine Environment Department, KISR, and the analyzed images are included in this report.

Chlorophyll-*a* (chl-*a*) measurement provides a valuable estimate of algal biomass. The fluorometric method has been used for the quantitative analysis of chlorophyll-*a* and phaeopigments for the ROPME samples. Fluorometry is much more sensitive for chlorophyll measurement than the spectrophotometric method.

The procedures we applied to measure chlorophyll-*a* and phaeophytin (phaeopigments) in this study are described here. They are based on the US EPA standard method 445.0 for aquatic fluorescence measurements (Arar and Collins, 1997). The concentrations of chlorophyll-*a* and phaeopigments in seawater in the current report are given as µg/l (equal to mg/m^3), according to Joint Global Ocean Flux Study (JGOFS) technical recommendations (UNESCO, 1994).

In total, 574 filters, individually packed in foil, were received from ROPME in dry ice (-40^oC) and were immediately transferred to ultra-low temperature freezer (with minimum temperature of -80^oC). The samples were stored in the above freezer until analysis (6 filters per day were processed). The temperature in the freezer was monitored daily. It varied from -76^oC to -68^oC, and average temperature in the freezer was -73^oC. One replicated filter (sample # Chla-079MR2, station 79, transect T14) was lost during processing accidentally (Appendix A, Table 1A).

These filters were obtained during ROPME 2006 Winter cruise for 104 sampling stations. For two of the stations (# 4 and # 43) QA/QC filters were provided (surface, middle and bottom layers).

There were three sampling layers (surface, middle and bottom) for each sampling station. However, from station #1 we received filters only from two layers (surface and bottom). Generally for each station, there were two replicates from each sampling depth (for

84 stations), excluding 20 stations, where only one replication for each sampling depth was received.

2.1 Sample Analysis Procedure

Algal pigments, particularly chlorophyll, fluoresce in the red (685 nm maximum) wavelengths after extraction in acetone when they are excited by blue (440 nm maximum) wavelengths of light. The fluorometer excites the extracted sample with a broadband blue light and the resulting fluorescence in the red is detected by a photomultiplier. The significant fluorescence by phaeopigments is corrected for by acidifying the sample, which converts all of the chlorophyll-*a* to phaeopigments. By applying a measured conversion for the relative strength of chlorophyll and phaeopigments fluorescence, the two values can be used to calculate both the chlorophyll-*a* and phaeopigments concentrations (source: http://ocean.stanford.edu/cal/JGOFS_chla.pdf).

2.2 Used Equipment and Chemicals

- Ultra-low temperature freezer (-80^{o}C) for storage of filters.
- Regular freezer (-20^{o}C) for pigments extraction.
- Glass centrifuge tubes for extraction, 15 ml volume
- Turner Designs TD-700 Laboratory Fluorometer, fitted with a red sensitive photomultiplier, a blue lamp, 5-60 blue filter and 2-64 red filter (*10-040R Chlorophyll-a Optical Kit for Extractive Analysis*)
- 100% acetone (HPLC grade)
- 1.2M HCl (100 ml HCl in 900 ml de-ionized water)
- Ultra-pure water (Milli-Q grade)

2.3 Procedure

All the samples were processed in subdued light and stored at -20º C in common freezer between all handling steps.

After the filter (sample) removal from ultra-low temperature freezer (-80^{o}C), the pigments were extracted by placing the filter in glass test-tube (13 x 100 mm borosilicate culture tube) with 5.0 ml of 90% acetone. The sample was covered with Parafilm to reduce evaporation and was allowed to extract for 4 hours in the freezer at -20°C. Following extraction, the sample was intensively shaken time to time.

The fluorometer was allowed to warm up and stabilize for at least 30 min prior to use, then this instrument was zeroed with 90% acetone in a clean test tube. Next, 1 ml of pigment extract was carefully mixed with 4.0 ml of 90% acetone in a new test-tube and the readings were obtained by the fluorometer according to the Operational Manual of the TD-700 equipment.

To determine phaeophytin concentration the sample was acidified, (by addition of acid to the sample). This procedure was used with addition of hydrochloric acid (2 drops of 1.2 M HCl per one tube) to the sample in which chlorophyll concentration was already measured (same test-tube) for two minutes. After acidification, the fluorescence of the sample was measured again to determine phaeophytin concentrations.

The ratio of the fluorescence before acidification (Fo) to that after (Fa), is the acid ratio, (US EPA Method 445.0).

2.4 Calibration and Standardization

The TD-700 fluorometer was calibrated before sample processing with commercially available chlorophyll-*a* standard (from *Anacystis nidulans*, Sigma-Aldrich Co., USA).

Linear calibration factor (Kx) was calculated as the slope of the non-acidified fluorometric reading vs. chlorophyll-*a* concentration based on spectrophotometric measurements (Beckman DU-600 spectrophotometer, see Appendix 2) according to the trichromatic spectrophotometric procedure (Strickland and Parsons, 1968).

The acidification coefficient (Fm) was calculated by averaging the ratio of the non-acidified and acidified readings (Fo/Fa) of pure chlorophyll-*a* standard.

Result of the calibration is shown in Figure 4. The obtained linear regression relationship between fluorescence readings (X-axis) and known concentrations of chlorophyll-*a* (Y-axis) is as follows:

$$Y = 0.0242 + 0.0129\,X$$

The obtained r^2 value (coefficient of determination) is 0.9975, which signifies 99.75% of the total variance in TD-700 fluorescence explained by the linear dependence between real chlorophyll-*a* concentrations and the raw fluorescence readings. That leaves the rest of the variance (0.0025% of the total) as variability of the data from possible impurities on glassware and in chemicals (chlorophyll-*a* standard, acetone and water purity), fluorometer electronic and lamp stability, and accuracy of all volumetric procedures.

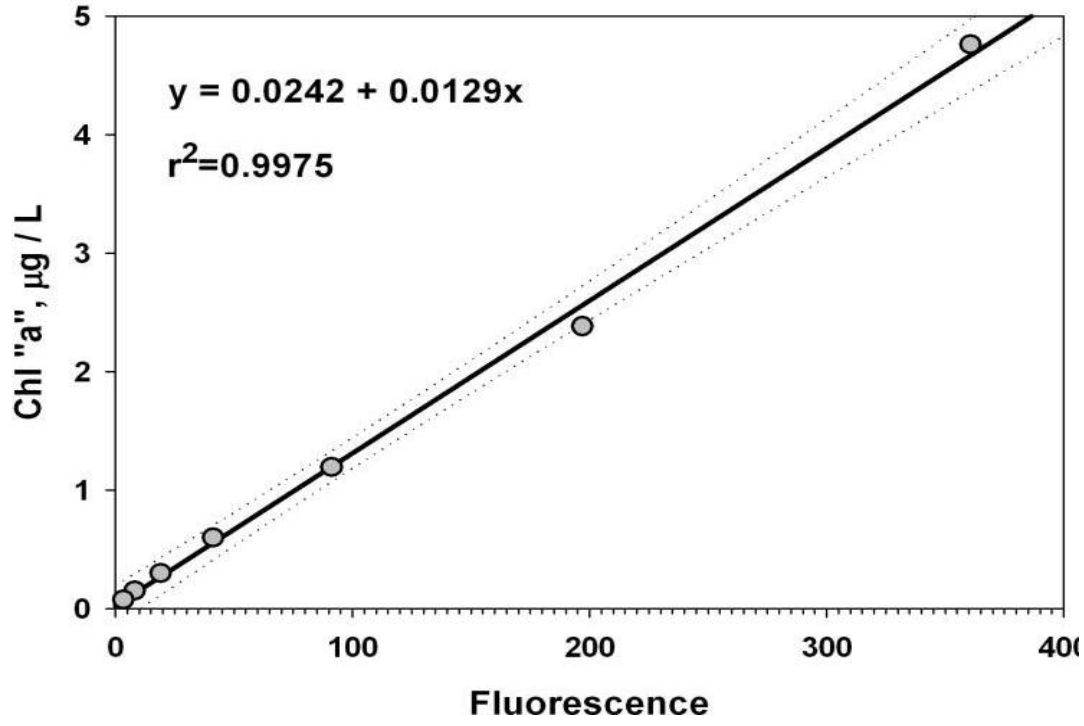

Fig. 4. Results of the quantitative calibration of the TD-700 laboratory fluorometer prior to chlorophyll measurements (X-axis – instrument fluorescence readings, Y-axis – chlorophyll standard values; solid line – linear regression, dotted line – 99% standard deviation).

After the fluorometer has been calibrated, a secondary standard (Turner Designs solid secondary chlorophyll-*a* standard TD7000-994) having reasonably similar spectral characteristics has been used. This secondary standard contains two ready-to-use fluorometric

standard concentrations: one high-level and one low-level concentration equivalent. The secondary standard was read at the time of initial calibration against chlorophyll and its reading was noted. Thereafter, the fluorometer was checked and adjusted with this secondary standard before each measurement.

All raw data for laboratory-measured chlorophyll-a as well as for phaeophytin are included in the Appendix, Table 1A.

2.5 Calculation and Expression of Results

The concentrations of chlorophyll-*a* and phaeopigments in the sample were calculated using the following equations:

$$\text{Chl } a \text{ (µg/l)} = \left(\frac{F_m}{F_m - 1}\right) \times (F_o - F_a) \times K_x \times \left(\frac{vol_{ex}}{vol_{filt}}\right) \qquad (1)$$

$$\text{Phaeo (µg/l)} = \left(\frac{F_m}{F_m - 1}\right) \times [(F_m \times F_a) - F_o] \times K_x \times \left(\frac{vol_{ex}}{vol_{filt}}\right) \qquad (2)$$

Where:

Fm	=	acidification coefficient (Fo/Fa) for pure Chl-*a*
Fo	=	reading before acidification
Fa	=	reading after acidification
Kx	=	factor from calibration calculations
Vol_{ex}	=	extraction volume
Vol_{filt}	=	sample volume

The factor Kx value = 0.0129 and the acidification coefficient Fm of 2.06 were used.

All calculated concentrations of chlorophyll-*a* and phaeophytin are included in the Appendix, Table 2A.

2.6 Statistical Analysis of the Results

All the statistical calculations were done using Systat v. 7.0 and Sigma Plot 7.1 software (Systat Software Inc.). In this report, the non-parametric Mann-Whitney U-test was used for testing whether values were significantly different from each other. We used the

Mann-Whitney U-test in preference to conventional ANOVA, because for many of the variables, the requirement of normal distribution of the data could not be met (even with data transformation).

Common statistics were calculated and data were tabulated. Tables include the number of non-missing values for the variable (N), minimum (the smallest non-missing value), maximum (the largest non-missing value), sum (the total of all non-missing values of a variable), mean (the arithmetic mean or average of a variable is the sum of the values divided by the number of non-missing values), SD [standard deviation, a measure of spread, is the square root of the sum of the squared deviations of the values from the mean divided by (n-1)] and other statistics.

2.7 Generation of Maps

For the spatial analysis of chlorophyll and phaeophytin data, and other cruise data that were provided by ROPME, we used Surfer v. 8.0 mapping software (Golden Software, Inc.).

2.8 Remote Sensing

For comparison of cruise results for chlorophyll and physical properties distribution, we used remotely sensed data, which are provided by infrared sensors for Sea Surface Temperature (SST), and for chlorophyll from the Sea-viewing Wide Field of View Scanner (SeaWiFS). Based on NASA OrbView-2 satellite and Moderate Resolution Imaging Spectroradiometer (MODIS), which is installed on NASA Terra and Aqua satellites, the obtained data from the above sensors allowed for the analysis of large-scale variations of chlorophyll values.

2.9 Quality Assurance and Quality Control

2.9.1 Instrument Detection Limits

The TD-700 Laboratory Fluorometer with a red sensitive photomultiplier tube has an extracted chlorophyll detection limit of 0.01µg/l using a 25 mm test tube.

2.9.2 System Performance

The performance of the fluorometer was monitored regularly by measuring the fluorescence of the solid secondary standard, according to the instructions given by the manufacturer, Turner Designs, Inc. The readings were stable and met the manufacturer's specifications.

2.9.3 Blanks

A procedural blank was measured for each sample series (samples from one station) and prepared simultaneously using the same solvents and tubes as was used for the samples. Its purpose was to check possible sample contamination by interfering compounds in the laboratory, which can lead to errors in quantification.

2.9.4 Internal Quality Control

Replicated filters, if available, were measured the same day for checking stability and precision of the method. Because QA/QC filters were available from only two stations (stations 4 and 43), we used control chart for stability and precision monitoring. The resultant control charts are included in Figure 5 (QA/QS filters). Figure 6 concerns the first set of replicates pooling all sampling depths at all stations versus second set of replicates for chlorophyll-*a* and phaeophytin. Figure 7 displays the first set of replicates from each depth at all stations versus second set of replicates for chlorophyll-*a* and phaeophytin.

Figure 5 indicates good agreement of chlorophyll derived from QA/QS filters with chlorophyll derived from ordinary filters. However, for phaeophytin, the figure demonstrates the disagreement between same sets of filters (r^2=0.04). The most likely reason for that disagreement is very low phaeophytin concentration in these samples together with insufficient number of QA/QS replications.

Figure 6 demonstrates better agreements between phaeophytin concentrations (r^2=0.64) in one replication set (all stations, all depths) plotted against another replication set (all stations, all depths), however, the relationship between concentrations of chlorophyll were not as good, as in the previous case.

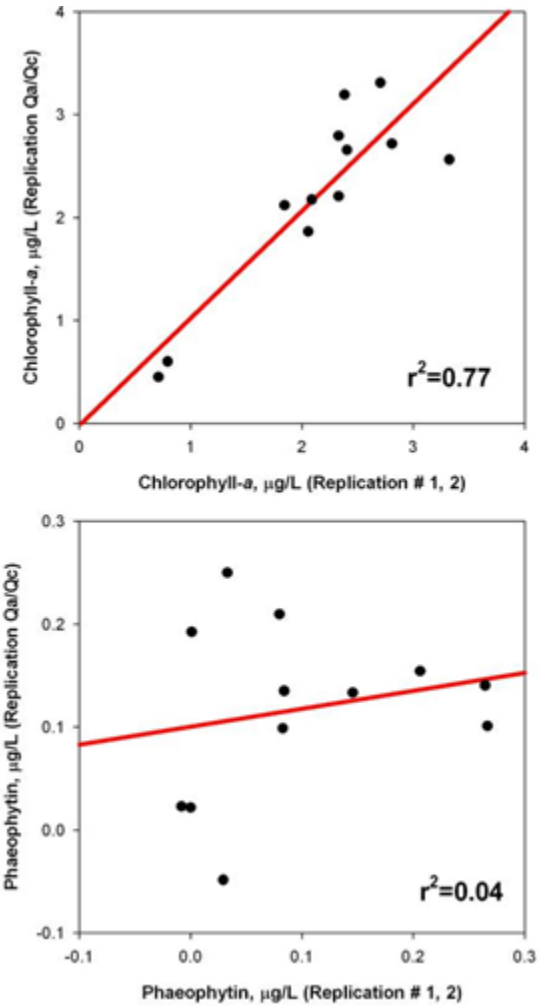

Fig. 5. Relationship between chlorophyll-*a* concentrations in QA/QC samples and in ordinary samples obtained from stations 4 and 43 (upper plot), and between phaeophytin concentrations in the same samples (bottom plot). Black dots are concentrations, and red solid lines are linear regression lines.

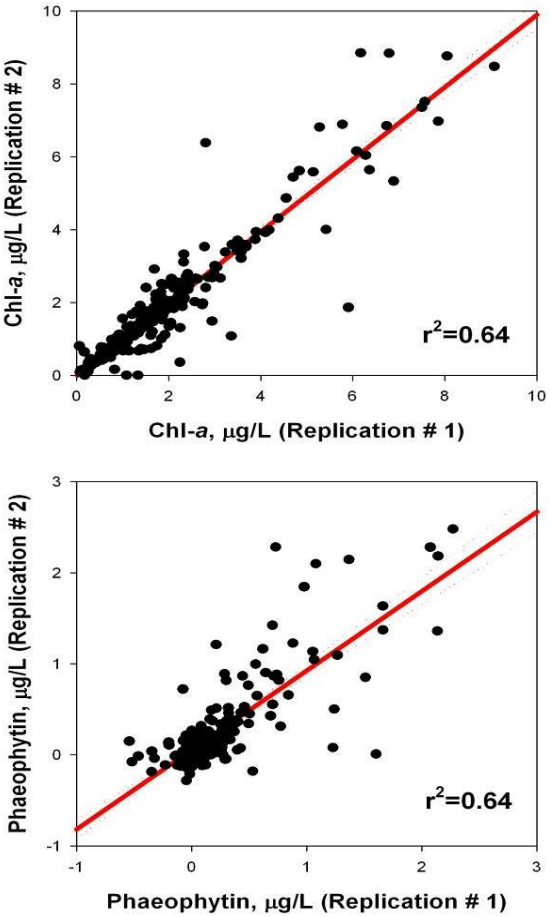

Fig. 6. Relationship between values in first and second replicates from each sampled station for chlorophyll-*a* concentration (upper plot) and phaeophytin concentration (bottom plot).

