

Atlas of Chlorophyll-*a* concentration for the North Sea based on MERIS imagery of 2003

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This Atlas is the product of the EC-FP5 REVAMP project

Published at the Vrije Universiteit, Amsterdam

Edition 3.0

23 May 2005

Colophon

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REVAMP:

REgional **VA**lidation of **MERIS** chlorophyll
Products in North Sea coastal waters.

REVAMP is an EC-FP5 project commissioned by:

European Commission under contract nr : EVG1-CT- 2001-00049

This atlas contains Chlorophyll-a maps based on:

MERIS Reduced Resolution images: source ESA
MERIS Full resolution images: source ESA
MERIS FR Surface Reflectances were kindly provided by the
ACRI-ST processing - Coastwatch GMES service

Map production:

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Institute for Environmental Studies (IVM),

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ISBN 90-5192-026-1

Preface

This atlas of the North Sea contains maps of Chlorophyll-a concentrations based on remote sensing images. Chlorophyll-a is one of the main photosynthetic pigments in phytoplankton and can be used to assess the degree of eutrophication of the water. The concentration of Chlorophyll-a is derived from the sea surface, at about the first attenuation depth, which is between 2 to 15 meters, depending on the turbidity of the water.

All maps are derived from the water leaving radiance reflectance spectra of the Medium Resolution Imaging Spectrometer (MERIS), after atmospheric correction. MERIS is operated on board the Earth Observation Satellite ENVISAT of the European Space Agency ESA.

The EC-FP5 project REVAMP (Regional Validation of MERIS chlorophyll-a Products in North Sea coastal waters EVG1-CT- 2001-00049 REVAMP) ran from 1st February 2002 to 31 January 05. The primary objective of the project was to support the monitoring of eutrophication in the North Sea and the effects of nutrient reduction by measuring and validating a key bio-geo-physical parameter (Chlorophyll-a concentration) using European Space Agency ENVISAT/MERIS satellite observations.

Over the three years of the project we have had suspense (will the launch of Envisat succeed..), we have analysed a lot of North Seawater through our spectrometers and we have learned that the science of retrieving Chlorophyll-a in these heterogeneous waters is complex.

Through an active participation in the validation of MERIS products, the REVAMP project team gained early insight in the quality of the MERIS water leaving radiances. Our validation measurements have, in turn, contributed to the fine tuning of the atmospheric correction by ESA. The MERIS observations are of high quality and we are grateful to ESA that we could use the complete 2003 MERIS image dataset covering the North Sea to produce this atlas.

Our thanks go to the European Commission for co-funding this research, to the REVAMP Quality Assurance Committee for guiding this project through to its successful fruition and to the Coastwatch End-User Federation for critical evaluation of our prototype results.

Working with the members of the REVAMP team has been a very pleasant and insightful experience and we hope that this book shows and shares something of this positive partnership.

Enjoy the Read!

Please note that the presentation of the maps of Chlorophyll-a concentrations in North Sea in this Atlas has been tailored to the specific requirements of end users (such as monitoring organizations) to highlight the salient Chlorophyll-a features each month.

The choice of colour scale shows less detail of Chlorophyll-a features than is actually present in the maps.

If you require further detail of the Chlorophyll-a images, we urge you to further analyse the daily Chlorophyll-a maps and the monthly and seasonal composites with the data and software available on our REVAMP website

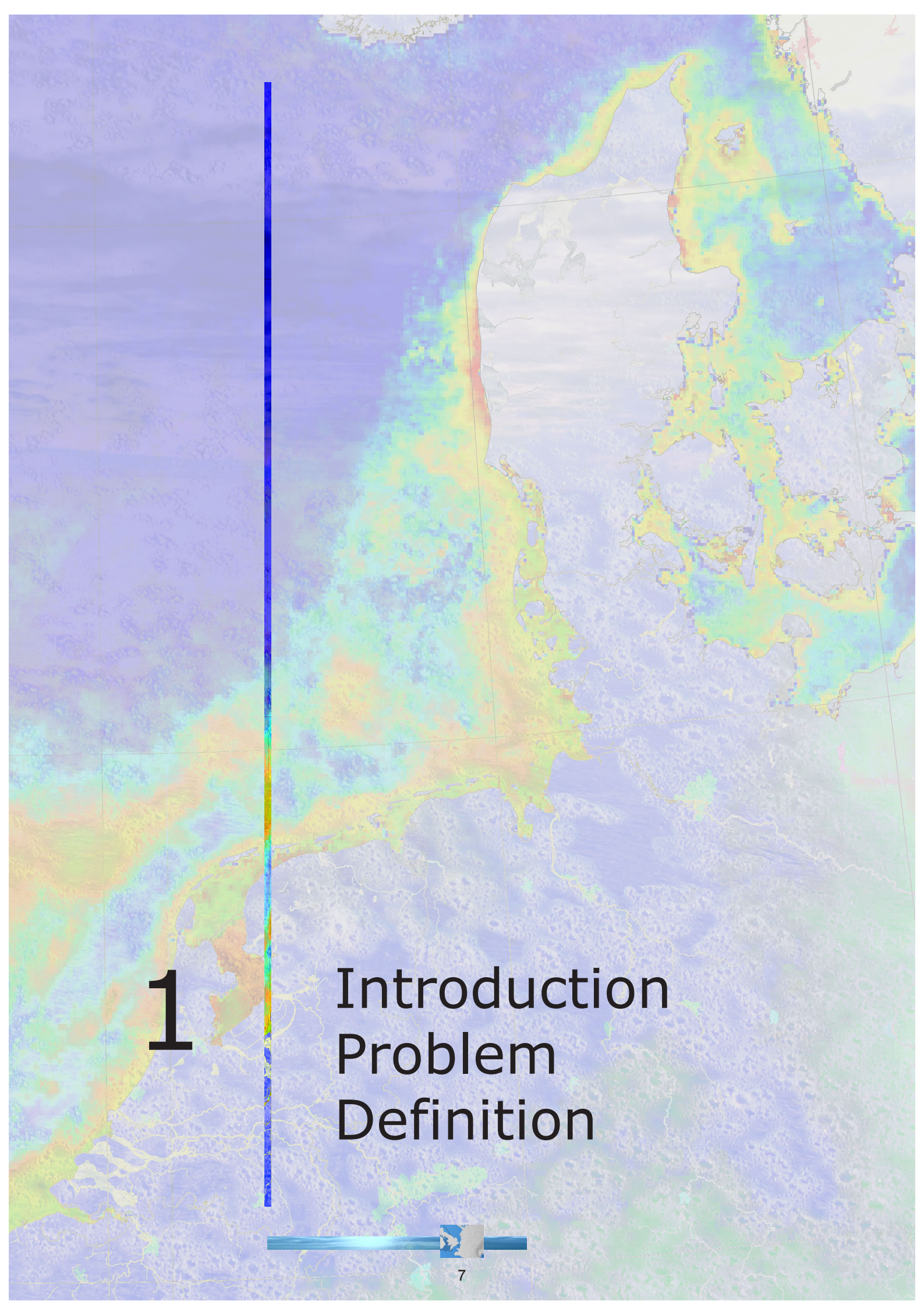
www.brockmann-consult.de/revamp/



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1

Introduction Problem Definition

Introduction

Knowledge of phytoplankton dynamics and distributions in North Sea coastal waters is vital to ensure a scientific basis for coherent management of the coastal environment and the human activities which impact on or benefit from it.

Phytoplankton abundance and species composition can be influenced by anthropogenic nutrient supply from agricultural and industrial sources, and at the same time the fisheries and mariculture industries are affected by phytoplankton abundance, since the plankton form the base of the marine food-web which ultimately limits fish catches and mariculture production.

Furthermore, phytoplankton plays a major role in the marine foodweb through the flow and cycling of carbon and other materials to higher trophic levels that helps to maintain high marine biodiversity.

Monitoring of phytoplankton, which is currently carried out by all North Sea states, is conventionally based on timely and costly water sampling programs. This results in sparse spatial and temporal coverage and gives only a vague impression of the dynamics of phytoplankton in relation to human activities.

Satellite remote sensing of Chlorophyll-a concentrations therefore offers a significant and powerful tool supplementing conventional sampling surveys by providing synoptic observations of the entire coastal zone.

OSPAR eutrophication strategy

All North Sea countries (as well as many neighbouring countries) have signed and ratified the 1992 OSPAR Convention, the current legislation which guides international cooperation on the protection of the marine environment of the North-East Atlantic.

One of the activities of the OSPAR group of countries is to combat eutrophication in order to achieve and maintain a healthy marine environment. "Eutrophication" is officially defined by the OSPAR Commission as "the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned".

One of the criteria used to determine whether a particular marine area has a eutrophication problem is whether maximum or mean Chlorophyll-a concentrations exceed a certain threshold.

In Belgian waters for example, those areas where the annual maximum Chlorophyll-a concentration exceeds a threshold of 15 µg/l are deemed to be eutrophied.