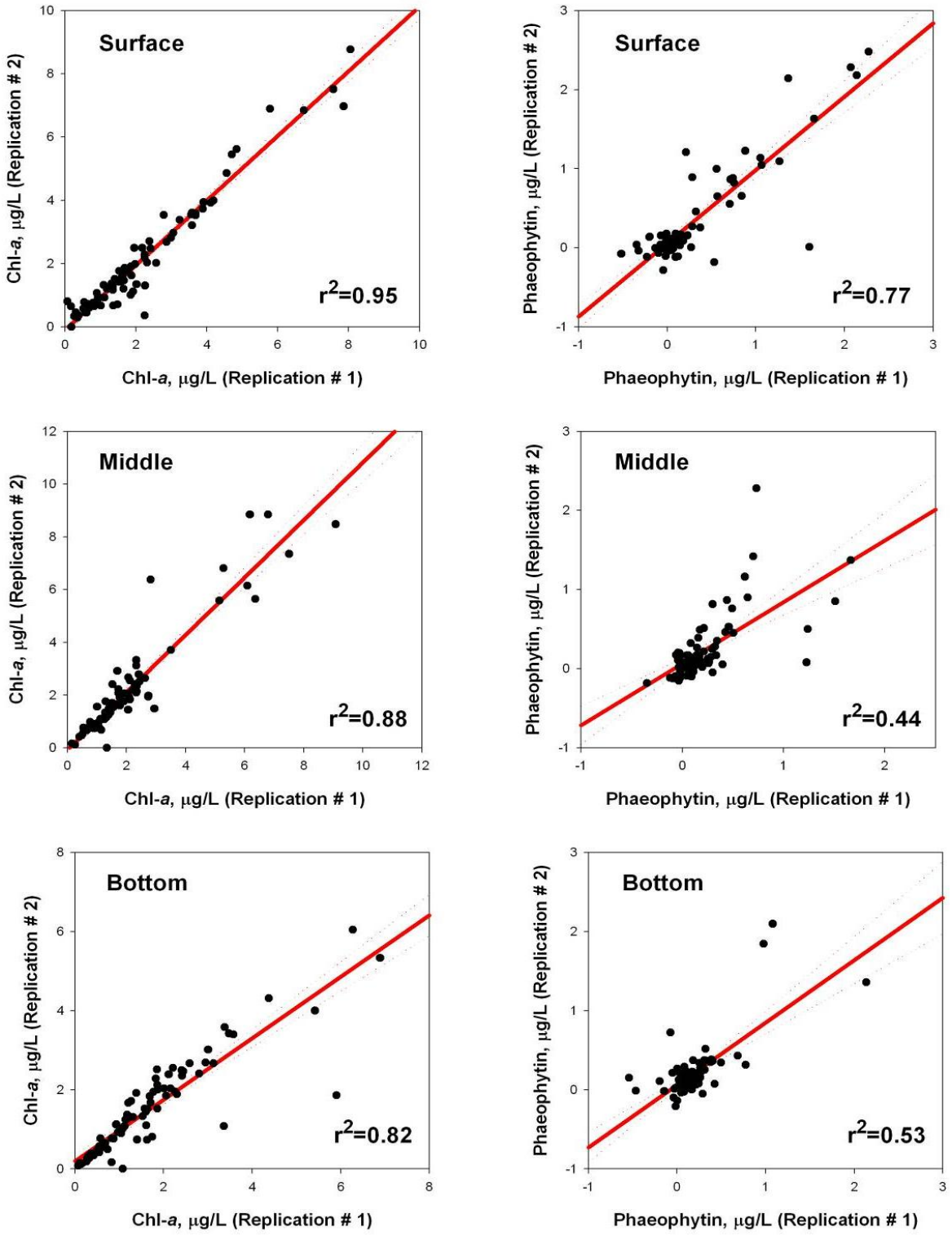

Fig. 7. Relationship between values in first and second replicates from each station, divided according to sampling depths for chlorophyll-*a* concentration (left plots) and phaeophytin concentration (right plots).

After dividing the whole data sets into three subsets, in accordance with sampling depth layers (Fig. 7), very good agreements within each subset for both the chlorophyll (r^2=0.95; 0.88 and 0.82 for surface, middle and bottom layers, respectively) and the phaeophytin (r^2=0.77; 0.44 and 0.53) were obtained. This could be explained by similar concentrations of pigments in each depth layer. The observed variability seems to be directly related to pigment concentration and to the total number of replicated filters.

Generally, quality control procedures show that the results of chlorophyll and phaeophytin measurements are reliable. All samples were processed at uniform environmental conditions in the laboratory and careful quality control measures were undertaken.

3. Results and Discussion

The enhanced plankton biomass and the elevated production in coastal waters reflect the combined effects of geophysical, chemical and biological processes. Of the many environmental factors that influence primary production, the light field and the rate of nutrient input to the primary producers are the most important. Unfortunately, there is lack of adequate information on the light field or the seasonal variability in physical characteristics of the water column for the ROPME Sea Area (RSA) waters (Kämpf and Sadrinasab, 2006). Even the Worldwide Ocean Optics Database (WOOD) included only few optics data related to RSA with no data related to Inner RSA (Smart, 2000) (Fig. 8 from WOOD, 2006, wood.jhuapl.edu).

For the primary producers of the RSA, factors such as the availability of sufficient light, dissolved oxygen, nutrients, and a suitable ambient temperature for metabolic activity are critical parameters for some areas in this region (Al-Yamani *et al*., 2006).

Summary of the results on phytoplankton biomass of several studies conducted in selected marine waters is included in Table 1.

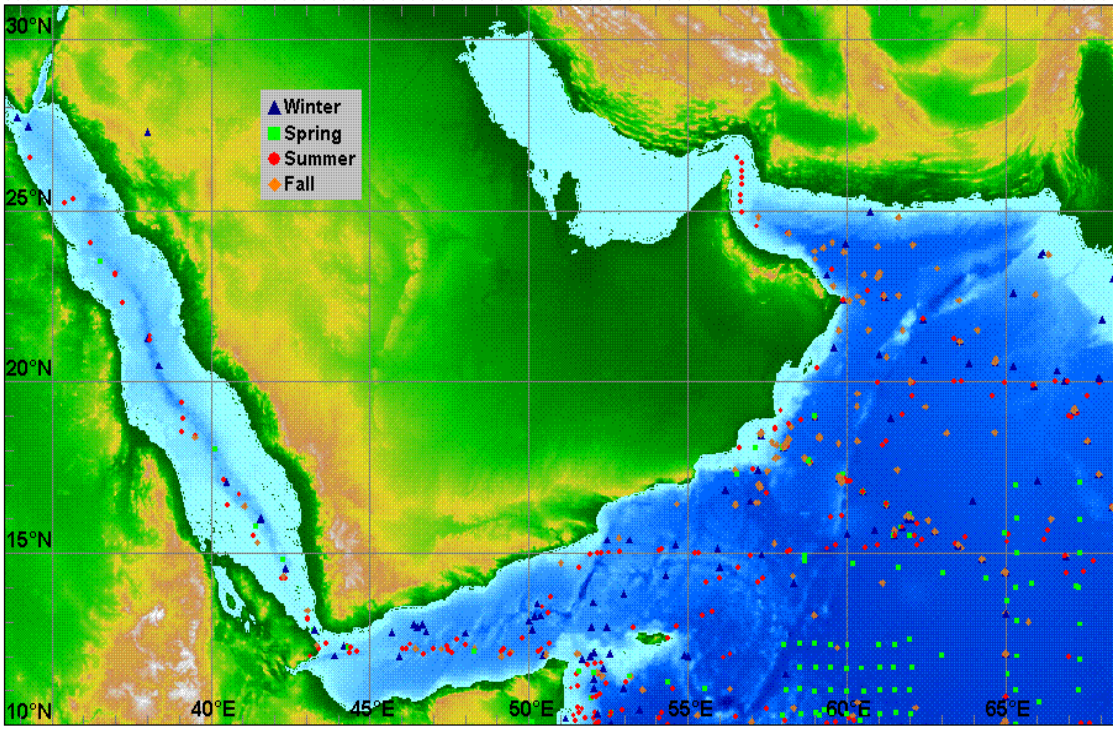

Fig. 8. Distribution of marine optics datasets, included in the Worldwide Ocean Optics Database, ROPME Sea Area (according to WOOD, 2006, http://wood.jhuapl.edu).

Table 1. Comparison of Phytoplankton Biomass in Selected Marine Waters

Region	Biomass (Chl-*a*, µg/l)	Reference
Kuwait's Waters	0.12 – 23.7	Al-Yamani *et al*., 2006
Kuwait's Waters (Red Tide)	55.4-262.7	Subba Rao *et al*., 1999
Inner RSA	0.4-2.8	Hirawake *et al*., 1998
Basrah, Shatt Al-Arab	0.5-3.3	Huq *et al*., 1981
NW Inner RSA	0.7-9.1	Huq *et al*., 1978
SE Inner RSA	1.11-1.25	El-Gindy & Dorgham, 1992
Sea of Oman	0.43-0.67	El-Gindy & Dorgham, 1992
Southwest coast of India	0.07-22.5	Radhakrishna, 1969
Red Sea	0.2-1.2	Shaikh *et al*., 1986
Central Red Sea off Jeddah	0.02-6.4	Dowidar, 1983

In the Inner RSA, a north to south gradient in the distribution of phytoplankton biomass appears to exist (Subba-Rao and Al-Yamani 1998). In the Sea of Oman and the Straits of Hormuz, biomass was reported to be lower (chlorophyll-*a* of 1.25-0.67 µg/l, respectively) than in the northwestern areas of the Inner RSA (El-Gindy and Dorgham 1992).

The raw results of fluorescence measurements (before and after acidification) obtained from this study are included in the Appendix, Table 1A. These values were converted to real chlorophyll and phaeophytin concentrations using the calibration relations (Fig. 4) and equations 1 and 2 (refer to the Materials and Methods section).

The converted data (represented as micrograms per liter or milligrams per cubic meter) are presented in Table 2A (Appendix Section). Descriptive statistics are presented in Table 2 for laboratory analyzed chlorophyll-*a* and for phaeophytin as well as for *in-situ* measured chlorophyll-*a* during the Winter Cruise. The results indicate that both average as well as maximum chlorophyll values are in general agreement with the published chlorophyll concentrations, which were recorded earlier for the region (Hirawake *et al*., 1998; Huq *et al*., 1978, El-Gindy and Dorgham, 1992). However, lower minimum values were obtained (0.07-0.09 µg/l) from this study than were recorded earlier (0.4-0.7 µg/l). This could be due to the sensitivity of the instrument used in this study (Turner Designs TD-700 fluorometer), and the precise instrument calibration during sample analysis, which allowed registering low concentrations of phytoplankton pigments.

3.1 Physico-chemical Characteristics

The physicochemical properties of the RSA vary both in their horizontal as well as vertical distributions. Figure 9 displays variability in the spatial distribution of seawater temperature, salinity, water density, and chlorophyll fluorescence across RSA from northern RSA to Sea of Oman. Difference in vertical distribution is evident for temperature, salinity, water density, and fluorescence. The intrusion of the Arabian Sea waters is clearly visible on the right side of the plot; low salinity waters coming from Shatt Al-Arab is evident on left side of the plot.

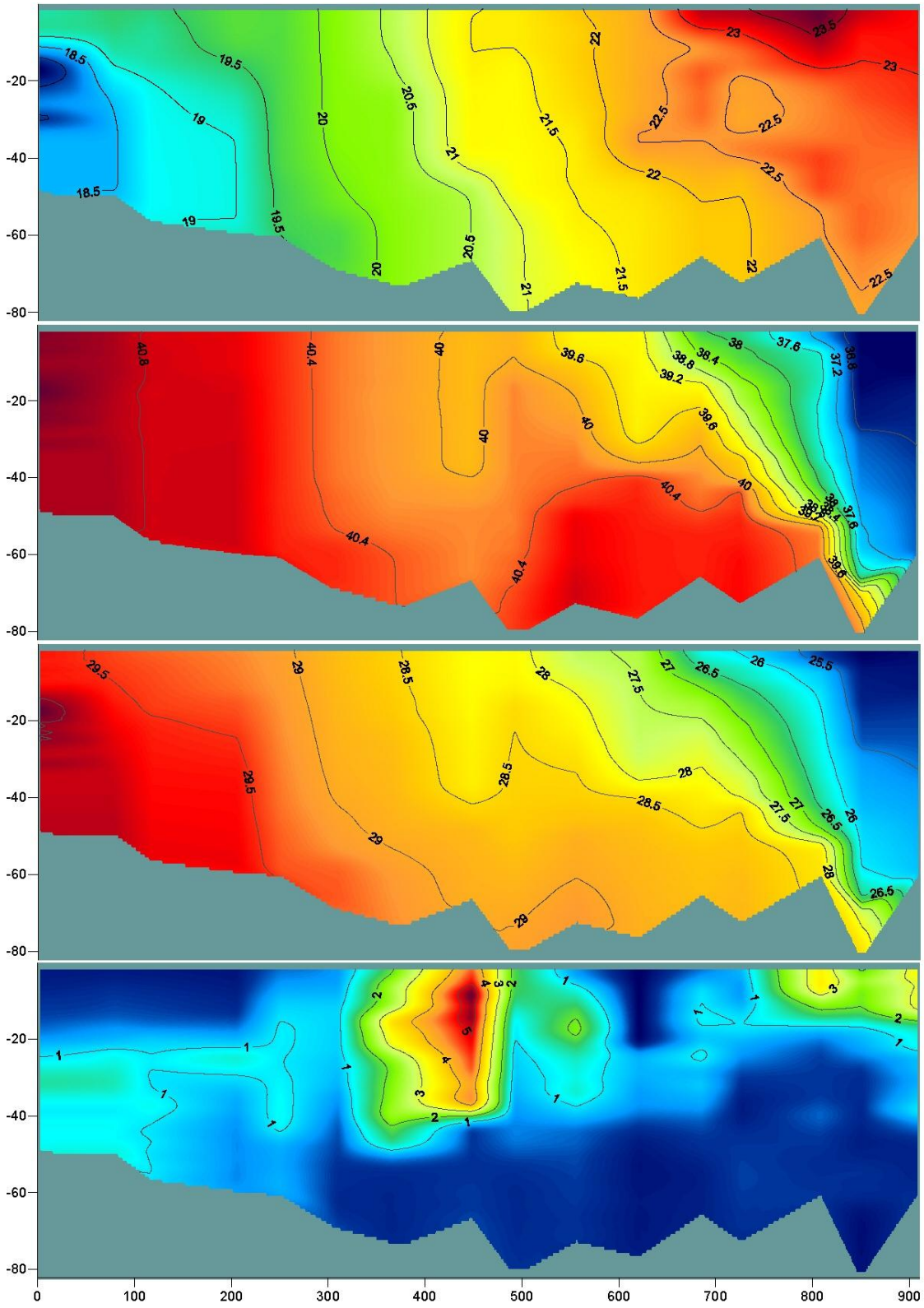

Fig. 9. Two-dimensional representations for temperature (°C), salinity (psu), potential water density (kg/m^3), and relative fluorescence (expressed as mg/m^3) for the RSA during Winter 2006. Left side is northern Inner RSA; right side is Sea of Oman. Higher values are in red, lower values are in blue.

Table 2. Descriptive Statistics for Laboratory-measured Chlorophyll-*a*, Phaeophytin, and *in-situ* Measured Chlorophyll-*a* (during Winter 2006) for the three Sampled Depths and for the Water Column

Statistic	Chlorophyll-*a*, µg/l (laboratory measurements)			
	Surface	***Middle***	***Bottom***	***Overall Mean for Water Column***
Average ± STD	2.54 ± 2.16	2.05 ± 1.79	1.68 ± 1.68	2.09 ± 1.92
Minimum value	0.09	0.15	0.07	0.07
Maximum value	9.45	8.77	10.08	10.08
Number of observations	104	103	104	311
Statistic	**Phaeophytin, µg/l (laboratory measurements)**			
	Surface	***Middle***	***Bottom***	***Overall Mean for Water Column***
Average ± STD	0.44 ± 0.75	0.29 ± 0.38	0.29 ± 0.47	0.34 ± 0.56
Minimum value	0.00	0.00	0.00	0.00
Maximum value	4.30	2.12	2.95	4.30
Number of observations	104	103	104	311
Statistic	**Chlorophyll *a*, µg/l (CTD *in-situ* measurements)**			
	Surface	***Middle***	***Bottom***	***Overall Mean for Water Column***
Average ± STD	1.07 ± 1.25	0.97 ± 1.04	0.75 ± 0.83	0.93 ± 1.06
Minimum value	0.00	0.00	0.00	0.00
Maximum value	6.50	7.00	5.77	7.00
Number of observations	104	104	104	312

3.2 Depth Distribution

Average concentrations of chlorophyll-*a* in the studied area during the Winter Cruise of 2006 were 2.54 ± 2.16, 2.05 ± 1.79 and 1.68 ± 1.68 µg/l for surface, middle and bottom layers, respectively. The mean concentration for the water column was 2.09 ± 1.92 µg/l. The mean surface laboratory-measured chlorophyll value (2.54 µg/l) was in good agreement with

satellite data obtained for February-March 2006, which has an average of 2.64 µg/l for the entire RSA.