Similar criteria are used by other North Sea countries, though the threshold level may change depending on winter mean and annual mean Chlorophyll-a concentrations.

There is a wide variety in the calculation per nation of a eutrophication threshold exceedence based on Chlorophyll-a levels.

Eutrophication problem areas are identified by comparing aggregated Chlorophyll-a measurements (period mean or maximum levels) with reference values. It is sometimes not clear if reference values are defined for means or maxima.

Elevated assessment levels (50% (25% for Denmark) above their related background concentrations) are in the range of:

- > 2 µg/l Denmark, Sweden*
- > 4,5 µg/l Norway, Dutch and German offshore North Sea*
- > 9-10 µg/l Western Scheldt, Ireland (median values for estuaries)*
- > 10 µg/l UK offshore > 34 salinity*
- > 15 µg/l Belgium, Dutch- and German coast, UK coastal waters <34 salinity*
- > 18-20 µg/l France, Ireland (90 percentile), Ems-Dollard estuary*
- > 22-24 µg/l Wadden Sea.*

Data availability with respect to sampling frequency and spatial coverage was considered to be too low for some areas to make a proper assessment.

On the basis of their assessments it was concluded by a number of Contracting Parties that many of their assessed coastal areas, fjords and / or estuaries, and some offshore North Sea areas, show elevated levels of Chlorophyll-a.

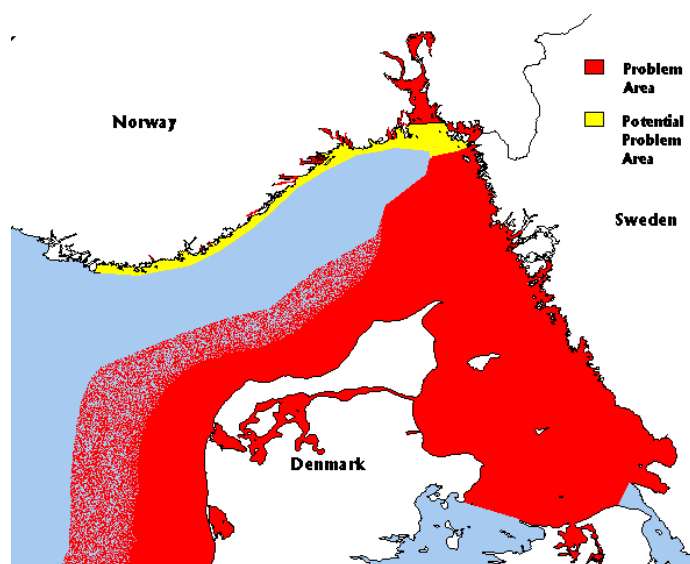




While chemical analysis of water samples taken at sea is likely to remain the main source of data for determination of eutrophication problem areas, satellite Chlorophyll-a maps as provided by the REVAMP project can provide valuable additional information, especially for regions and periods which are missed by the conventional *in situ* monitoring surveys.

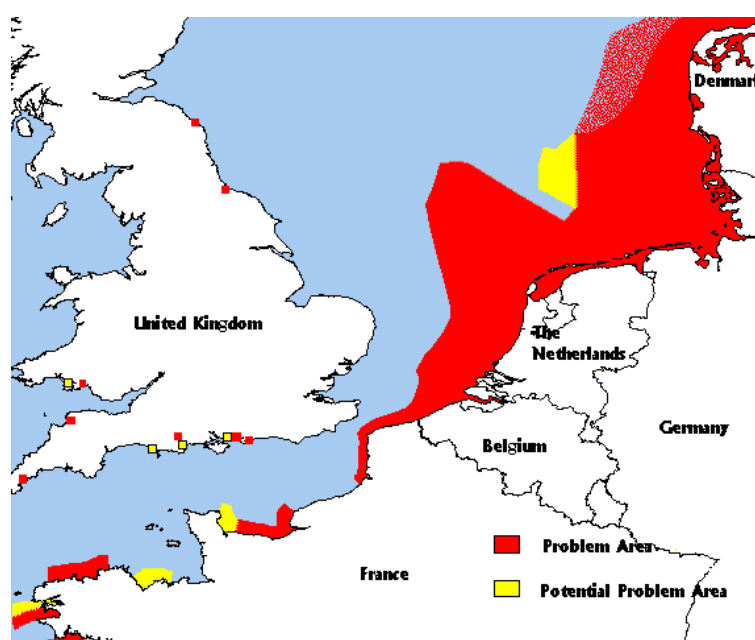
The "OSPAR Integrated Report 2003 on the Eutrophication Status of the OSPAR Maritime Area based upon the First Application of the Comprehensive Procedure" notes in respect of these *in situ* monitoring programmes that:

"data availability with respect to sampling frequency and spatial coverage was considered to be too low for some areas to make a proper assessment".



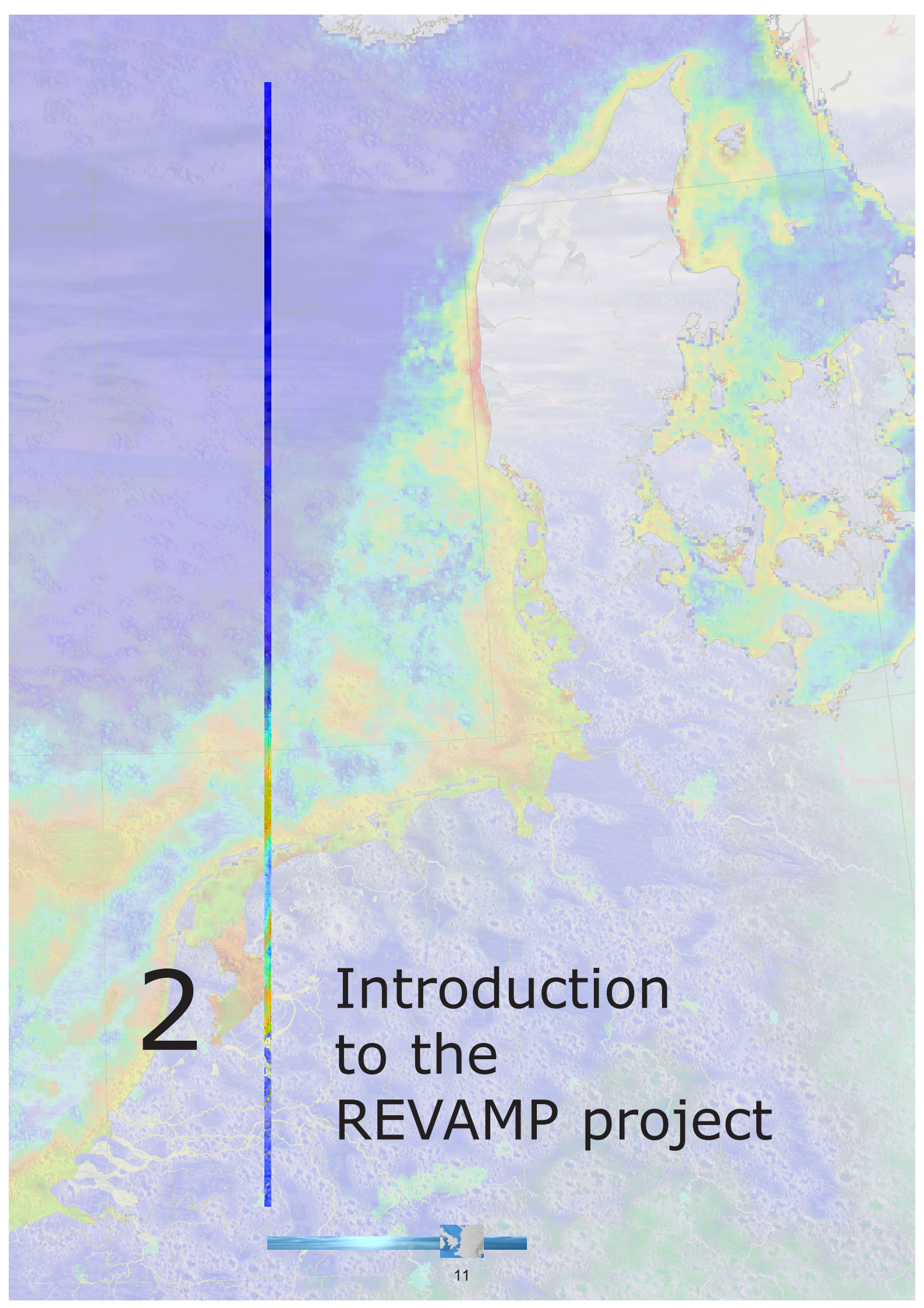
*Kattegat
Skagerrak and
Eastern North
Sea*

Map of eutrophication problem areas in the North Sea, Skagerrak and the Channel taken from the "OSPAR Integrated Report 2003 on the Eutrophication Status of the OSPAR Maritime Area based upon the First Application of the Comprehensive Procedure" Available from: www.ospar.org © OSPAR Commission 2003.



*Southern North
Sea and
Channel*





2

Introduction to the REVAMP project



Introduction to the REVAMP project

The EC-FP5 project REVAMP (REgional VALidation of MERIS chlorophyll Products in North Sea coastal waters EVG1-CT- 2001-00049 REVAMP) started on the 1st of February 2002. Its primary objective was to support the monitoring of the eutrophication status of the North Sea and the effects of nutrient reduction by measuring and validating a key bio-geo-physical parameter (Chlorophyll-a concentration) using ENVISAT/MERIS satellite observations.

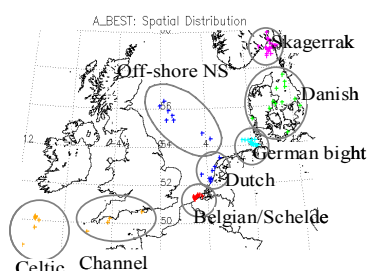
To fulfil this objective, REVAMP addressed the following secondary objectives in corresponding work packages:

WP1 Historic Data	WP2 Regional Algorithm	WP3 In-Situ Cal/Val Data	WP4 MERIS Processor and Confidence Products	WP5 User Requirements Value added prods	WP6 2003 CHL Atlas Of The North Sea
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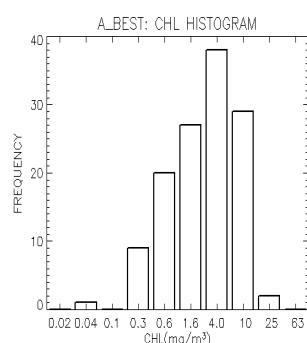
- 1) To collect and analyse historical North Sea data on concentrations and optical properties of optical active constituents of the North Sea. To integrate selected, complete and validated data into one database.
- 2) To use the historical database, together with data collected in 2002/2003, to select parameterise, calibrate and validate bio-optical models and inversion algorithms that are suitable for regional Chlorophyll-a concentration retrieval from MERIS observations.
- 3) To collect a limited, complementary field data-set of high quality observations to further calibrate bio-optical models and inversion algorithms (2002 data), but especially to validate regional Chlorophyll-a products derived from MERIS observations.
- 4) To build a MERIS Regional Chlorophyll-a Products Processor (MEP) based on existing building blocks. Preceding the actual processing, requirements for image suitability and indicators (flags) for Chlorophyll-a product quality will be developed and incorporated into MEP. The products will not only include Chlorophyll-a but also a data quality assessment.
- 5) To develop relevant Value Added Products; to produce a prototype Chlorophyll-a atlas (including prototype Value Added Products) and to liaise with intermediate user consultants to fine-tune the products to user requirements.
- 6) To make the final 2003 ATLAS of Chlorophyll-a and Value Added Products maps, to print and disseminate the atlas and to conduct a final workshop to demonstrate the product and to define future versions in collaboration with the end users.



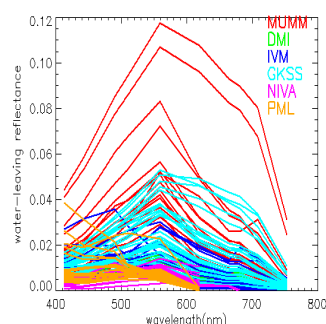
WP1: Historic data collection, quality control and data-base setup



Locations of algorithm selection measurements (A_best dataset)



Chlorophyll-a values of algorithm selection dataset (A_best)



Shipborne measured spectra of MERIS reflectance used for algorithm selection (A_best)

Historic data (also from other programmes such as COASTLOOC, COLORS and MULTICOLOR) have been collected in a common format, and have been made available to all project partners in the form of a very large Case-II water data-base. Together with institute-managed campaigns data from 18 data-sets were collected.

In total 15 single parameters were catalogued, of which 30.000 measurement values were compiled. The database now contains, for 11 types of spectra, a total of 3.300 measured spectra. These data, primarily intended for algorithm selection and validation, now represents a valuable resource for increasing data mining.

The REVAMP database is basically a relational database system. Some additions are specifically made for REVAMP as a subset of tables and a special user interface allowing data-retrieval in different formats. It is accessible via internet by means of standard browsers with a java implementation. The address is:

<http://www.mumm.ac.be/datacentre/Databases/REVAMP/>

The documentation is open to the public. For data retrieval, a user-ID/password combination has been provided to projects-partners.

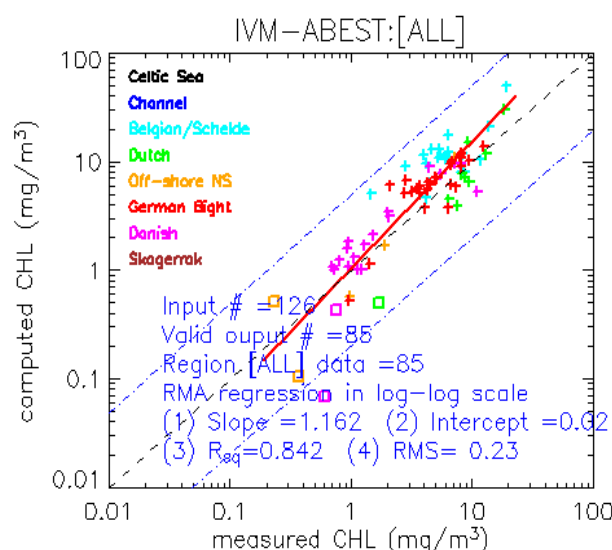
WP2 Algorithm selection and calibration

Out of a suite of North Sea algorithms the most appropriate algorithm to retrieve Chlorophyll-a concentrations from MERIS was selected.

It has the advantage of being adaptable for other regions.

The applicability of the algorithm was tested with real and simulated data and match-up data sets (the locations of the final evaluation set (A-best) of shipborne spectral measurements, accompanying Chlorophyll-a values, measured spectra in MERIS bands and the algorithm testing results can be found in the figures on this page).

Despite of the fact that the MERIS data were not fully stable in the early stages of the project (e.g. atmospheric correction), testing of the REVAMP reference algorithm was successful.



Results of the comparison between laboratory observed Chlorophyll-a and Chlorophyll-a retrieved from the A_best dataset of reflectance spectra with the preferred REVAMP algorithm.

WP2 Algorithm description

Out of a suite of North Sea algorithms the most appropriate algorithm to retrieve Chlorophyll-a concentrations from MERIS was selected. It has the advantage of being adaptable for other regions. The applicability of the algorithm was tested with real and simulated data and match-up data sets. Despite of the fact that the MERIS data were not fully stable in the early stages of the project (e.g. atmospheric correction), testing of the REVAMP reference algorithm was successful.

The REVAMP algorithm is a new water quality algorithm to retrieve concentrations from reflectance spectra in turbid coastal waters. Because of the optical complexity of such waters, frequently used simplified equations were abandoned in favour of the more sophisticated Hydrolight radiative transfer code (1)+(2).

This code can predict the observed remote sensing reflectance under any angle as a function of absorption and scattering within the water, taking into account the angular distribution of the downwelling radiance and the transmission through the air-water interface for a given wind speed.

Approximating the Hydrolight output with high degree polynomial functions substantially reduced the execution time of the algorithm. The use of absorption and scattering as independent variables instead of the concentrations has the big advantage that conversion of concentrations to optical properties (by multiplication, probably with a power-law factor, with the specific inherent optical properties or SIOP) remains outside the model. As a result, the SIOP can be defined on a regional or even pixel-by-pixel basis without the need to run Hydrolight or recalculate the polynomial coefficients.

To retain the angular dependence of the remote sensing reflectance, and to include the pure water volume scattering function for each wavelength, the polynomial coefficients are computed and stored for each combination of MERIS-wavelength, solar zenith, viewing zenith and differential azimuth angle.

The inversion of the forward model is accomplished by fitting the modelled remote sensing reflectance to a measured reflectance spectrum, while varying the concentrations of Chlorophyll-a, Total Suspended Matter and Coloured Dissolved Organic Matter.

The 'best-fit' concentrations belonging to the minimum difference are then assumed to be the most likely concentrations corresponding to the measured spectrum. The difference CHI^2 is defined as the squared difference between the differences in reflectance between consecutive bands.

Band differences are used instead of absolute reflectance because the band differences of wavelength bands that are close together are less vulnerable for wavelength independent errors due to atmospheric correction errors.

Because the remote sensing reflectance is a nonlinear function of the concentrations, the Levenberg and Marquard non-linear optimization method was implemented because it is well established, fast and reliable.

Apart from the concentrations, the algorithm also calculates a statistical measure of the so-called goodness-of-fit and standard errors in the retrieved concentrations.

REVAMP partners provided 15 algorithms (simple formula, matrix inversion, neural network, etc.)