The chlorophyll concentration, determined by *in-situ* fluorometer, was significantly lower than laboratory measured chlorophyll (Table 2). Highest values of chlorophyll-*a*, determined by laboratory method, were 9.45, 8.77 and 10.08 µg/l for surface, middle and bottom, respectively.

Average concentrations of phaeophytin were significantly lower (0.44±0.75, 0.29±0.38, 0.29±0.47 µg/l for surface, middle and bottom, respectively) than chlorophyll concentrations. The water column mean concentration of phaeophytin was 0.34±0.56 µg/l. Maximum values reached 4.30, 2.12 and 2.95 µg/l at surface, middle and bottom layers, respectively, in the zones of intensive blooms in the Sea of Oman.

3.3 Transect Differences

There is an obvious spatial distribution in chlorophyll concentration among transects (data were averaged for all stations along each transect, for all sampling depths) (Fig. 10). The highest mean concentration (averaged for stations along each transect) was recorded at the Strait of Hormuz (Transect 14a), in the Sea of Oman (transects 16 and 17), in the middle of the Inner RSA (transect 6, Inner RSA from Iran to Qatar), and off Shatt Al-Arab and Karun deltas.

Chlorophyll concentrations along each transect studied (Fig. 3) were within the general range for the RSA, with higher values in general for the inshore sampled stations (excluding transects 6, 7 and 8 in the Inner RSA and transect 18 in the Sea of Oman). Transect 18 crossed the chlorophyll-rich eddies coming from RSA, and transects 6-8 partially crossed the chlorophyll-rich, turbid zone behind the Mond river mouth (Latitude 28.145 N, Longitude 51.27138 E). Such chlorophyll distribution is connected with hydrodynamic properties of Inner RSA and Sea of Oman, as well as with seasonal patterns in the phytoplankton community and river discharge into the Inner RSA. Freshwater is delivered into the Inner RSA from Shatt Al-Arab and Karun river systems and from several rivers on Iranian shore.

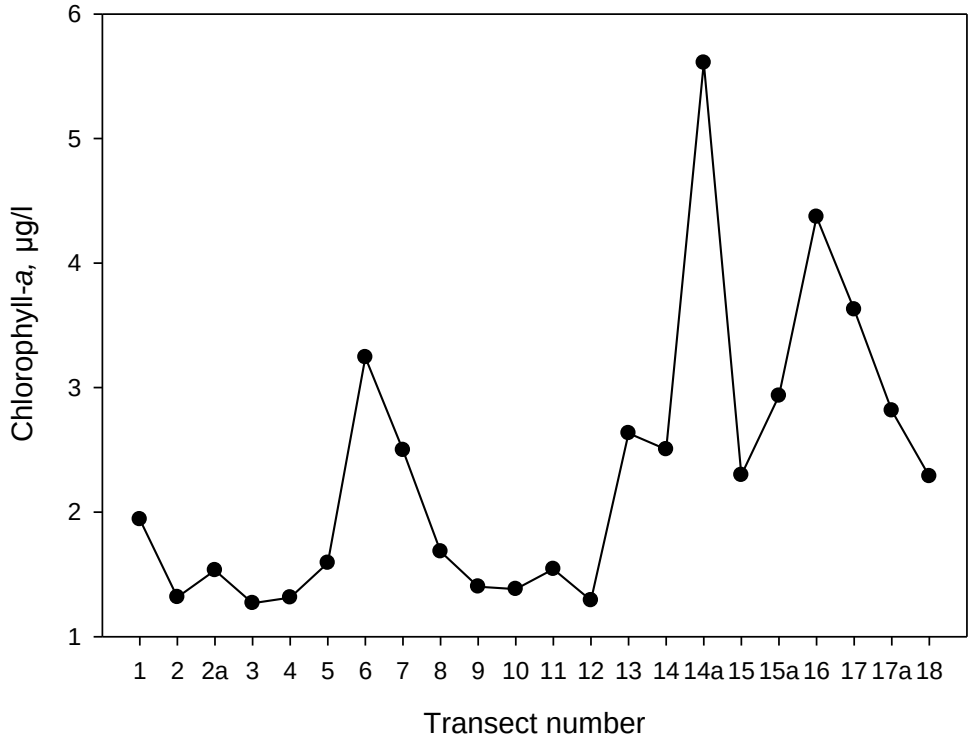

Fig. 10. Average water column concentration of chlorophyll-*a* (µg/l) for the different sampled transects in the RSA during Winter 2006 (transects 1-14 – Inner RSA, transect 14a – Strait of Hormuz, and transects 15-18 – Sea of Oman). Chlorophyll-*a* concentrations were averaged for all sampled depths per station and all sampled stations per transect.

3.4 Large Spatial Differences

Because chlorophyll concentrations ranged widely in the RSA, the horizontal distribution patterns were plotted for the studied area, which were obtained from laboratory measurements (Fig. 11). Chlorophyll samples in the shallow waters of the northernmost waters off river mouths as well as southern coastal waters of the Inner RSA (Saudi Arabia, Bahrain, Qatar and UAE were not collected and hence estimates were extrapolated from adjacent waters where chlorophyll values were measured. Therefore, these areas have estimated chlorophyll values since no samples were collected there.

Results indicate the occurrence of high spatial variability in the studied regions of the RSA, which is displayed by Figure 11. Relatively few zones had pronounced low-chlorophyll values (< 1µg/l), while high concentrations (> 4 µg/l) were observed in central eastern side of the Inner RSA near the Iranian coast, in the southeastern part of the Inner RSA (Strait of

Hormuz), and in the Sea of Oman. Unfortunately, no samples were obtained from transect 1a, which is very close to the Shatt Al-Arab and Karun discharge zones. These areas are expected to have high chlorophyll concentrations in the northwestern Inner RSA.

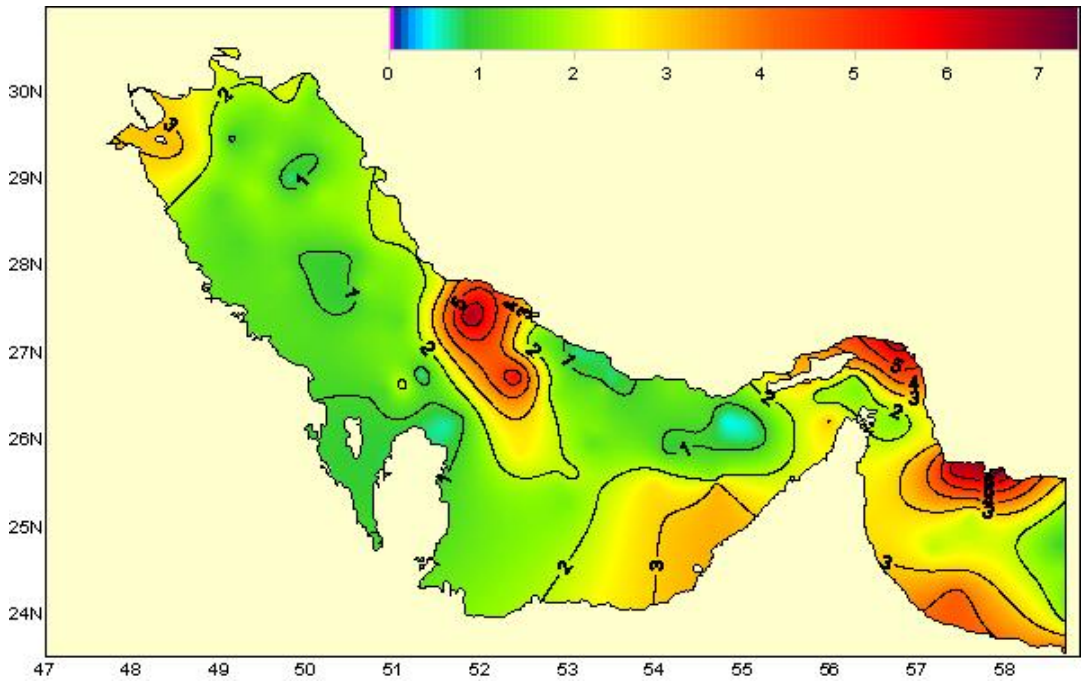

Fig. 11. Spatial distribution of the average laboratory measured chlorophyll concentrations (µg/l) in the water column, in the studied regions for Winter 2006. No data from shallow waters of the south Inner RSA coastwise Saudi Arabia, Bahrain, Qatar and UAE, values extrapolated from adjacent data.

Figure 12 presents the spatial distribution of chlorophyll-*a* at each sampling depth (surface, middle and bottom layers). Surface chlorophyll measurement is very important for the verification of the values obtained from remote sensing, as indicator of algal biomass and for the development of algal blooms. There is no doubt that the general chlorophyll distribution in the Inner RSA is complex, and a more detailed analysis of the factors, forming these phytoplankton patterns, is necessary.

The non-parametric Mann-Whitney U-test was applied to the whole laboratory chlorophyll data set. Results are shown in Table 3. Significant difference was found between surface and bottom chlorophyll records with statistical significance ($p = 0.001$) and between bottom and middle layers ($p = 0.037$). No significant differences were found between surface and middle values.

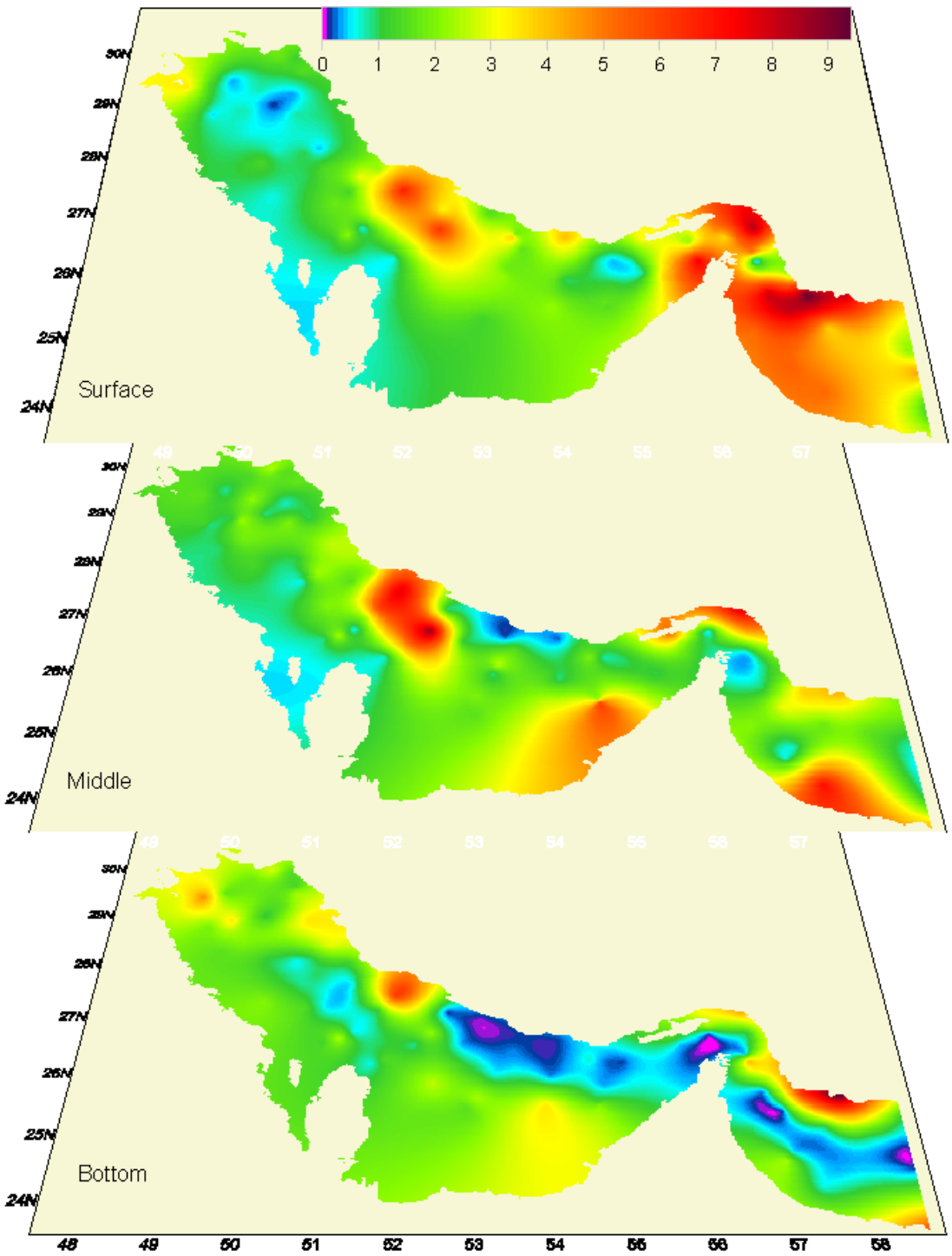

Fig. 12. Chlorophyll-*a* concentrations (µg/l) at different sampling depths (surface, middle and bottom layers) during Winter 2006.

Table 3. Results of Comparison for Chlorophyll-*a* Values from Different Depths by Mann-Whitney U-Test

Pairs	Mann-Whitney	Probability
Surface-Middle	5923.5	0.188
Middle-Bottom	6254.0	**0.037**
Surface-Bottom	6870.0	**0.001**

Figures 13-15 show the similarity in the broad scale spatial distributions of the surface chlorophyll at the three sampled depths, based on laboratory and *in-situ* measurements for the whole Inner RSA and Sea of Oman. The above figures show laboratory-measured chlorophyll data provide more detailed distribution, with higher chlorophyll concentrations than the *in-situ* measured chlorophyll. Maximum concentration obtained for laboratory-measured chlorophyll was 9.41 μg/l compared to 6.42 μg/l for *in-situ* measured chlorophyll. Therefore, *in-situ* chlorophyll measurements can be used only to show relative values of chlorophyll distribution and to compare with satellite-based chlorophyll. However, for accurate phytoplankton biomass estimations, the laboratory-measured chlorophyll should be used.

Cluster analysis of factors obtained from the ROPME cruises was performed using the method of average linkage clustering (Pearson distances between groups) classification technique realized by Systat v. 7.0. This technique involves the calculation of a Pearson correlation matrix for many variables or samples.

Three figures (Fig. 16, a-c) are presented to show classification of the environmental parameters in relation to chlorophyll (both measured *in situ* and extracted). For all three sampling depths (surface, middle and bottom), the most correlated parameters were laboratory measured and *in situ* chlorophyll and phaeophytin (decay product of chlorophyll). Whereas at mid and bottom layer has good correlation with turbidity (Fig. 16, b-c), surface chlorophyll more correlated with a water temperature. Such agreement can be a circumstantial evidence confirmed what the main feature of the Inner RSA waters circulation during winter is a leading role of the temperature and water density. Negative correlation of chlorophyll with salinity also confirms such hypothesis (Table 3).

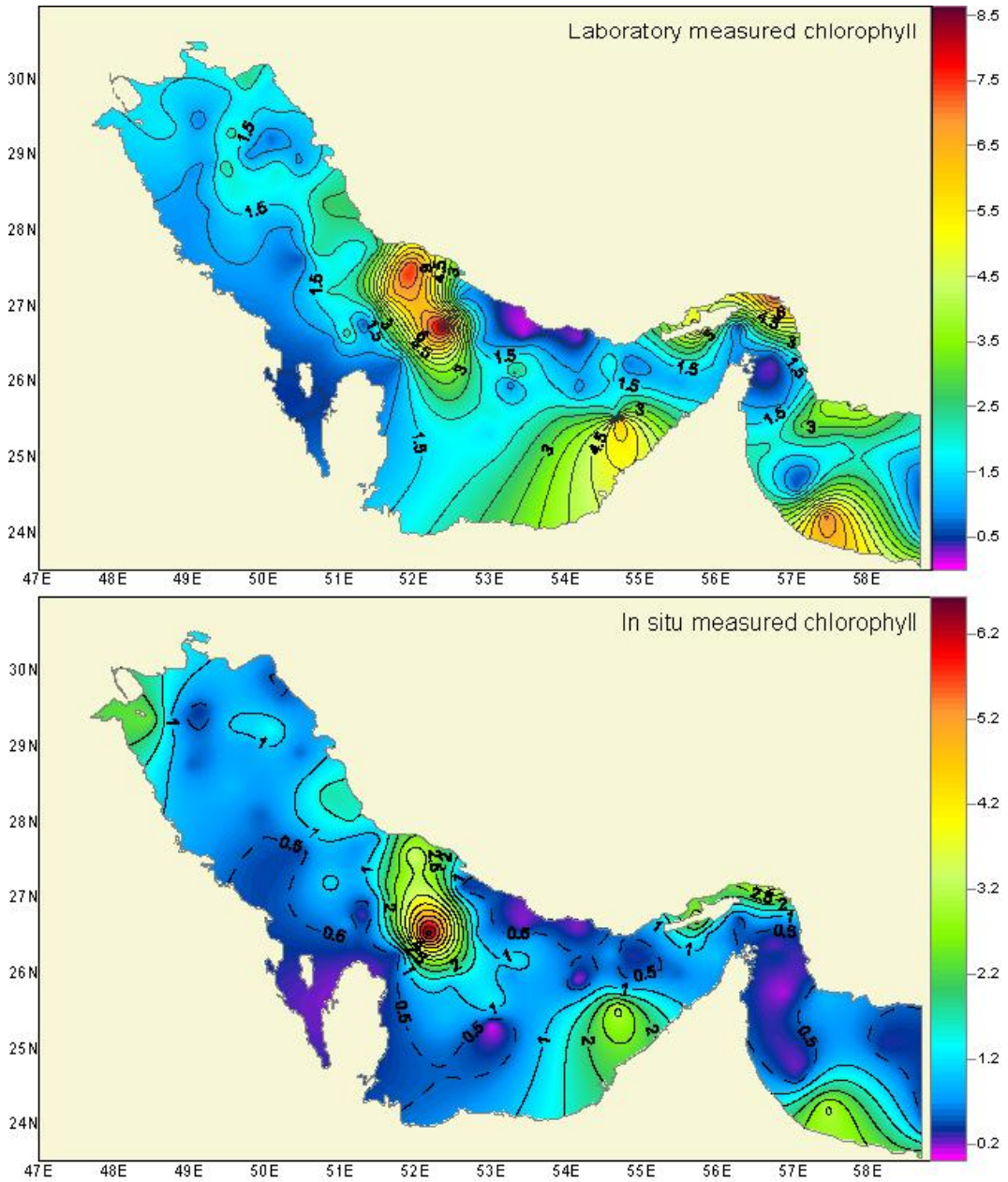

Fig. 13. Spatial distribution of surface chlorophyll (µg/l), measured in laboratory and *in situ* during Winter 2006. Note that the variability is apparently lower for *in situ* measurements, suggesting that the profiling fluorometer could underestimate chlorophyll values greatly.