A preferred algorithm was chosen based on predefined evaluation criteria:

Accuracy:

*performance vs in situ
(error norm: a weighted
combination of slope,
intercept, R^2 , RMS-error)*

Regionality:

*possibility to adapt for
different regions*

Robustness:

variety of conditions

Error estimation:

*products includes an error
estimate*

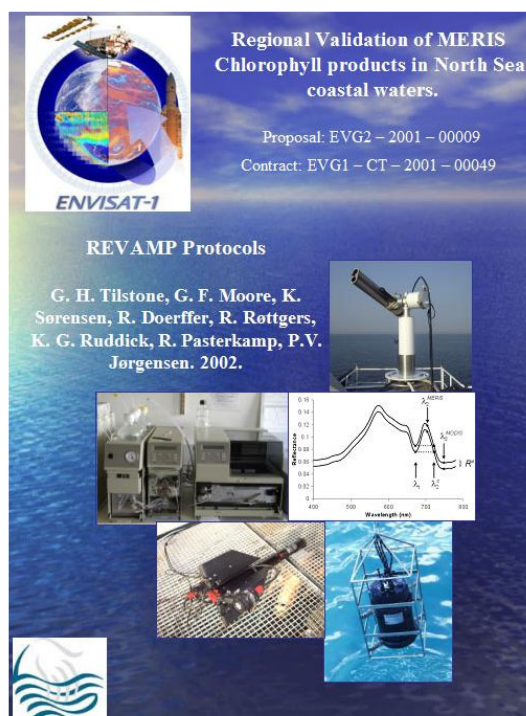
Error sensitivity:

*minimisation of impact of
upstream errors e.g. from
atmospheric correction*

- (1): C. D. Mobley. *Light and water; Radiative transfer in natural waters*. Academic Press, London, 1994.
(2): C. D. Mobley. *Hydrolight 4.0 users' guide*, 1998.



WP3 regional in-situ sampling for algorithm calibration and validation



Measurement protocols and round robin exercises were consolidated in REVAMP and yielded good agreement in the retrieval results between the various partners measuring the Chlorophyll-*a* concentrations in phytoplankton in different ways.

In WP3 the concentration, and spectra of the inherent optical properties of the water column in North Sea environments were determined according to REVAMP protocols and the data was quality control checked following the REVAMP data quality control guidelines.

The data was then used for the testing and development of algorithms for the production of the final Chlorophyll-*a* Atlas.

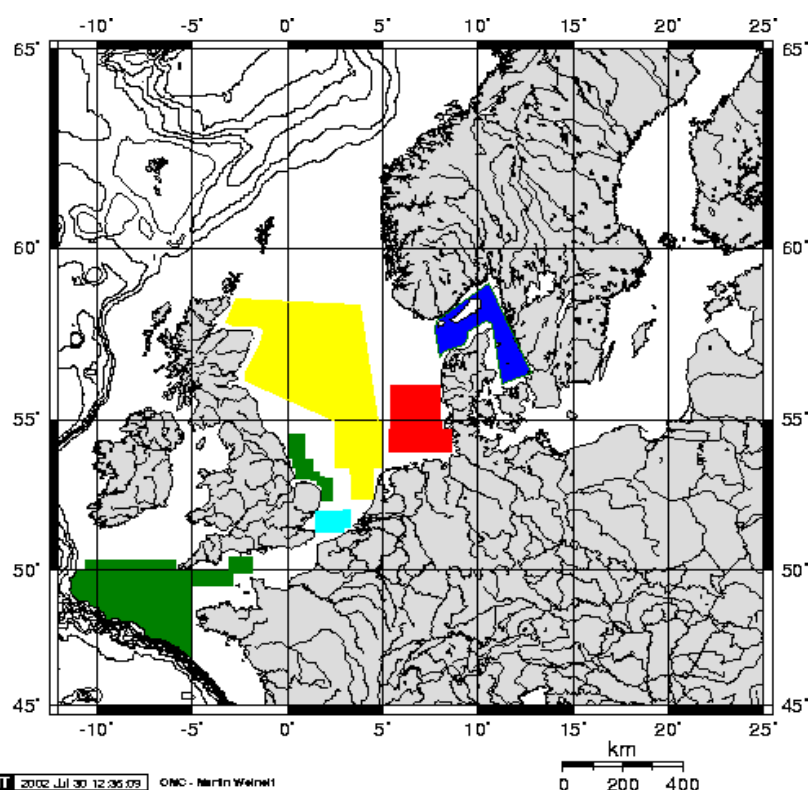
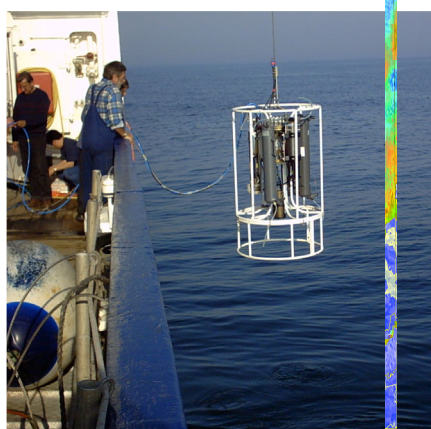
Data collection was done in 2002 and 2003 in the period March to September. 22 cruises were undertaken in 6 major areas of the North Sea, Western Channel and Celtic Sea.

11 ship days were also undertaken in the Skagerrak. To maximize MERIS match-ups for validation purpose, PML, MUMM, NIVA and IVM also used opportunistic "blue skies" sampling regimes at time series sites in the North Sea and Western Channel. Data collected from the ESA and Norwegian Space Centre project VAMP (Validation of MERIS data Products) contributed to the algorithm development and are now a part of the REVAMP database.

The REVAMP database is now one of the largest datasets documenting the inherent optical properties of Case 2 European shelf seas and extends and complements data collected in previous EU projects; COLORS & COASTLOOC.

The database has been used successfully to validate, test and compare the proposed 15 bio-optical Case 2 Chlorophyll-*a* algorithms.

Principal areas sampled from March to September 2003 under the REVAMP contract.



WP4 MERIS processor definition and construction

The **REVAMP** MERIS processor has been built as a standalone software package for fast processing of satellite images based on the selected retrieval algorithm.

Through the parallel development of the ESA BEAM data processing software the **REVAMP** processor could be established within a quality-controlled environment.

Some technical data:

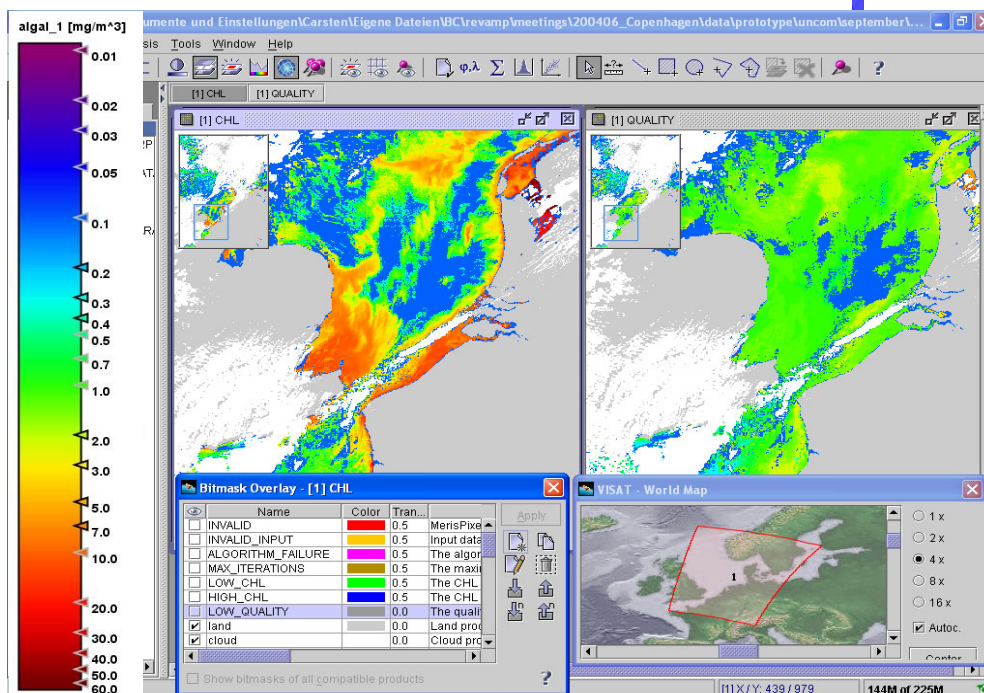
The **REVAMP** MERIS Processor was implemented using the BEAM Application Programming Interface (API) (BEAM = Basic ENVISAT AATSR and MERIS Toolbox). BEAM is available free of charge at:

<http://www.brockmann-consult.de/beam/downloads.html>

Some advantages are:

- 1) BEAM is a widely used standard for working with MERIS data
- 2) BEAM is coded in Java
- 3) The REVAMP map files can be analysed with the image processing functionalities of BEAM because the product format is BEAM DIMAP

The MERIS Processor is capable of handling large data volumes and multiple input data files



The **REVAMP** production processor is specifically set-up to handle the production of aggregated products, mainly temporal composites of a large number of MERIS scenes.

WP5 Value added products definition

Based on individual Chlorophyll-a maps REVAMP should develop demonstration Value-Added Products (VAPs) for the North Sea Region. Therefore prototype Chlorophyll-a maps were produced with specifications based on earlier user requirements inventories. This prototype atlas was subsequently discussed with a forum of end-users.

REVAMP's Chlorophyll-a products workflow.

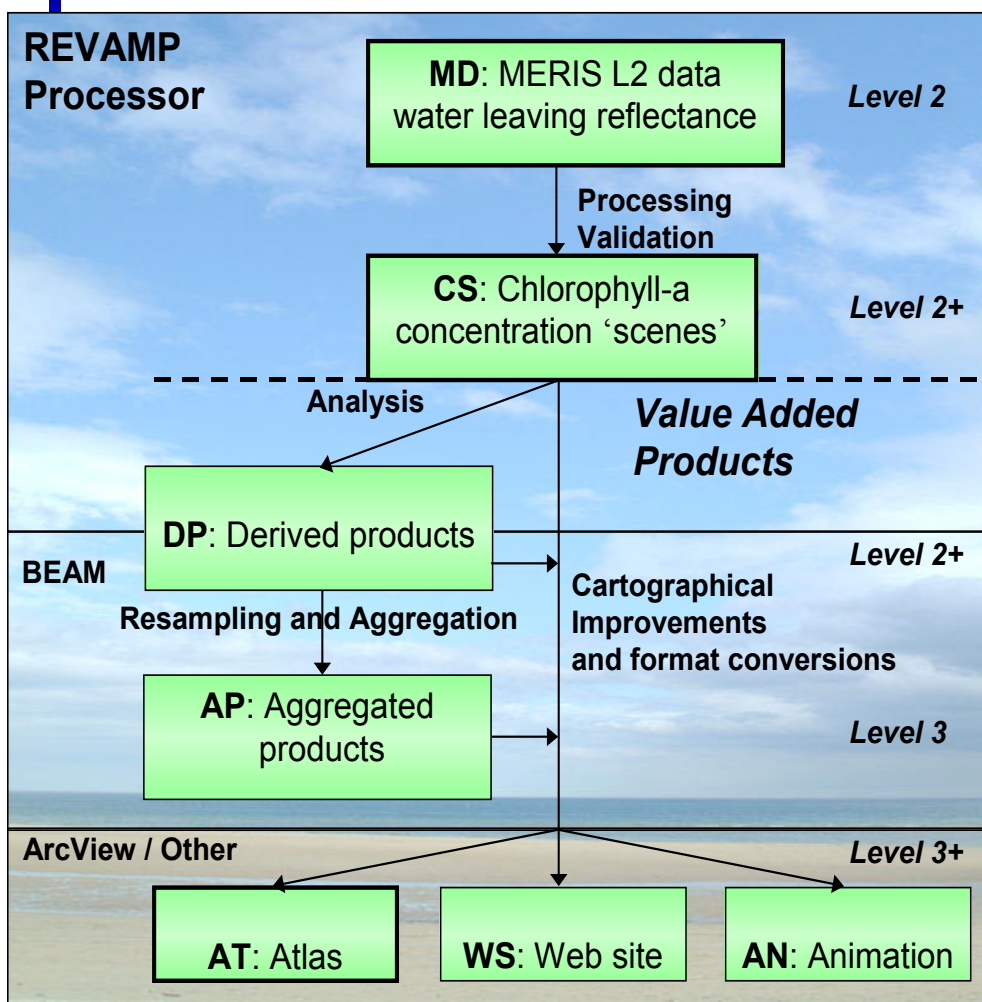
Level 2 indicates water leaving reflectance.

All products below the dashed line are Value Added Products.

Level 2+ a bio-geophysical product (or its derivative) in satellite coordinates.

Level 3 Resampled combined bio-geophysical product (or its derivatives).

Level 3+ cartographical projection and layout.



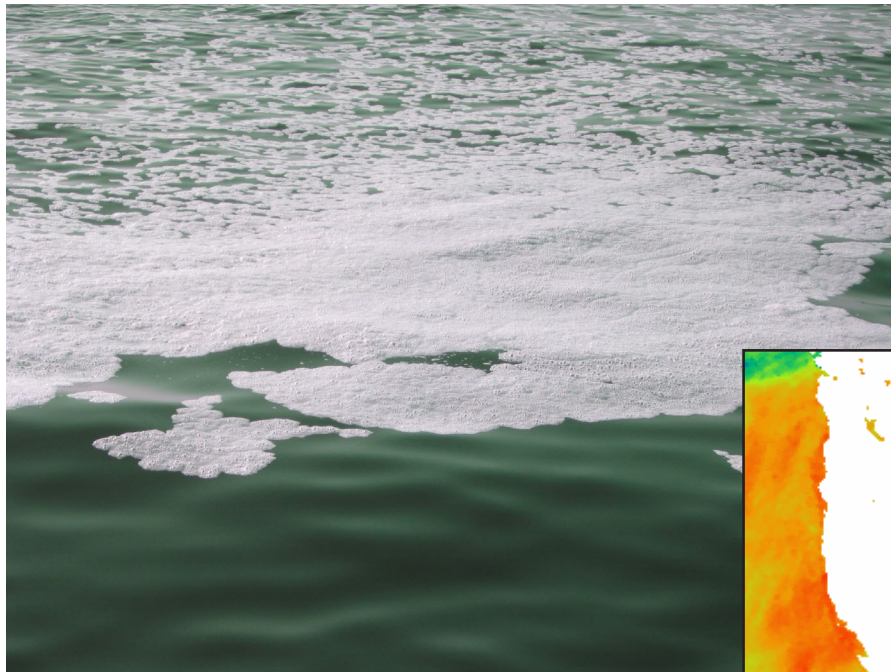
Recommendations from consulted users:

The following VAPs MUST result from REVAMP:

1. REVAMP MUST deliver a comprehensive time-series during the growing season
2. REVAMP MUST deliver some MERIS-FR products of special events such as an algal bloom (preferably at an interesting location, such as an off-shore wind park)
3. REVAMP MUST provide a comparison with in situ measurements
4. The paper Atlas MUST be available on the Internet in PDF format

The following VAPs SHOULD result from REVAMP:

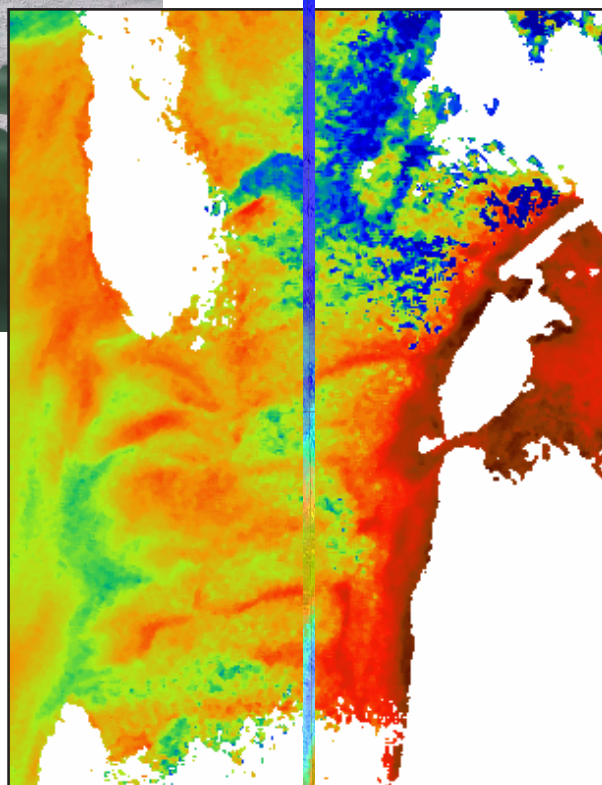
1. REVAMP SHOULD enable users to process its/some Chlorophyll-a scenes in BEAM
2. REVAMP SHOULD deliver information about eutrophication



*Photo: R.Pasterkamp
Foam on Dutch North Sea water
observed during the 22nd of
April 2003*

Derived products (DP) were asked for by end-users but proved to be mostly beyond the scope of REVAMP. Some examples of identified derived products are:

1. Description and interpretation of special events (special maps: Image to the right: Strands of *Phaeocystis* bloom observed in full resolution image)
2. Characterisation of phytoplankton blooms (position, duration, and area covered)
3. Identification of potentially toxic blooms
4. An experimental eutrophication indicator based on Chlorophyll-a concentrations (and ancillary data)



Aggregated products (AP) are an important way to overcome some of the drawbacks of satellite remote sensing, such as partial cloud cover.