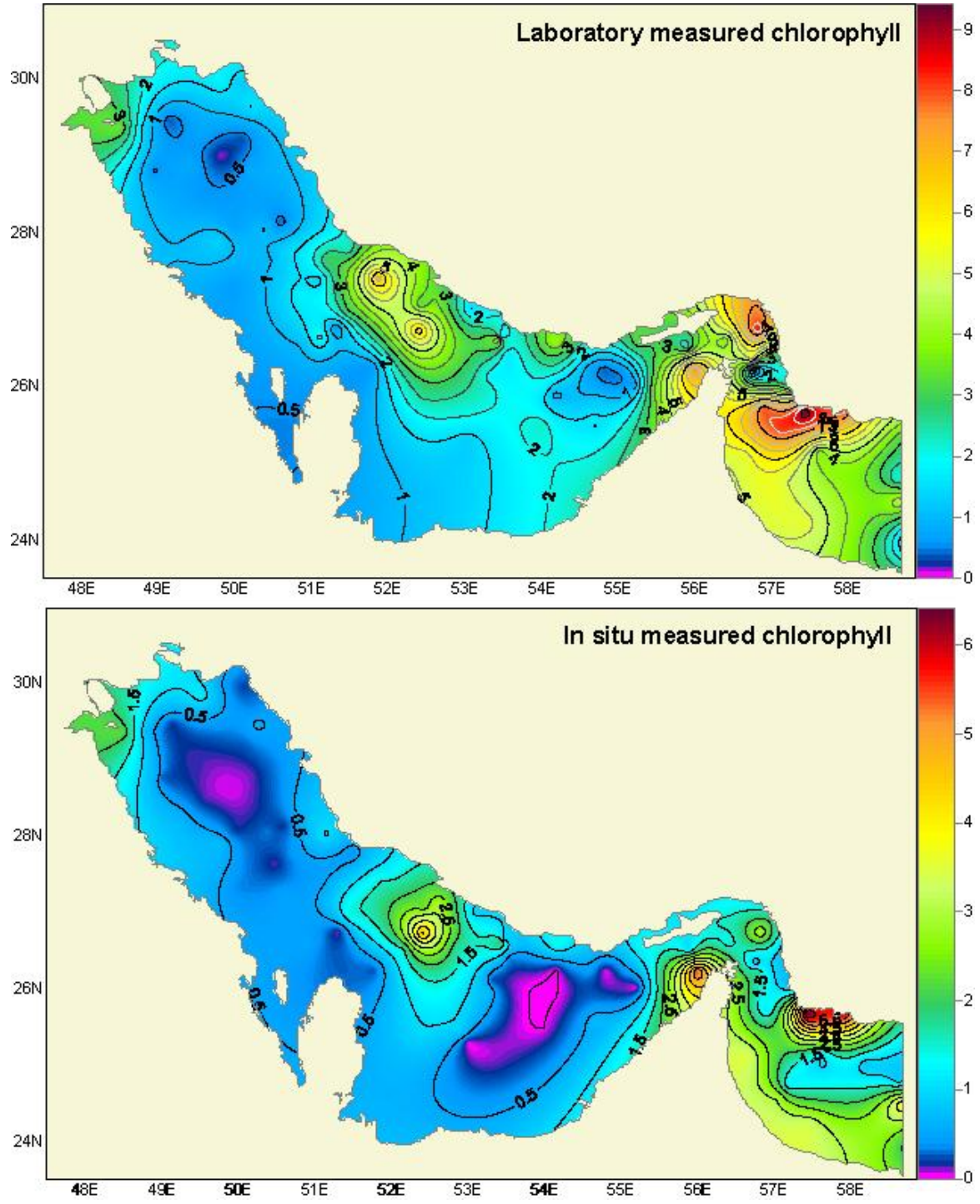

Fig. 14. Spatial distribution of the middle-layer chlorophyll (µg/l), measured in laboratory and *in situ* during Winter 2006.

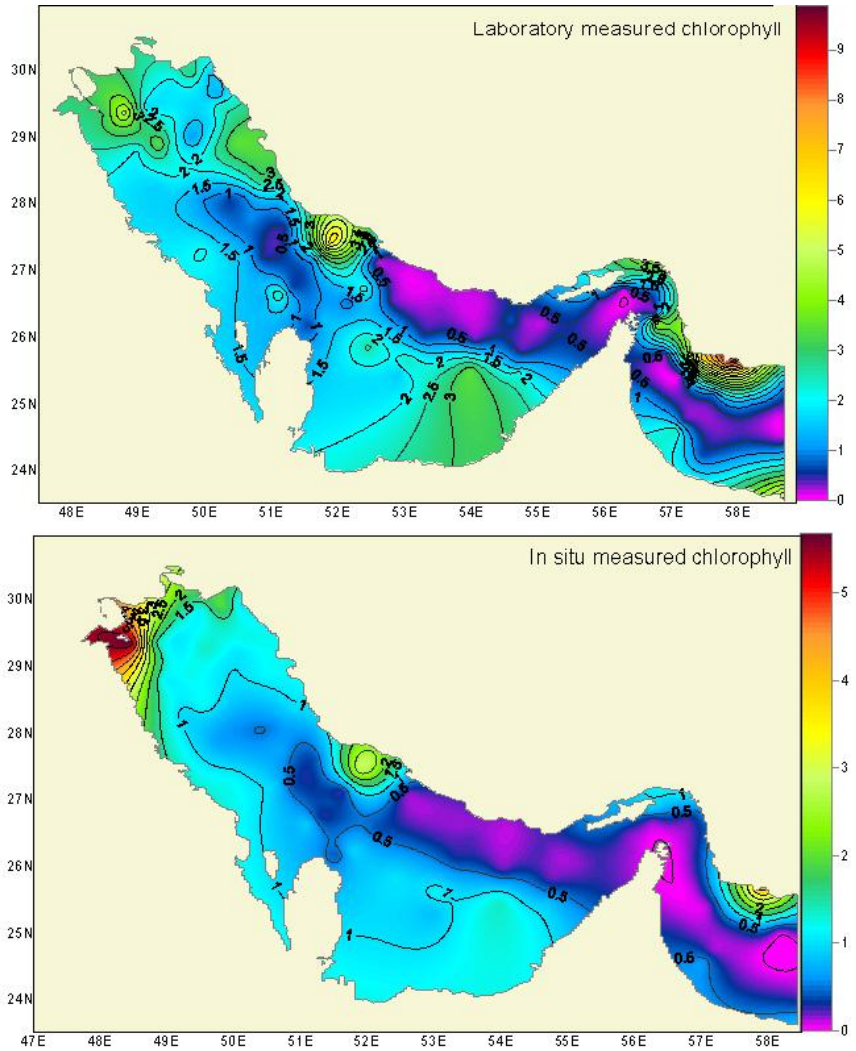

Fig. 15. Spatial distribution of the bottom-layer chlorophyll (µg/l), measured in laboratory and *in situ* during Winter 2006.

Phaeophytin values held to all sampling depths significantly lower than chlorophyll, for all stations and significantly lower (up at two times) in middle and bottom layers than at surface. Phaeophytin values ranged widely. However, all regions where phaeophytin concentrations have been considerable, were inside the two zones revealed substantial chlorophyll-*a* as well. The concentrations of phaeophytin can serve as a tracer for the past phytoplankton activity and the vertical distribution of the phaeophytin in the water column conforms to the expected pattern. From other hand, low phaeophytin values confirm the intensive growth of phytoplankton during winter stage of seasonal succession and relative low mortality (or very high turnover rate of died phytoplankton biomass).

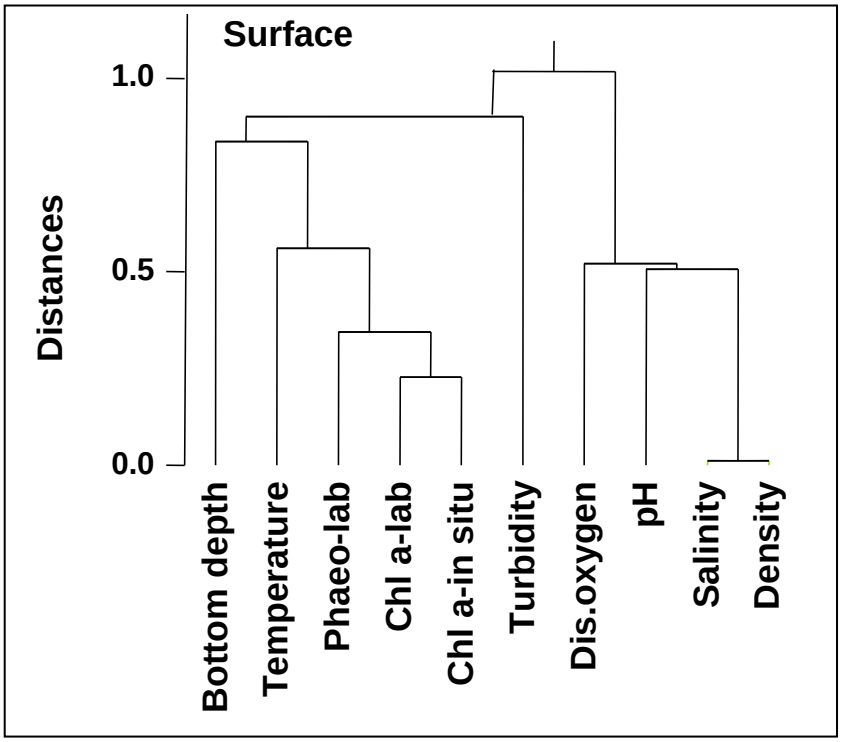

Fig. 16a. Analysis of similarity (Pearson correlation coefficient) between chlorophyll and selected environmental variables in surface depth.

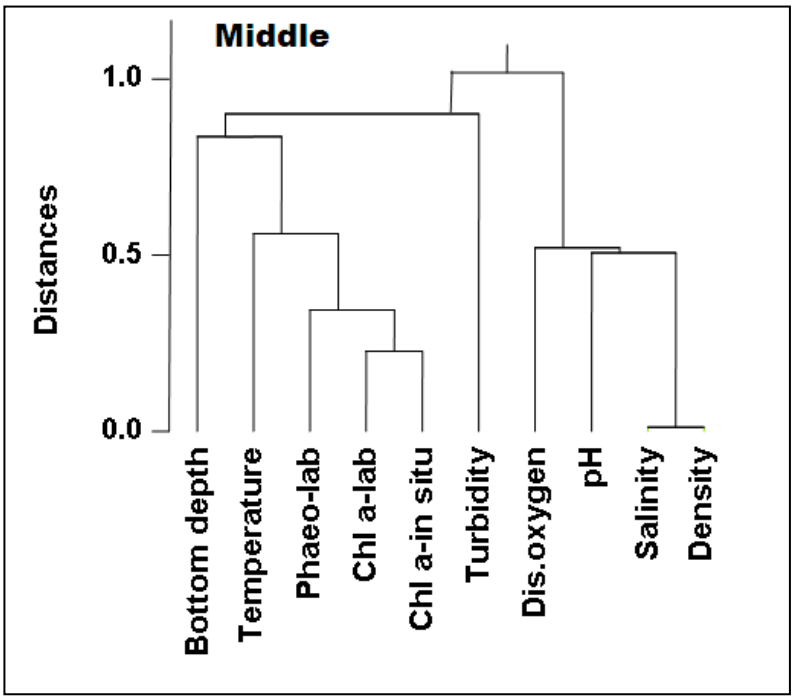

Fig. 16b. Analysis of similarity (Pearson correlation coefficient) between chlorophyll and selected environmental variables in middle depth.

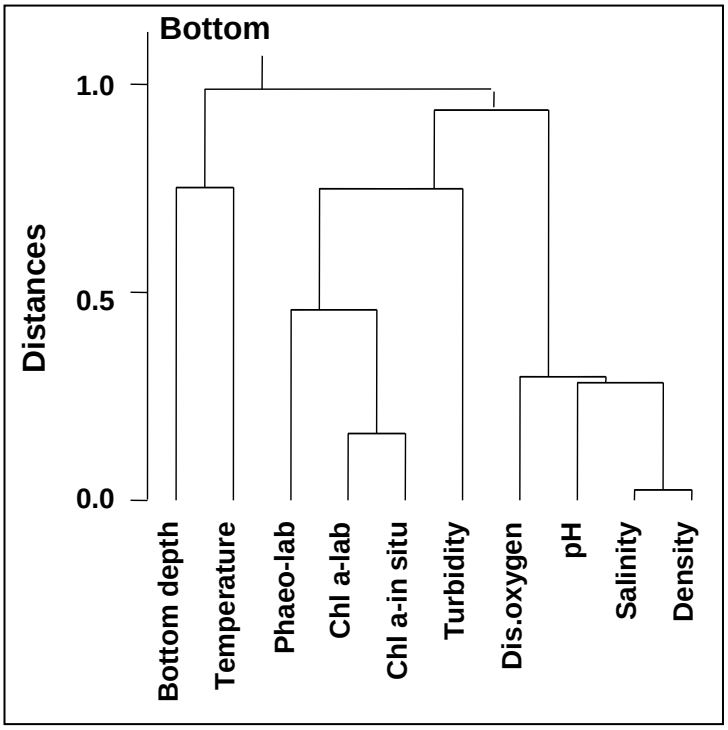

Fig. 16c. Analysis of similarity (Pearson correlation coefficient) between chlorophyll and selected environmental variables in bottom depth.

Dividing the data by cruise legs allowed clearer understanding of the relationships of laboratory-measured chlorophyll-*a* with temperature and salinity variables (Fig. 17, a and b). Regression slope is less for the leg 2 data, where frontal zone and coastal upwelling were observed. Weak negative correlation between chlorophyll and temperature in leg 1 data can be explained by water masses features.

Figure 18 shows the relationship between chlorophyll values and very high salinity levels (more than 40 psu). Although the interpretation of such relationship needs further investigation, however, Figs. 18 and 19 confirm that zones of high salinity correspond to low surface chlorophyll values, obtained by laboratory measurements. Moreover, the distribution of satellite-derived chlorophyll (Fig. 20) agreed in general with temperature distribution. Satellite information about chlorophyll distribution is very useful for studies of broader patterns and for understanding dynamics of the surface phytoplankton.

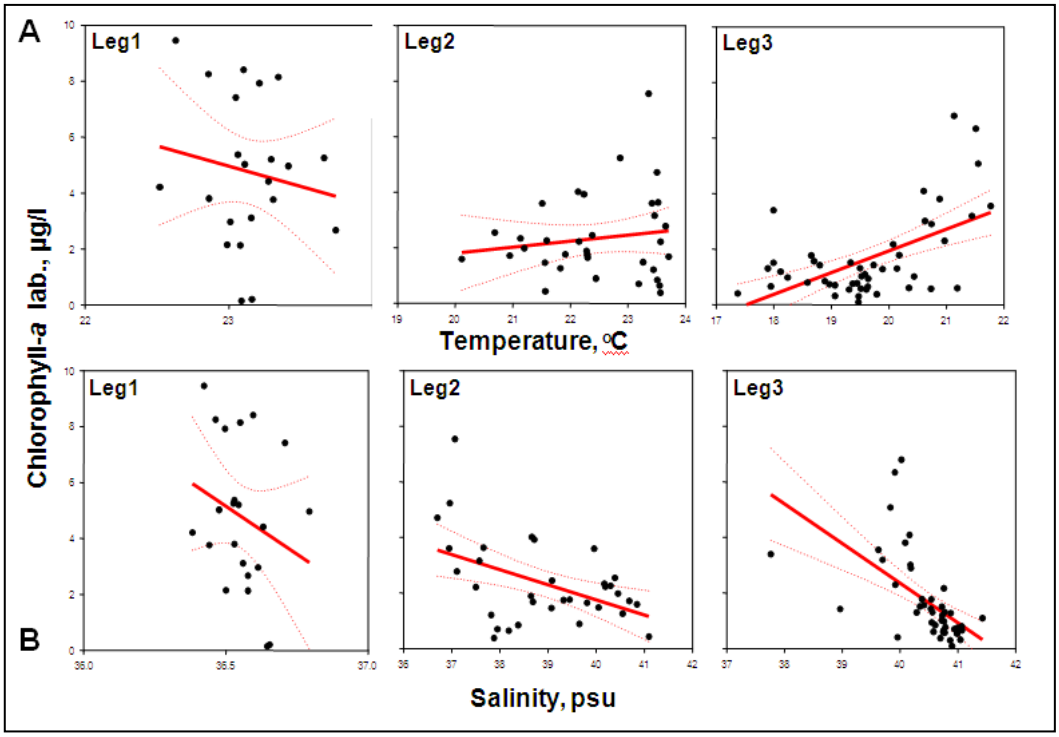

Fig. 17. Correlations of acid-corrected chlorophyll with water temperature (A) and salinity (B) for the different legs of cruise.