Therefore a great deal of attention was given to the aggregation in time of the individual Chlorophyll-a maps into:

Monthly, seasonal and yearly Median and Maximum composites.

The maps displayed in this Atlas will be mainly of this type.

*In chapter 6:
"REVAMP processing"
the binning process
(aggregation in time)
will be explained.*



The REVAMP Quality Assurance Committee

The REVAMP Quality Assurance Committee was composed of three members who monitored the project in detail during its course.

Mike Rast (ESA-ESTEC), Hartmut Heinrich (BSH) and Eon O'Mongain (UCD) have given us the benefit of their wisdom and experience and have critically examined project deliverables and decisions. From their last report we give the following quotes:

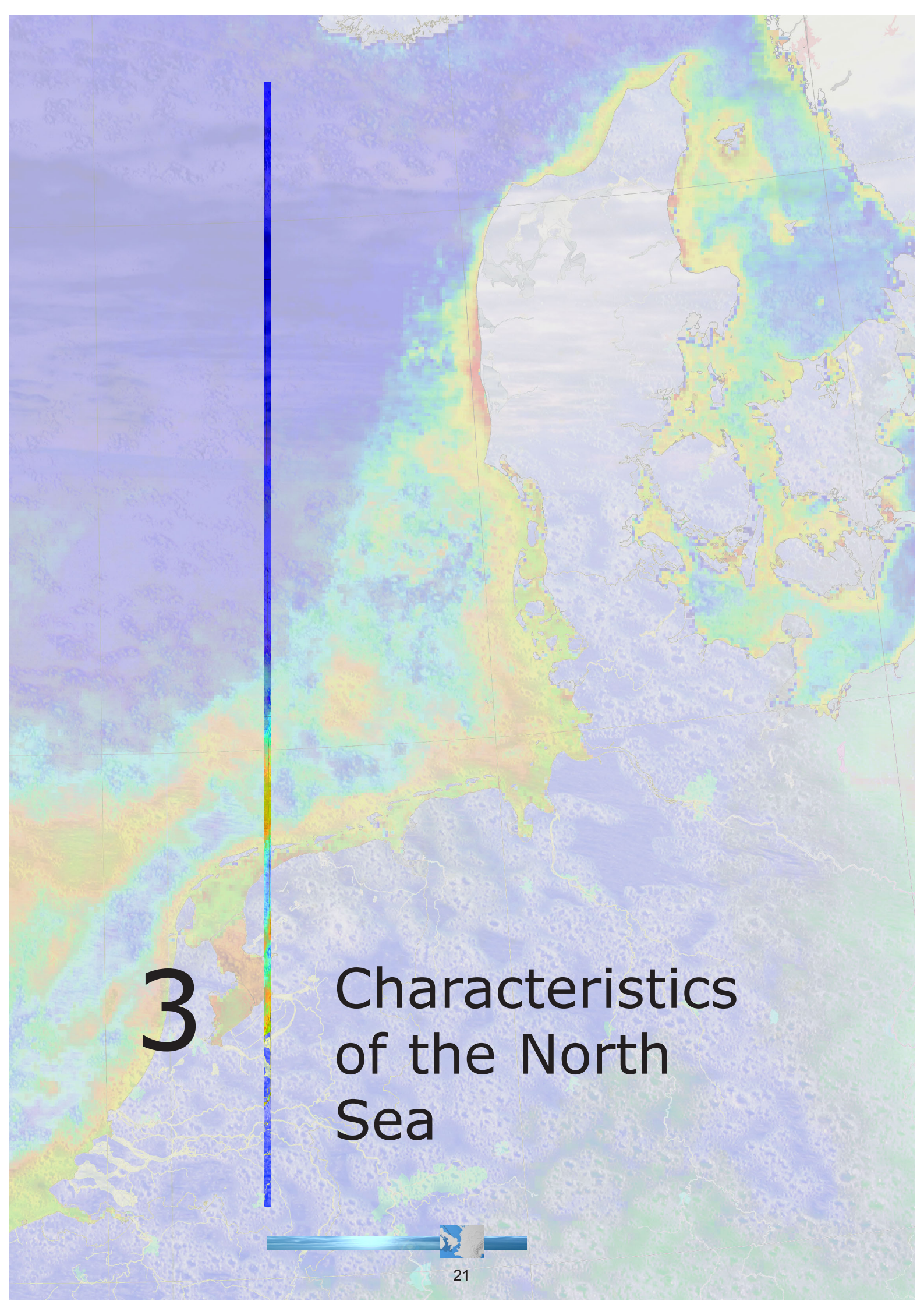
"Measurement protocols and round robin exercises were consolidated in REVAMP and yielded good agreement in the retrieval results between the various partners measuring the Chlorophyll-*a* concentrations in phytoplankton in different ways.

It needs to be continually emphasised that different methods of determining Chlorophyll-*a* concentrations will never agree with laboratory-like precision: indeed even separate laboratories do not always agree. "

"The validation of the REVAMP results and the concluding comparison between the yearly mean of in-situ vs. REVAMP Chlorophyll-*a* concentrations showed impressive results, qualifying the REVAMP products as user relevant."

"The long-term continuity of products from space-borne sensors and their availability for the end-user is considered important and needs to be reflected strongly as one of the REVAMP conclusions and recommendations. Especially for the application in governmental marine monitoring a long-term perspective is crucial."





3

Characteristics of the North Sea

The North Sea

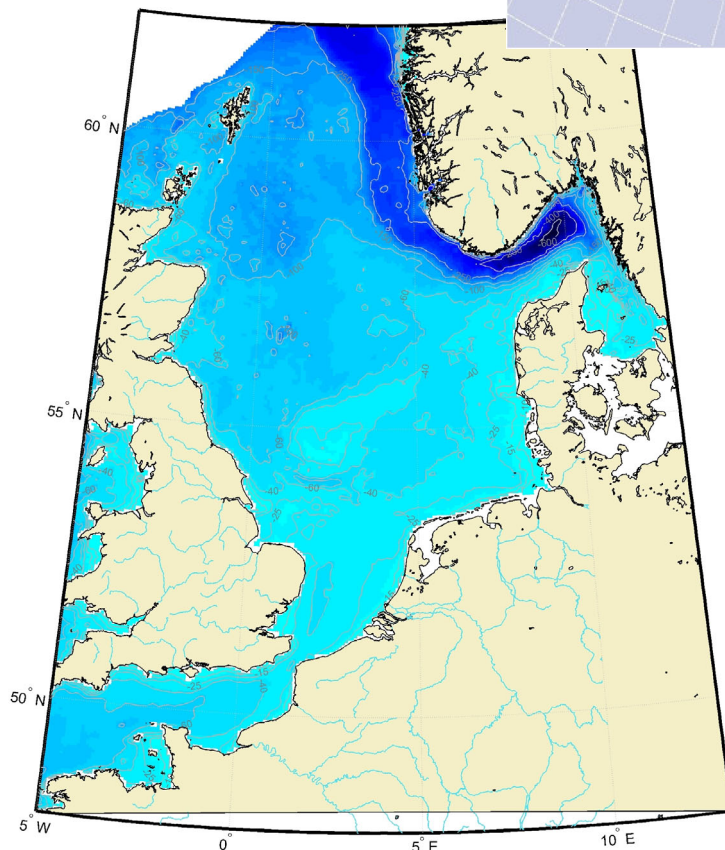
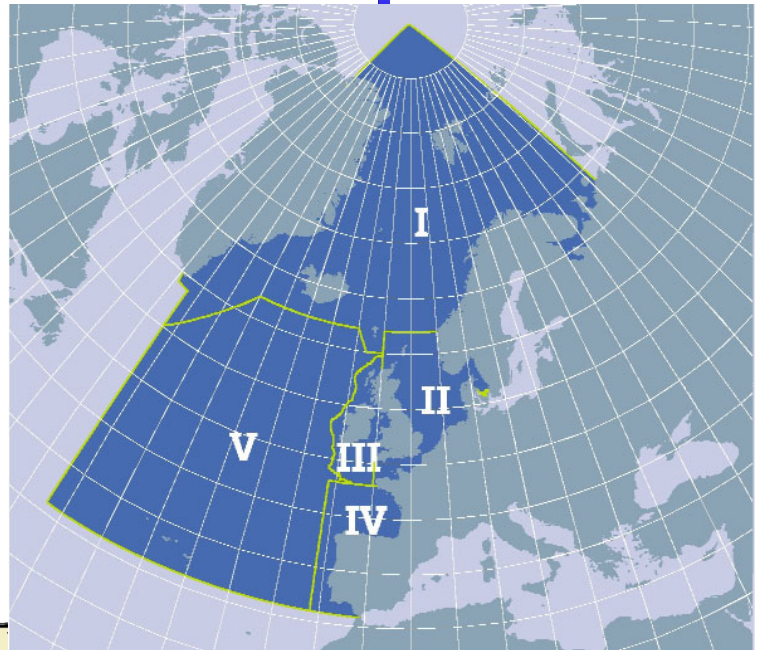
Areal extend of the North Sea

The North Sea (51° to 61° N, 3° W to 9° E) is a large coastal sea bounded by the British Isles, the Scandinavian peninsula, and the mainland of northwestern Europe.

Although this sea is often called a shelf sea, almost half the area has a depth well in excess of 100 m and is essentially oceanic in character.

In order to be able to consider also case 1 water conditions we have included for REVAMP the English Channel and part of the Celtic Sea.

The OSPAR Convention Area covers the Northeast Atlantic, including parts of the Arctic. The OSPAR Convention Area has a surface area of approximately 13 million km^2 and a volume of approximately 30 million km^3 , of which about 750,000 km^2 of surface area and 94,000 km^3 of volume are in the North Sea (II).

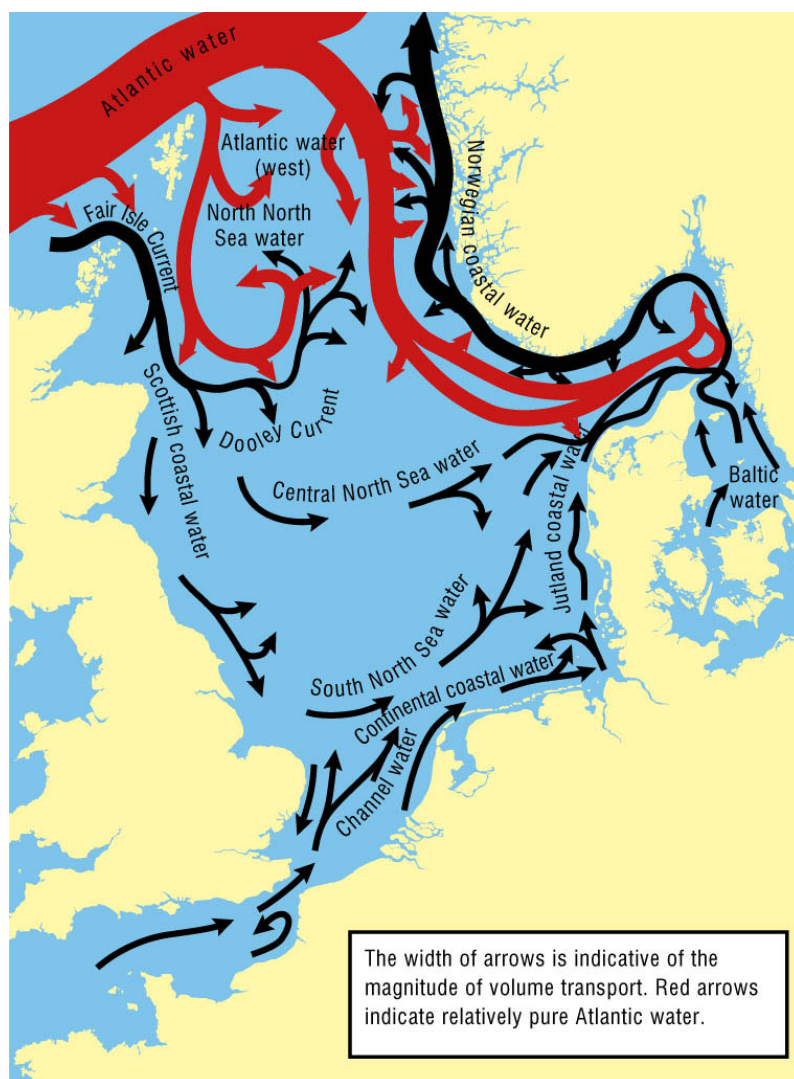


The total catchment area covers approximately 5 million km^2 with an overall population of about 307 million people. Of this, the North Sea catchment area amounts to 841,500 km^2 , with a population of about 184 million people.



Currents of the North Sea

The North Sea is relatively shallow; large areas of the southern North Sea reach only 30 m depth, although it does have deeper areas, the deepest being the Norwegian Trench that goes down to 700 m.



The North Sea is strongly influenced by the adjacent North Atlantic Ocean.

The North Atlantic Current brings oceanic water of high salinity into the northern North Sea in two branches: an inflow through the Fair Isle channel off the north of Scotland, and a more significant inflow along the western slope of the Norwegian Trench.

This branch also supplies saline water for the deep inflow through the Skagerrak and Kattegat into the Baltic Sea.

The Norwegian Coastal Current forms a contrasting outflow along the eastern side of the Trench, carrying less saline surface water from fjords and rivers northward.

In addition to the oceanic inflow to the northern North Sea, the saline water of Atlantic origin also penetrates into the southern North Sea through the Dover Straits.

Currents in the shallower parts of the North Sea are mainly driven by the tide.

The tide enters as a wave from the North Atlantic, and travels anti-clockwise around the North Sea basin.

Wind-driven currents also have a major effect, particularly in the winter months.

Map adapted from: Turrell, W. R. Henderson, E.W., Slesser, G., Payne, R., and Adams, R.D.

1992. Seasonal changes in the circulation of the Northern North Sea. *Continental Shelf Res*, 12 (2-3): 257-286.

The coupling and exchange with the Baltic Sea consists of a surface current with brackish water that flows out of the Baltic through the Kattegat, to the Skagerrak and the North Sea, and a counter-current in deeper layers with higher salinity water going into the Baltic Sea during favourable wind conditions.

North Sea phytoplankton history

Since the 1970's, the growing season for phytoplankton has extended from March to early winter, providing food that can be passed upwards to other parts of the food web for all but the winter months.

Prior to the 1970's, there were thought to be just two peaks annually in phytoplankton growth, one in spring and one in autumn. The gap in between was thought to happen when the spring bloom of phytoplankton had used up all the nutrients in the upper water column, and to persist until autumn storms mixed the surface waters more deeply and brought up fresh nutrients. The seasonal patterns are different in different parts of the North Sea. In the northern deep water part, the two maxima are still present.

If the change in the pattern of the phytoplankton growth period, since the 1970's, reflects a true change in mixing in the North Sea then many other dynamics of the food web may also have changed in recent decades.

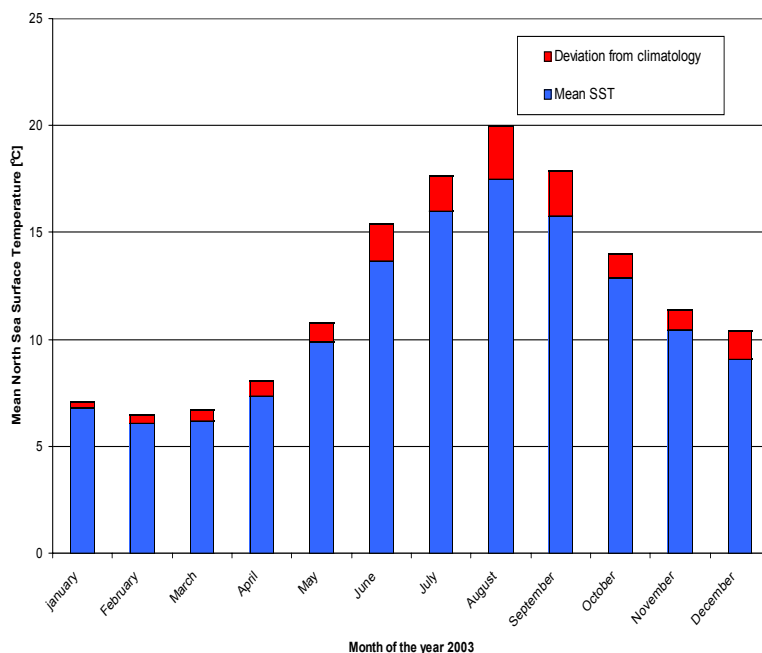
As well as alterations in the growing season, the actual species that make up the phytoplankton have also changed. Long-term North Sea trends in both phytoplankton and zooplankton show a parallel decline in abundance from 1955 to a trough in 1979-1980, followed by a marked recovery after 1980.

After the recovery, the phytoplankton community also changed, with a decrease in the proportion of diatoms and an increase in flagellates. These changes represent a major shift in the composition of this component of the ecosystem. They have major implications for the food chain because the newly dominant flagellates may be of poorer food value and in some cases are not even eaten by the zooplankton.

North Sea surface temperatures in 2003

Water temperatures for the German North Sea part are published in MURSYS: (<http://www.bsh.de/en/Marine%20data/Observations/MURSYS%20reporting%20system/>)

Published water temperatures were put down in a graph showing nicely the yearly trend of Sea Surface Temperature (SST, blue bars) and the deviation from the reference temperature. The year 2003 was extremely warm and in all months the reference SST was exceeded.