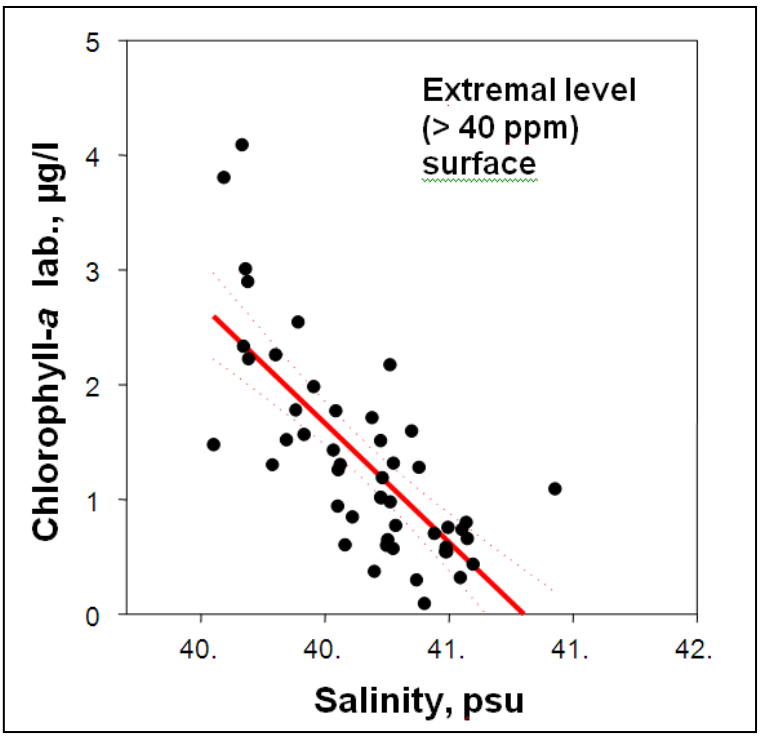

Fig. 18. Relationship between chlorophyll-*a* and very high salinity values in Inner RSA.

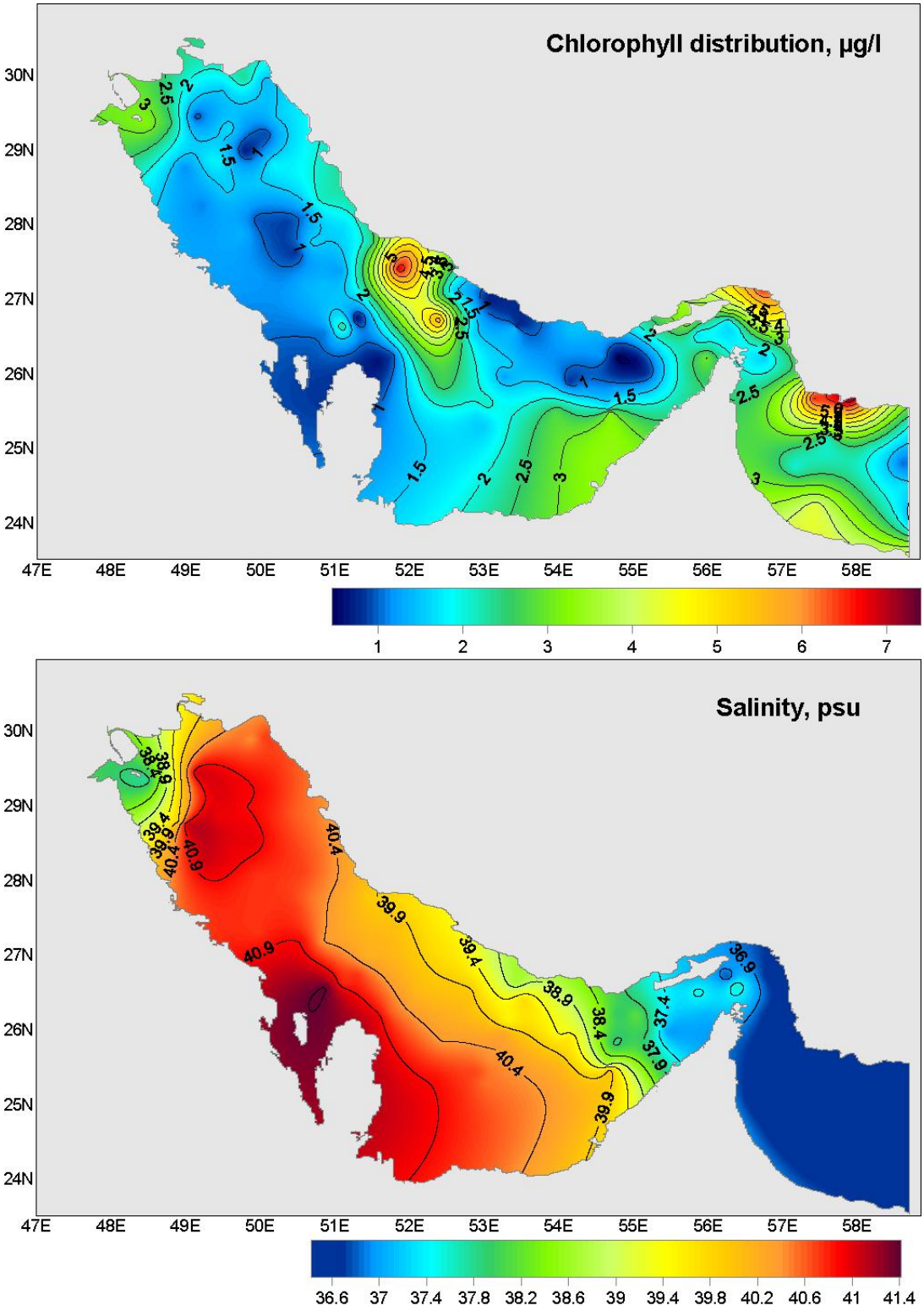

Fig. 19. Spatial distribution of the salinity (psu) and depth-averaged chlorophyll (acid-corrected values, µg/l) in the Inner RSA and Sea of Oman, during February-March 2006.

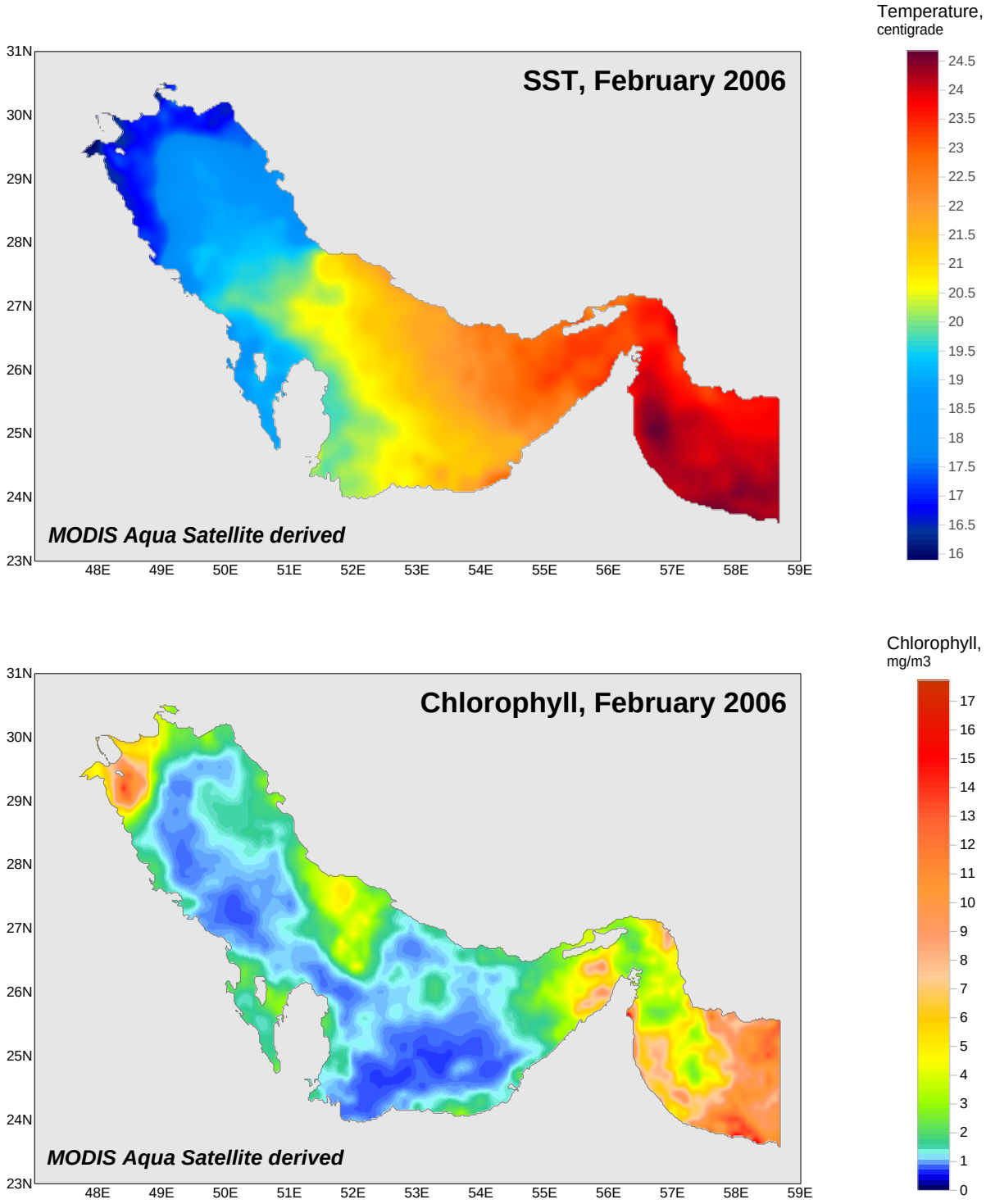

Fig. 20. Spatial distribution of the sea surface temperature (°C) and satellite-derived surface chlorophyll (µg/l = mg/m^3) in the Inner RSA and Sea of Oman, during February 2006.

We can estimate the agreement between satellite-derived chlorophyll (Fig. 21, upper plot) and laboratory-measured chlorophyll (Fig. 21, bottom plot) as being generally in good agreement. Differences between those images are based on different spatial scale (MODIS sensor is registered 9x9 km spots as one point, basin-wide, while samples during cruise were taken usually within about ten kilometers intervals) and time scale. The satellite image is a composite one, prepared for the month of February based on monthly-accumulated daily data for the RSA. Data obtained from MODIS were processed using OC3 algorithm, which is most effective for open ocean waters, and can produce underestimates or overestimates in shallow turbid waters.

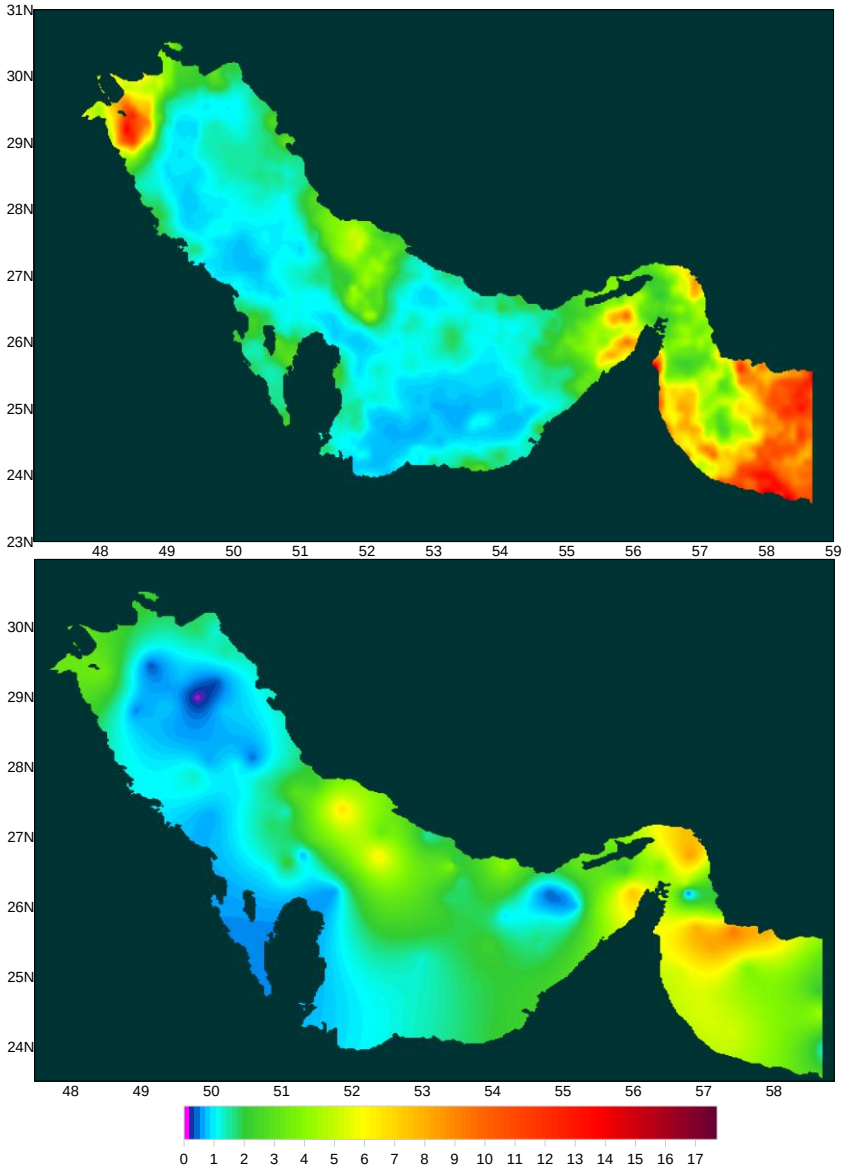

Fig. 21. Comparison between satellite derived chlorophyll (µg/l) distribution in February 2006 (upper plot, derived from Aqua MODIS sensor) and laboratory measured chlorophyll, Winter 2006 Cruise (bottom plot).

Figure 22 shows the spatial distribution of satellite-derived chlorophyll and sea surface temperature and salinity values (based on CTD-measurements during cruise).

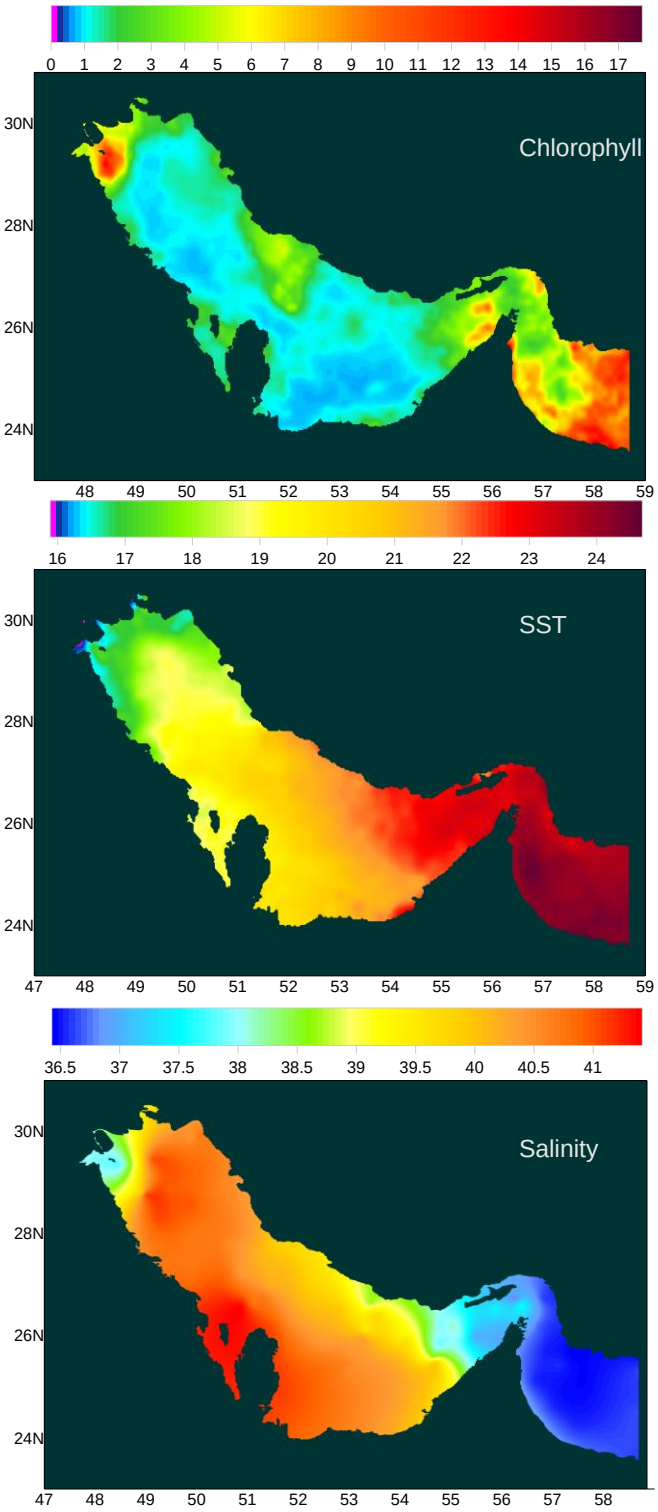

Fig. 22. Spatial distribution of the satellite derived chlorophyll (top, µg/l), sea surface temperature (middle, ^{o}C) and CTD *in-situ* salinity (bottom, psu) during February, 2006 in RSA.

The maps of salinity and chlorophyll distribution show Shatt Al-Arab waters entering and tending to flow southwards along the Kuwaiti and Saudi Arabian coasts. Sea surface temperature (SST) in that region also demonstrates that cold water mass extends further southwards, and chlorophyll distribution corresponds well with both salinity (high chlorophyll concentration with lower salinity) and SST (lower chlorophyll concentration with higher temperature) along Kuwait's coast. What is remarkable is that very similar salinity and temperature surface gradients were observed in late winter-early spring during research cruises onboard RV *Atlantis II* (1977) and *Mt. Mitchell* (1992). Therefore, such large-scale chlorophyll patterns also could be of permanent or periodic occurrence. For checking the suggestion of the periodic nature of chlorophyll distribution, a Hovmoller diagram (time versus longitude) has been plotted (Fig. 23) for twenty-two months period (January 2005 – October 2006) based on chlorophyll data derived from MODIS sensor (Aqua spacecraft). This figure shows the two-year dynamic of the chlorophyll spatial pattern in the Inner RSA and Sea of Oman. Two yellowish-red zones at the top of this plot represent the signs of monsoons activity – increasing of the chlorophyll content in the Sea of Oman; and two dark-blue zones – represent the inter-monsoon periods. Blue patterns inside the Inner RSA correspond to the low chlorophyll zones in southeast and northwestern parts of Inner RSA (see Fig. 20 for reference). Yellowish-red zone at bottom of the plot is corresponding to Shatt Al-Arab region. The periodicity in the spatial distribution of chlorophyll in the Inner RSA is most probably related to two physical forces – freshwater outflow from Shatt Al-Arab and Karun rivers on northwest and monsoon-induced inflow from Arabian Sea and Sea of Oman in the southern end of the Inner RSA. Combination of these forces forms a pattern of currents in the Inner RSA, described by Reynolds (1993) and represented on Fig. 23 (Reynolds, 1993). It is likely that the winter water masses form there a circulation pattern, described by Reynolds (1993) (Fig. 24) and obtained from the mathematical model by Kampf and Sadrinasab (2006). In general, the present cruise data of Winter 2006 support the above pattern, displayed by the classical T-S plot from the cruise (Fig. 25) – which also indicate that the warmest waters has a lowest salinity and vice versa. Kampf and Sadrinasab (2006) concluded what the winter surface currents are spatially and temporarily highly variable; including eddies that attain diameters of 50–100 km.

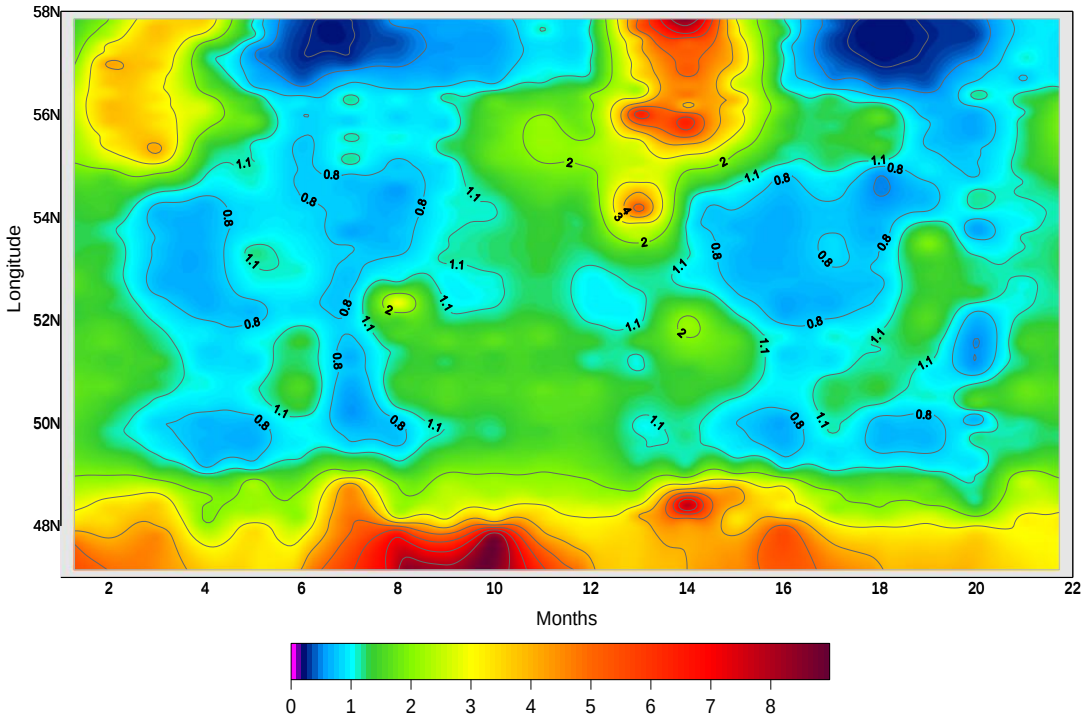

Fig. 23. Hovmoller diagram (time vs. longitude). Distribution of the chlorophyll-*a* in the Inner RSA and Sea of Oman, January 2005 – October 2006, µg/l (satellite derived chlorophyll). The Shatt Al-Arab region is shown at the bottom of the plot; at the top – the Sea of Oman is shown.

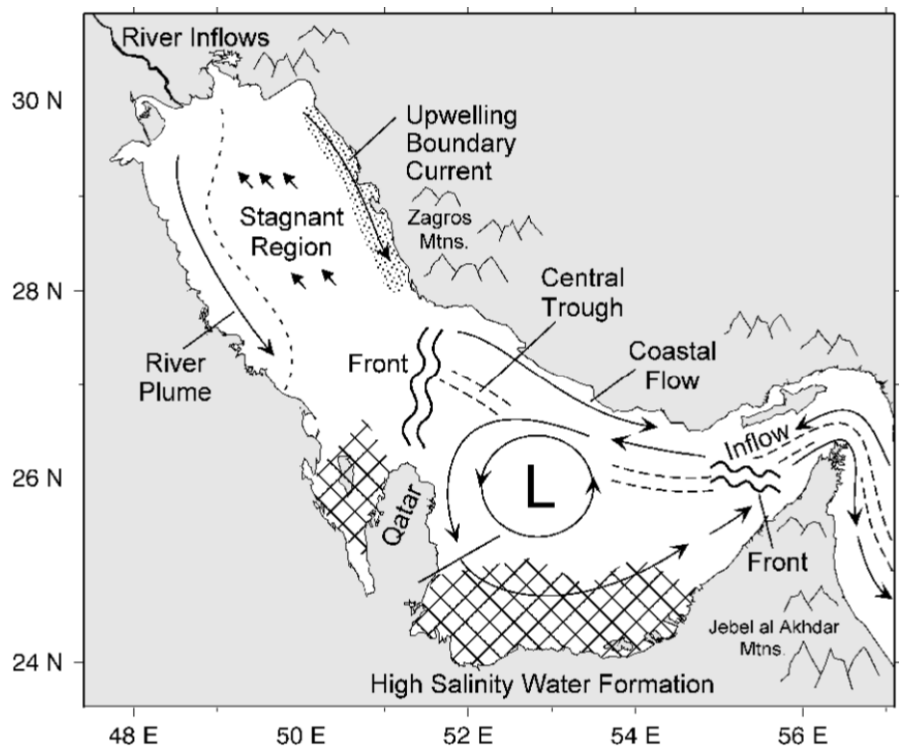

Fig. 24. General winter circulation pattern in the Inner RSA (from Reynolds, 1993).

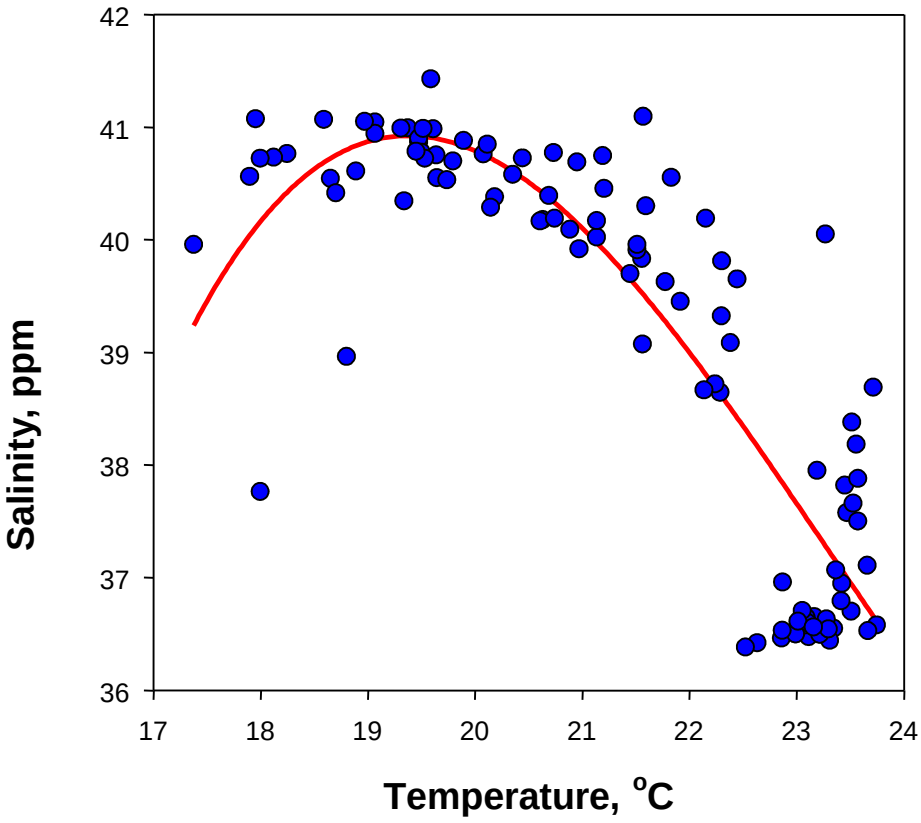

Fig. 25. Temperature-salinity (T-S) diagram for Winter 2006 Cruise (for all stations).

3.5 Nutrients

Concentrations of nutrients varied significantly within the studied area for the winter of 2006 (Table 4). Comparison of surface distributions of temperature, salinity, oxygen, phosphate, nitrate, nitrite, ammonia, turbidity, and silicates all suggest that the RSA should be separated to several zones- the Sea of Oman, the Strait of Hormuz, the Southeastern and the Northwestern Inner RSA regions and relatively narrow central zone, where density front forms and where upwelling-like area along the Iranian coast persist year-round.

The comparison of the three-dimensional maps in Figs. 26-29 (divided by depth layers) shows that the most limiting nutrients for the sampled region were phosphate and nitrate, with low surface values at all Inner RSA locations during winter, except for the southeastern part of the Sea of Oman. Vertical distribution of phosphates demonstrates a

pronounced increase in concentration from surface to bottom. Similar trend was found for nitrates and silicates in general.

Several areas in the RSA showed moderate silicates levels (Fig. 29), which are in contrast with what was reported by Brewer and Dyrssen (1985), that the silicates are very low in the Inner RSA and the RSA during winter.

Dependence between nutrient concentrations and chlorophyll-*a* distribution was not revealed by correlation analysis (Table 5). Only a slight positive relationship between ammonia and chlorophyll was registered ($r = 0.25$, $p<0.01$). High positive correlations ($r \geq 0.5$, $p<0.01$) were noted for both nitrates and phosphates with station depths and longitude.

The spatial distribution of nitrates and phosphates within the studied area indicates decreasing trend of their concentrations from south to north in the Inner RSA, while there was an increase in concentration towards the southern-eastern direction (to the Sea of Oman) during 2006. Significant similarity ($r = 0.93$) was observed between nitrate and phosphate spatial distributions. High negative correlations ($r \leq -0.5$, $p < 0.001$) were observed also between nitrates and phosphates only and latitude, salinity, dissolved oxygen, pH and water density (all these parameters are indicators of water masses, which change mostly with latitude in the Inner RSA). High significant interaction were lacking between nitrite, ammonia and silicate, as well as the other measured environmental factors.

Table 4. Concentration of Nutrients for the Surface, Middle and Bottom waters of the Winter 2006 Cruise

Depth	Value	Nitrate, NO_3, µg/l	Nitrite, NO_2, µg/l	Silicate, SiO_2, µg/l	Phosphate, PO_4, µg/l	Ammonia, NH_3, µg/l
Surface	Average ± STD	29.11 ± 48.33	1.39 ± 2.59	27.13 ± 52.34	14.67 ± 54.02	10.47 ± 9.65
	Minimal value	0.00	0.00	0.00	0.00	0.45
	Maximal value	270.97	15.63	303.77	448.00	38.07
	N of samples	75	75	74	73	71
Middle	Average ± STD	120.48 ± 148.25	15.13 ± 19.88	52.28 ± 58.28	23.71 ± 23.96	9.26 ± 8.02
	Minimal value	0.00	0.00	0.00	0.00	0.82
	Maximal value	568.17	72.93	304.83	100.33	36.40
	N of samples	76	76	75	76	71
Bottom	Average ± STD	345.32 ± 233.62	18.82 ± 29.95	140.49 ± 85.52	63.92 ± 43.71	8.65 ± 6.56
	Minimal value	5.30	0.00	0.00	0.00	0.57
	Maximal value	804.13	170.97	324.43	247.33	25.37
	N of samples	75	75	74	75	71
Overall	Average ± STD	164.22 ± 111.89	12.09 ± 11.73	73.55 ± 52.16	34.06 ± 30.90	9.46 ± 7.73
	Minimal value	6.33	0.00	0.00	0.00	0.96
	Maximal value	413.36	58.79	311.01	221.00	32.51
	N of samples	76	76	75	76	71

Table 5. Pearson Correlation Matrix (surface + middle + bottom) for Results of the Winter 2006 Cruise

	Depth	Latitude	Longitude	Chl-Lab	Phaeo-Lab	Chl-CTD	Temperature	Salinity	Dis. oxygen	pH	Turbidity	Density	NO_2	NO_3	NH_3	PO_4	SiO_2
Depth	1.00																
Latitude	-0.37**	1.00															
Longitude	0.40**	-0.82**	1.00														
Chl-Lab	-0.03	-0.13	0.21	1.00													
Phaeo-Lab	0.00	-0.17	0.31**	0.67**	1.00												
Chl-CTD	0.00	-0.08	0.10	0.81**	0.53**	1.00											
Temperature	0.20	-0.76**	0.87**	0.20	0.29**	0.12	1.00										
Salinity	-0.39**	0.59**	-0.87**	-0.34**	-0.40**	-0.21	-0.72**	1.00									
Dis. oxygen	-0.42**	0.58**	-0.68**	0.15	0.00	0.25*	-0.43**	0.53**	1.00								
pH	-0.33**	0.40**	-0.56**	-0.14	-0.16	-0.04	-0.38**	0.60**	0.54**	1.00							
Turbidity	-0.13	0.16	0.05	0.22	0.25*	0.11	0.02	-0.13	-0.04	-0.18	1.00						
Density	-0.35**	0.66**	-0.90**	-0.34**	-0.40**	-0.22	-0.84**	0.98**	0.48**	0.56**	-0.10	1.00					
NO_2	0.24*	-0.26*	0.26**	-0.04	0.08	-0.08	0.16	-0.26*	-0.28*	-0.21	0.03	-0.22	1.00				
NO_3	0.48**	-0.58**	0.72**	0.04	0.14	-0.09	0.42**	-0.68**	-0.82**	-0.56**	0.05	-0.61**	0.29**	1.00			
NH_3	-0.05	-0.10	0.18	0.25*	0.17	0.10	0.16	-0.21	-0.03	-0.13	0.20	-0.21	0.15	0.05	1.00		
PO_4	0.56**	-0.60**	0.74**	0.08	0.18	-0.03	0.43**	-0.75**	-0.80**	-0.61**	0.05	-0.68**	0.35**	0.93**	0.10	1	
SiO_2	0.15	-0.13	0.13	-0.15	-0.09	-0.13	0.09	-0.07	-0.36**	-0.19	-0.01	-0.05	0.09	0.29	-0.03	0.319**	1.00

* - $p < 0.01$, ** - $p < 0.001$

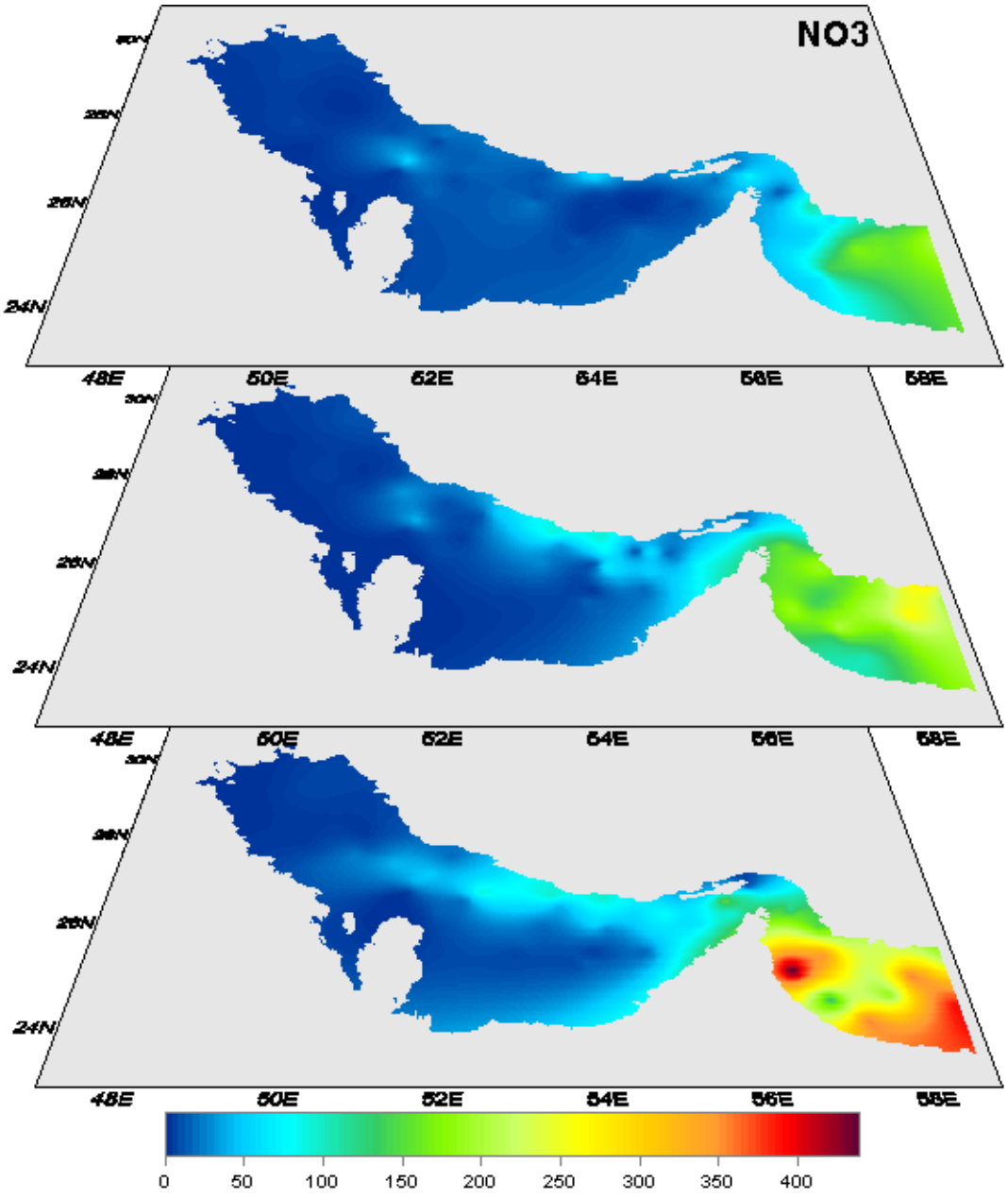

Fig. 26. Spatial distribution of nitrates (µg/l) in the RSA, Winter 2006.

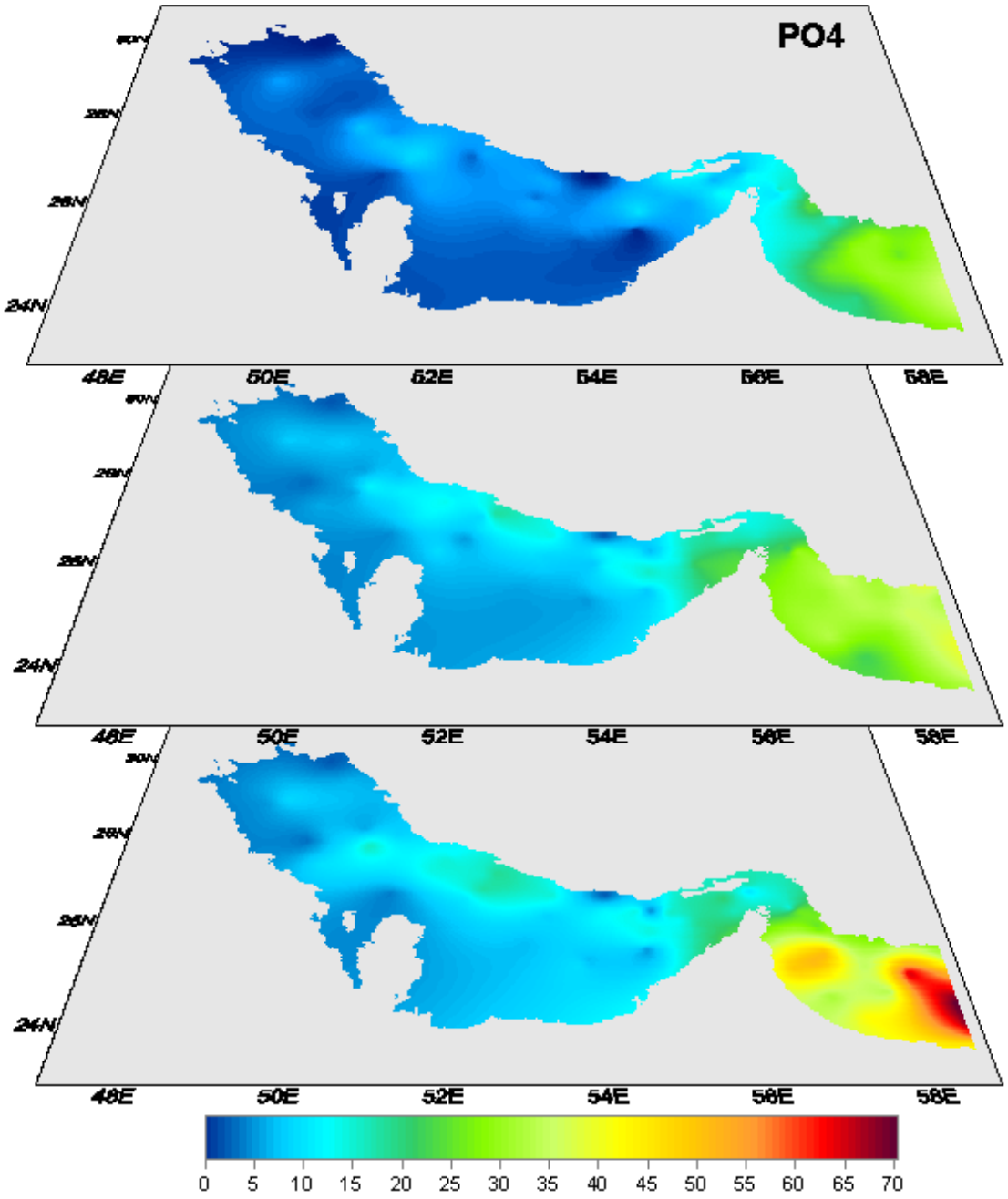

Fig. 27. Spatial distribution of phosphates (µg/l) in the RSA, Winter 2006.

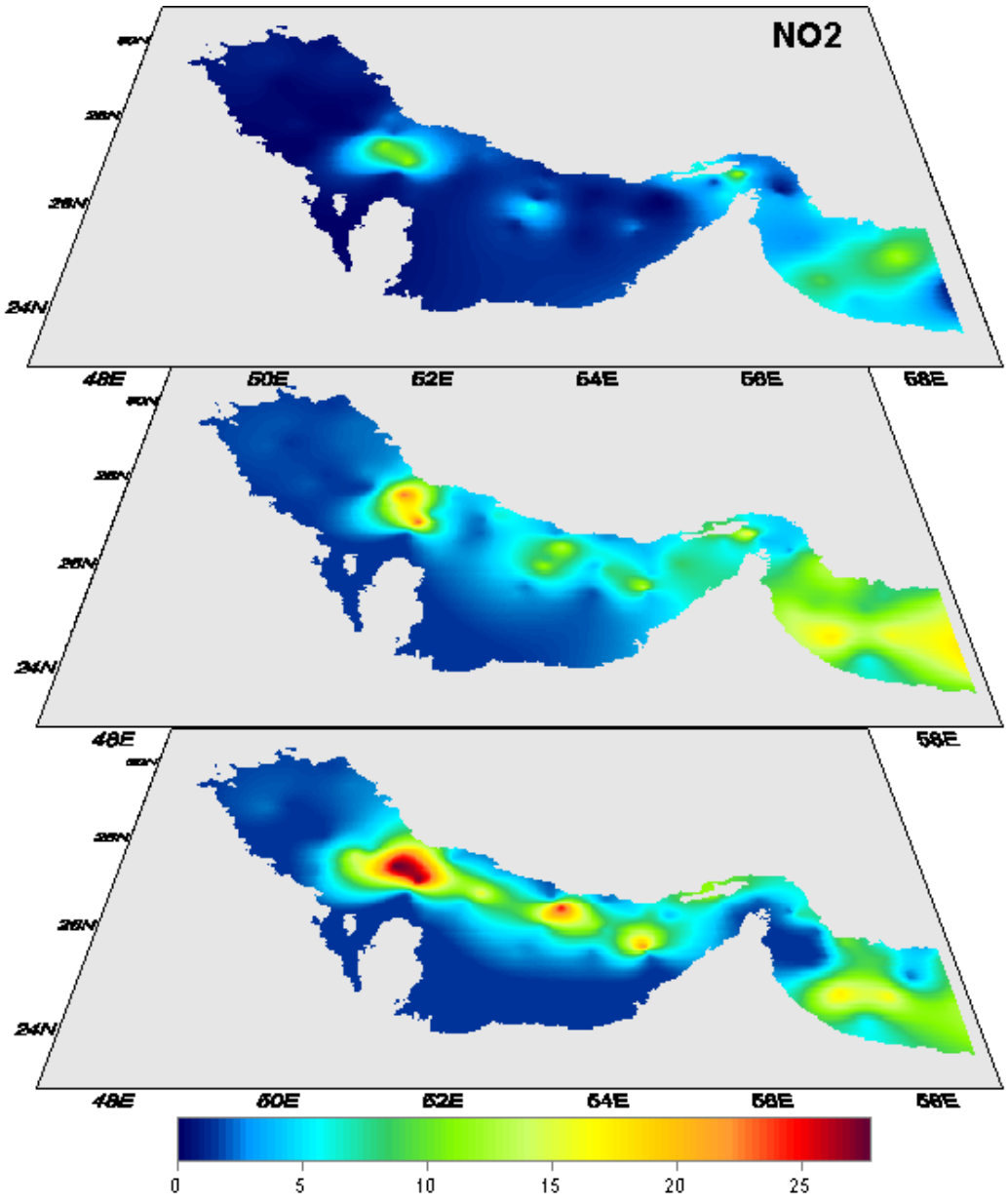

Fig. 28. Spatial distribution of nitrites (µg/l) in the RSA, Winter 2006.

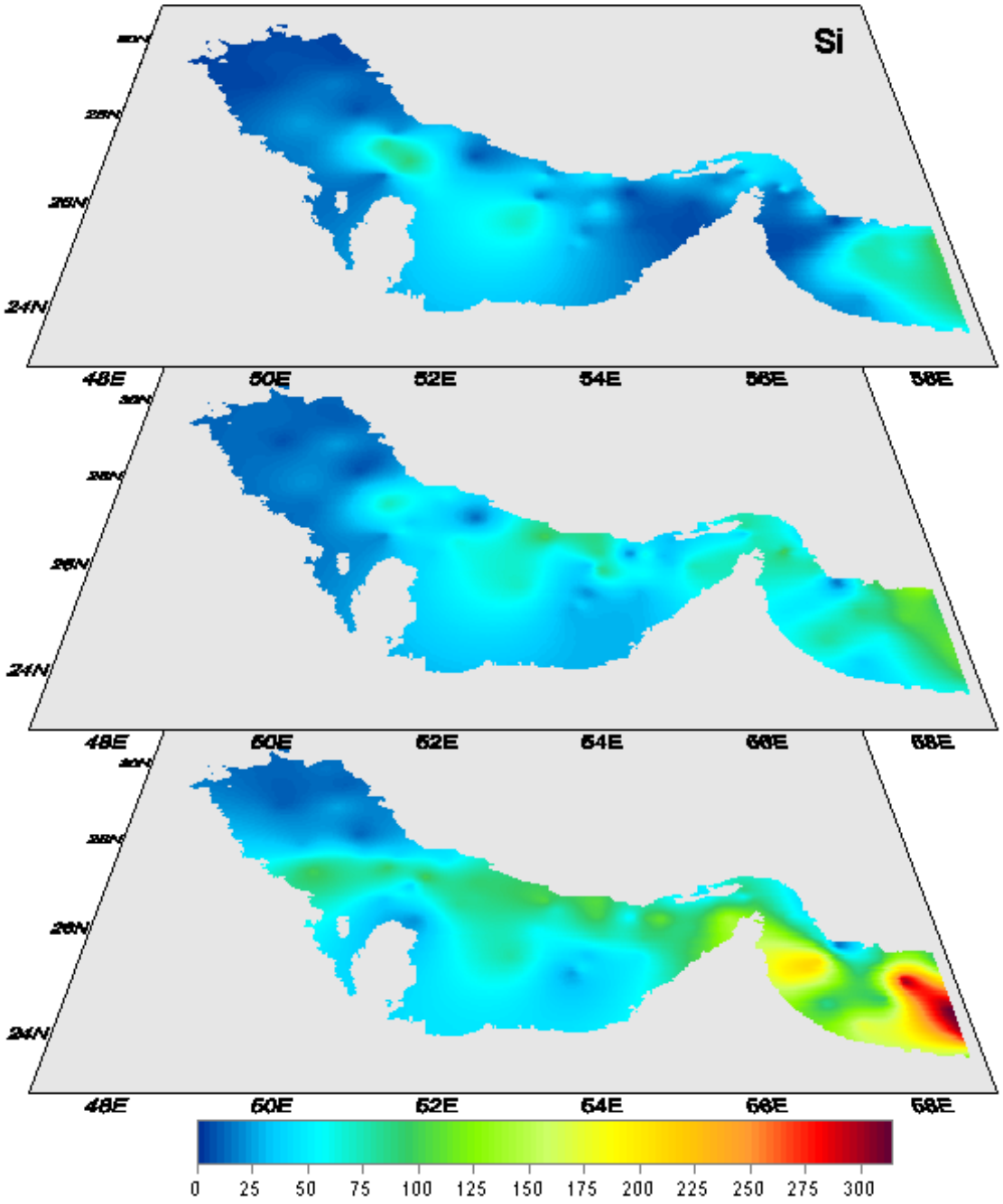

Fig. 29. Spatial distribution of silicates (µg/l) in the RSA, Winter 2006.

3.6 Comparisons between Winter 2006 and Summer 2001

Nutrients concentrations were different for Summer 2001 compared to Winter 2006 for all the measured nutrients (Tables 4 and 6). Vertical distribution of nutrients concentrations within the water column was not uniform.

Unfortunately, for the concentration of chlorophyll, we could compare only the approximate *in-situ* values obtained from the filed fluorometer for the above two seasons (Winter 2006 and Summer 2001), because we did not have acid corrected chlorophyll data for Summer 2001 and only surface nutrients concentrations were available for 2001. The data from the Summer 2001 cruise was interpolated by Kriging methods, shown in Fig. 30.

It is clear from Fig. 31 that during the summer time, surface chlorophyll values were much lower, than during winter. Central regions of the Inner RSA, which characterizes very low chlorophyll values, can be comparable with oligotrophic waters of the open ocean. Only one zone, near the Shatt Al-Arab River outflow clearly demonstrated moderate chlorophyll concentrations. The zone close to Shatt Al-Arab deltaic system also can be described as area with highest water density during summer, and waters near southern shore of the Inner RSA appeared denser as well (Fig. 32). However, during summer water density did not correlate directly with the surface chlorophyll concentrations, when comparing between the maps of Figs. 31 and 32.

Most probably, during Summer 2001, surface chlorophyll distribution in the Inner RSA was regulated mostly by available nutrients. Since their concentrations are low during summer (Fig. 31), only river outflow and re-suspension of the bottom sediments in shallow waters can support a moderate phytoplankton growth. As contrasted with summer season, winter distribution of chlorophyll was more contributed by water density, because nutrients are not limiting the phytoplankton distribution during winter.

Comparison between *in situ* measured chlorophyll for Summer 2001 and satellite-derived pigments (during August 2001) demonstrated an acceptable correspondence between spatial distributions of the above two data sets. However, the range of chlorophyll, derived from SeaWiFS data, was higher, because correct recalculations can be processed only by regional remote sensing algorithms for chlorophyll-*a*. In general, remote sensed chlorophyll confirms the *in situ* chlorophyll distribution in the open parts of the Inner RSA (Fig. 33), where standard OC3 algorithm is working well, comparable with waters of the open ocean.

Table 6. Concentration of Nutrients for the Surface, Middle and Bottom waters of Summer 2001Cruise

Depth	Value	Nitrate, NO_3, µg g/l	Nitrite, NO_2, µg g/l	Silicate, SiO_2, µg g/l	Phosphate, PO_4, µg g/l	Ammonia, NH_3, µg g/l
Surface	**Average ± STD**	41.07 ± 53.44	3.06 ± 3.34	36.32 ± 32.13	12.35 ± 8.56	5.86 ± 4.72
	Minimal value	0.95	0.00	1.45	1.01	1.00
	Maximal value	205.41	14.69	208.53	36.11	33.06
	Size	83	81	82	82	81
Middle	**Average ± STD**	72.42 ± 78.58	6.53 ± 6.12	67.32 ± 128.38	16.19 ± 11.02	6.19 ± 4.22
	Minimal value	0.97	0.01	6.75	1.34	0.27
	Maximal value	318.63	25.71	1181.37	43.70	29.26
	Size	83	81	82	82	81
Bottom	**Average ± STD**	97.22 ± 113.51	6.98 ± 7.24	93.66 ± 133.73	18.37 ± 15.17	6.14 ± 3.71
	Minimal value	1.29	0.00	7.31	1.41	0.49
	Maximal value	451.52	28.13	1152.94	70.63	19.31
	Size	83	81	82	82	81
Overall	**Average ± STD**	70.24 ± 76.61	5.52 ± 4.72	65.77 ± 93.37	15.64 ± 11.05	6.06 ± 3.63
	Minimal value	1.30	0.02	6.12	1.25	0.86
	Maximal value	264.66	21.89	847.61	48.73	21.82
	Size	83	81	82	82	81

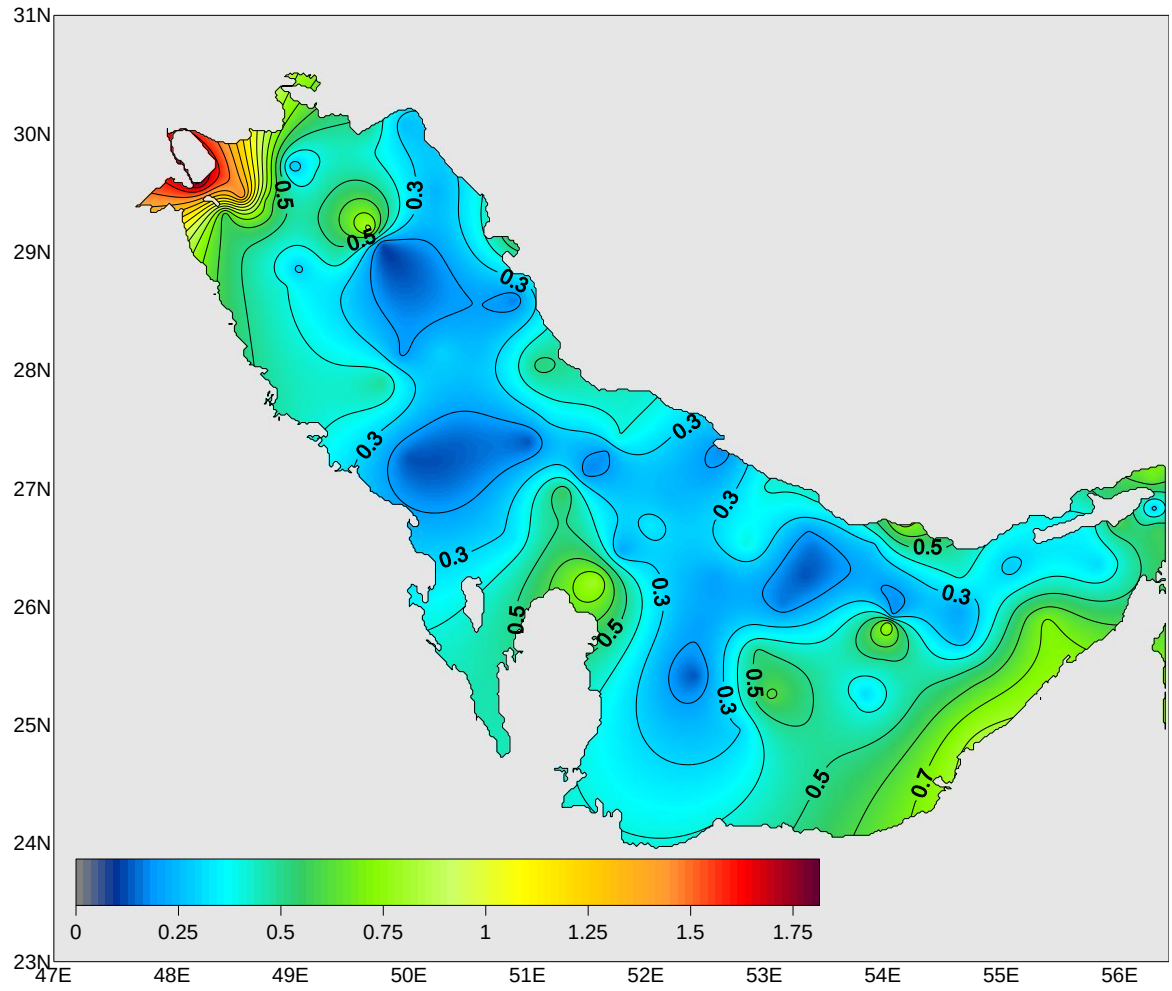

Fig. 30. Surface chlorophyll-*a* (*in situ* data, μg/l), August 2001.

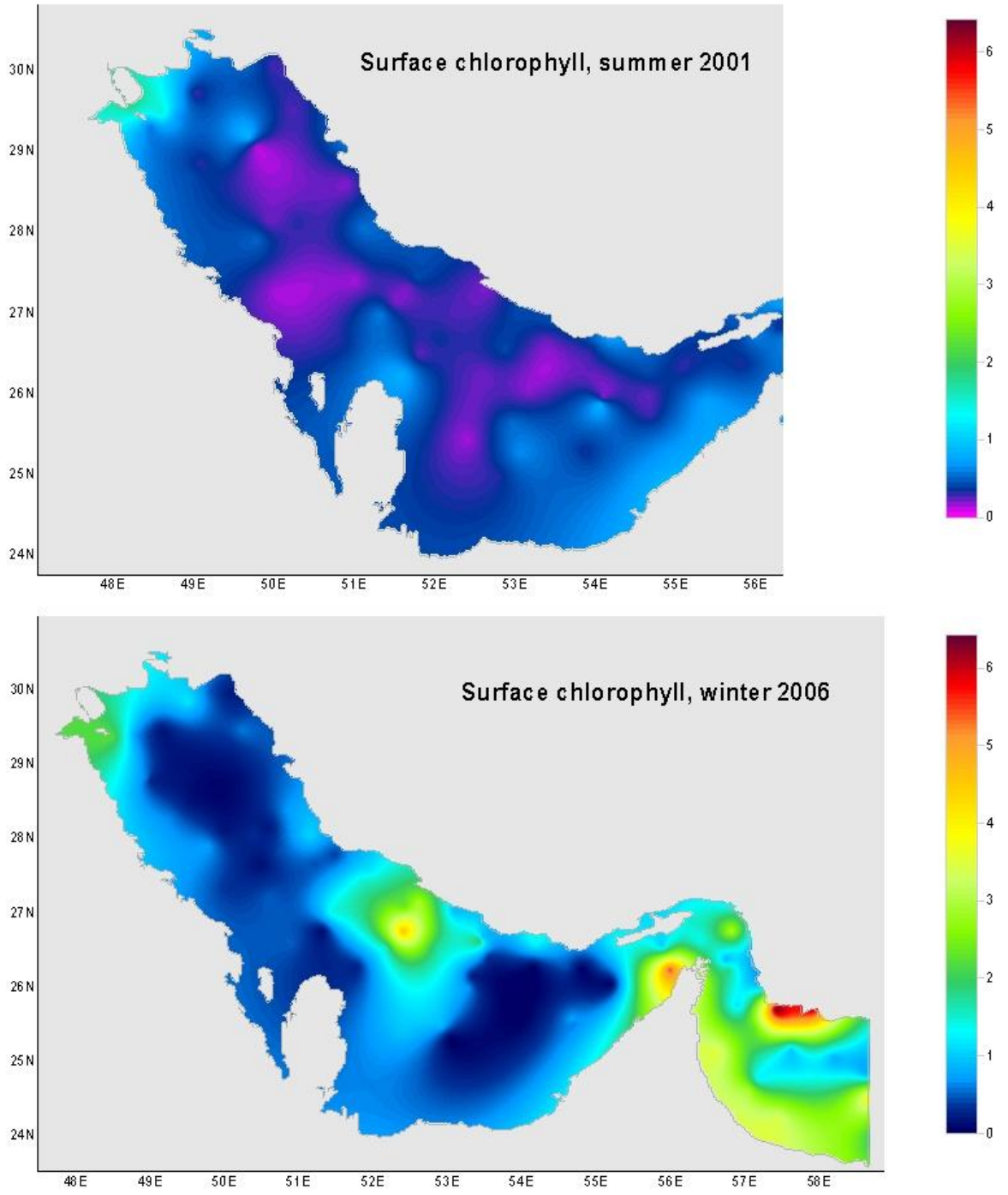

Fig. 31. Comparison between distributions of *in situ* measured chlorophyll-*a* (μg/l) in 2001 and 2006 cruises.

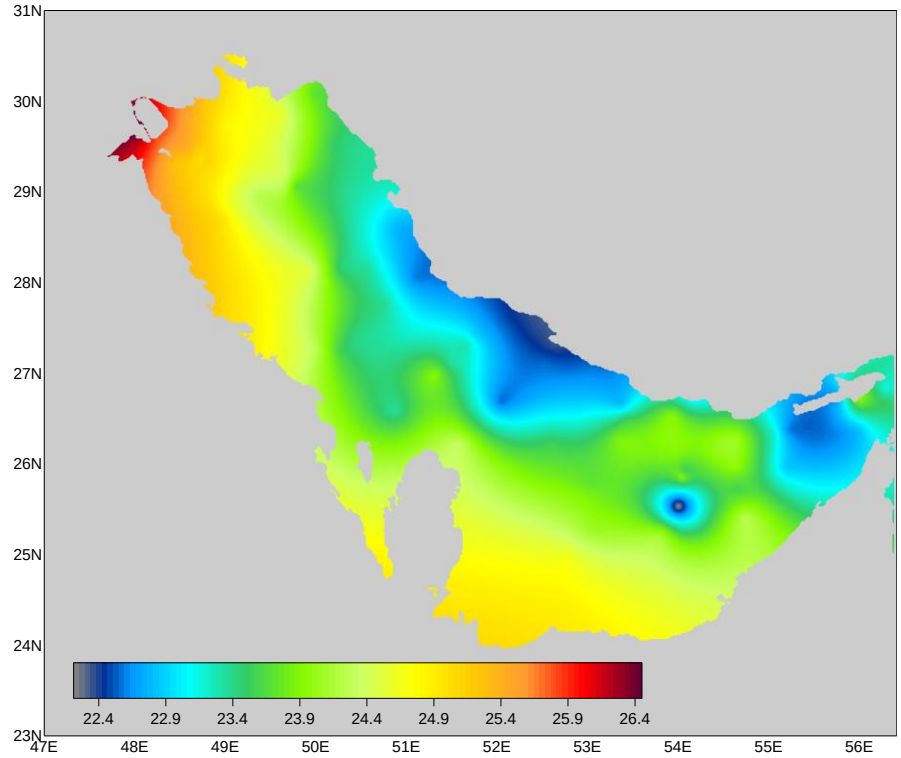

Fig. 32. Surface water potential density (kg/m^3) distribution in Inner RSA, August 2001.

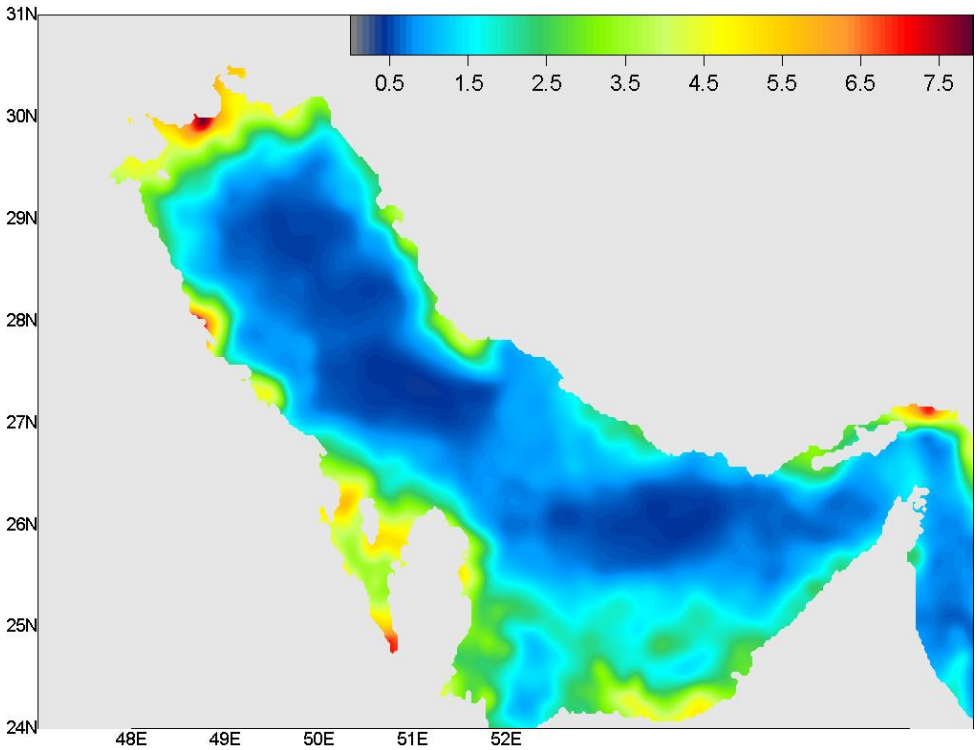

Fig. 33. Spatial distribution of chlorophyll (mg/m^3) in Inner RSA, based on satellite data (SeaWiFS sensor), August 2001.

4. Conclusions

The primary purpose of this report was to produce precise chlorophyll and phaeophytin results for the ROPME samples, and then compare these results with the data obtained from profiling instruments and derived from satellite sensors. The postulated hypotheses for this study were:

- There is spatial distribution in the physico-chemical values and the chlorophyll concentrations in the RSA
- The chlorophyll concentration results obtained from the analysis of the Winter 2006 samples are comparable to previous published results for chlorophyll
- There is a difference between the spatial chlorophyll distributions in Winter 2006 compared to Summer 2001

This study confirmed the above hypothesis, and the following main points summarize the key findings of this study:

- The study results indicate that the RSA has heterogeneity horizontal and vertical distribution for its physicochemical as well as its biological (chlorophyll) properties
- There is variability in the spatial distribution of seawater temperature, salinity, density, fluorescence, turbidity, oxygen, nutrients and chlorophyll. Difference in vertical distribution is evident for temperature, density, fluorescence, turbidity, nutrients and chlorophyll
- The study was able to demonstrate significant differences in the chemical and biological characteristics of the RSA waters between Summer 2001 and Winter 2006
- Comparison between Winter and Summer chlorophyll distribution indicates a much lower surface chlorophyll concentrations during summer in the Inner RSA (maximum 1.6 μg/l). It can be explained by phytoplankton growth limitation by nutrients during August, when stock of nutrients was depleted due to the uptake by the microalgae, during the period of low river outflow in the Inner RSA
- The chlorophyll concentration, determined by *in-situ* fluorometer, was significantly lower than laboratory measured chlorophyll

- Average concentrations of phaeophytin were significantly lower than chlorophyll concentrations
- The mean concentration of chlorophyll-*a* for the water column was 2.09±1.92 µg/l. Average concentrations of chlorophyll-*a* in the studied area during the Winter Cruise of 2006 were 2.54±2.16, 2.05±1.79 and 1.68±1.68 µg/l for surface, middle and bottom layers, respectively
- Average concentrations of phaeophytin were significantly lower than chlorophyll concentration. Mean phaeophytin values were 0.44 ± 0.75, 0.29 ± 0.38. 0.29 ± 0.47 µg/l for surface, middle and bottom, respectively. The water column mean concentration of phaeophytin was 0.34±0.56 µg/l
- The highest mean concentrations for chlorophyll were recorded at the Strait of Hormuz (Transect 14a), in the Sea of Oman (transect 16), in the middle of the Inner RSA (transect 6, Inner RSA from Iran to Qatar), and off Shatt Al-Arab and Karun deltas
- Analysis of the correlations between chlorophyll concentrations and meteorological parameters was not performed due to uncertain data obtained from shipboard automatic weather station

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