MURSYS is a regularly published report providing information on physical and chemical parameters

(weather, sea surface temperatures, water levels, current conditions, nutrient concentrations, oxygen situation)

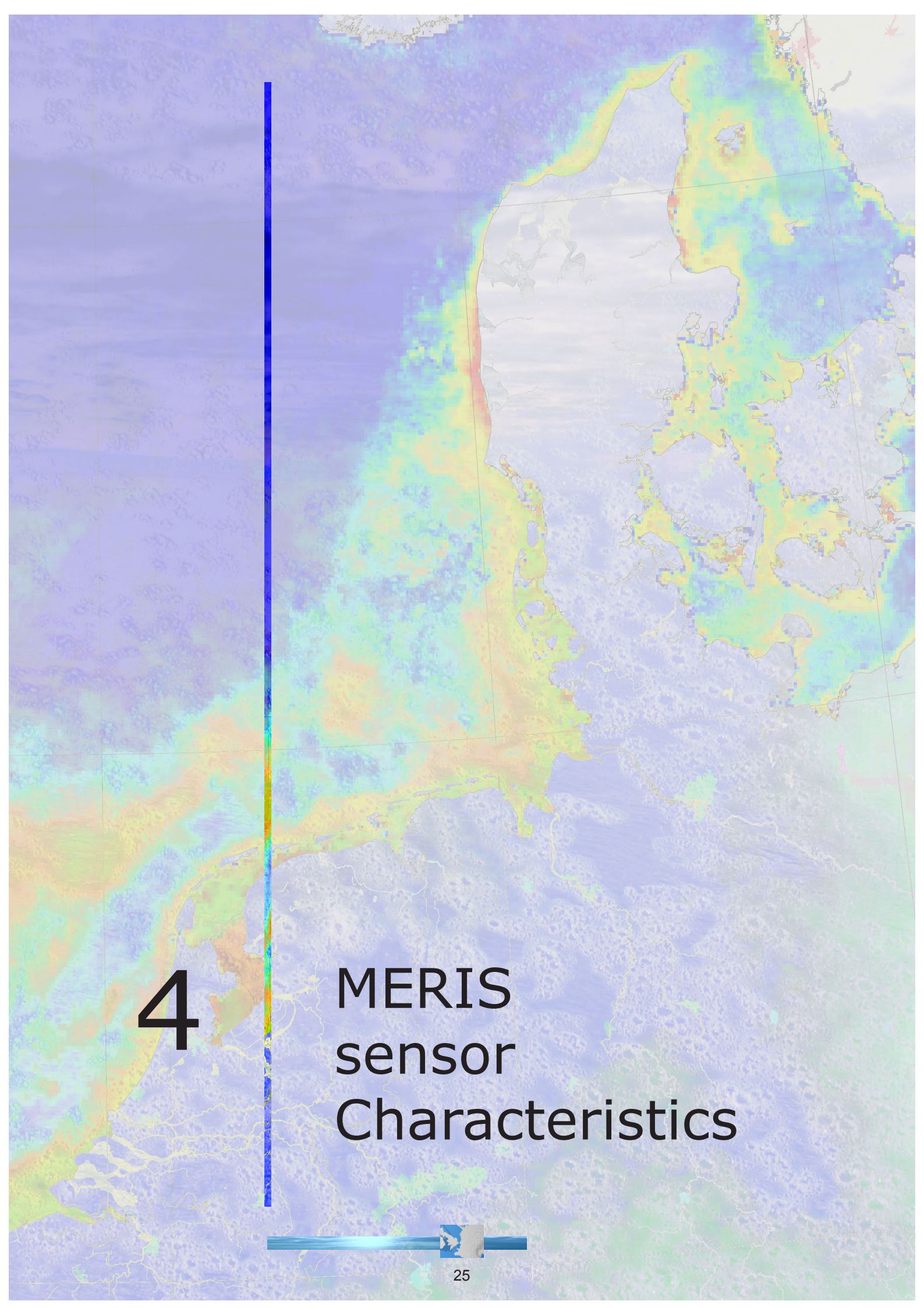
and biological parameters

(occurrence of algae and toxic algae, blue mussel stocks, fish stocks etc.)

in the area of the North and Baltic Seas.

MURSYS is issued by the BSH (Federal Maritime and Hydrographic Agency of Germany), Hamburg.





4

MERIS sensor Characteristics

MERIS for ocean colour monitoring

The information published here was extracted from amongst others:

<http://envisat.esa.int/instruments/meris/>

<http://www.crisp.nus.edu.sg/~research/tutorial/meris.htm>

ESA's Environmental Satellite Envisat was launched on 1 March 2002.

One of the instruments on board is the Medium Resolution Imaging Spectrometer (MERIS), which is an imaging spectrometer that measures the solar radiation reflected by the Earth.

The primary mission of MERIS is the measurement of sea spectral reflectance in oceans and coastal areas.

MERIS has a high spectral and radiometric resolution and a dual spatial resolution (1200m and 300m), for a global mission dedicated to open ocean and coastal zone waters and a regional mission covering land surfaces.

The instrument has 15 spectral bands in visible and near infrared which are programmable in width and position. MERIS allows global coverage of the Earth every 3 days.

MERIS has no tilt capability, with the consequence that half of the image is contaminated by sun glint quite often, which causes significant problems in the atmospheric correction.

Knowledge of sea spectral reflectance can be converted into a measurement of the Chlorophyll-a pigment concentration, suspended matter concentration, yellow substance concentration and aerosol loads over marine areas. It is also used for land and atmospheric monitoring.

MERIS is designed to acquire 15 spectral bands in the 390 - 1040 nm range. The spectral bandwidth is variable with an integer multitude of 1.25 nm depending on the width of a spectral feature to be observed and the amount of energy needed in a band to perform an adequate observation.

Over open oceans an average bandwidth of 10 nm is required for the bands located in the visible part of the spectrum. Driven by the need to measure the intensity of the oxygen absorption in the oxygen absorption band at 761 nm a spectral bandwidth of 3.75 nm is required.

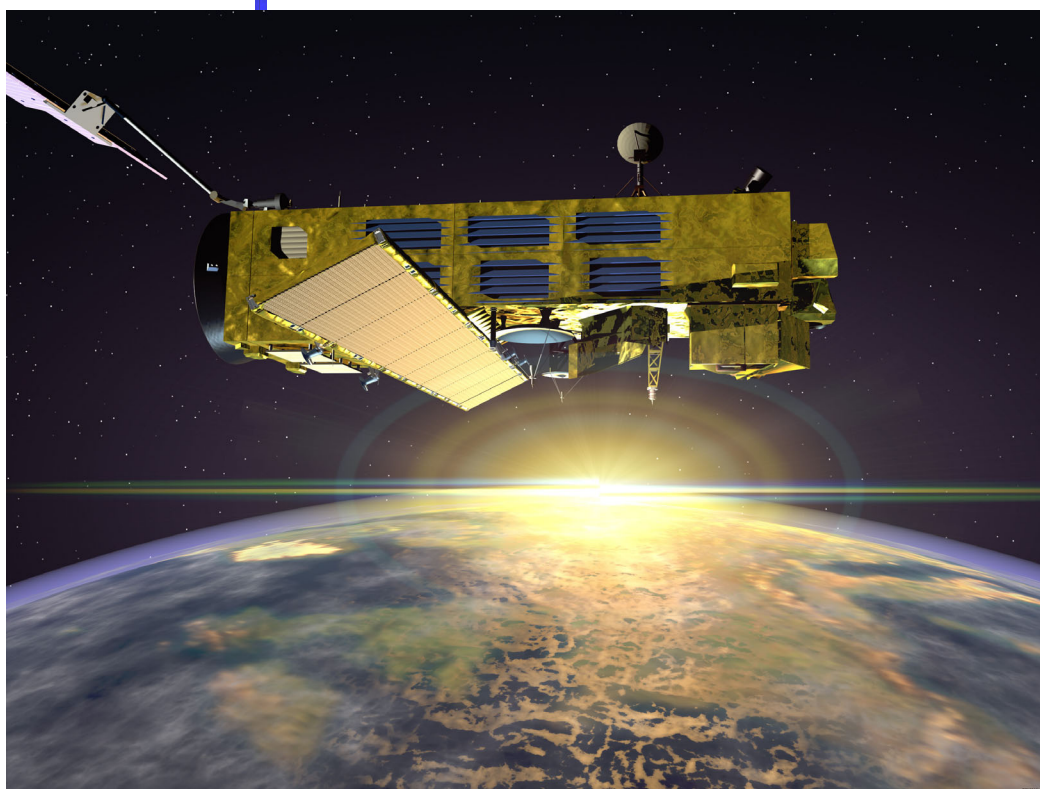
The oceanographic mission is radiometrically the most demanding in terms of low radiance levels and their associated high signal-to noise ratios.

Therefore, the instrument was designed to detect the low levels of radiation emerging from the ocean (linked to the water constituents by the processes of absorption and scattering).



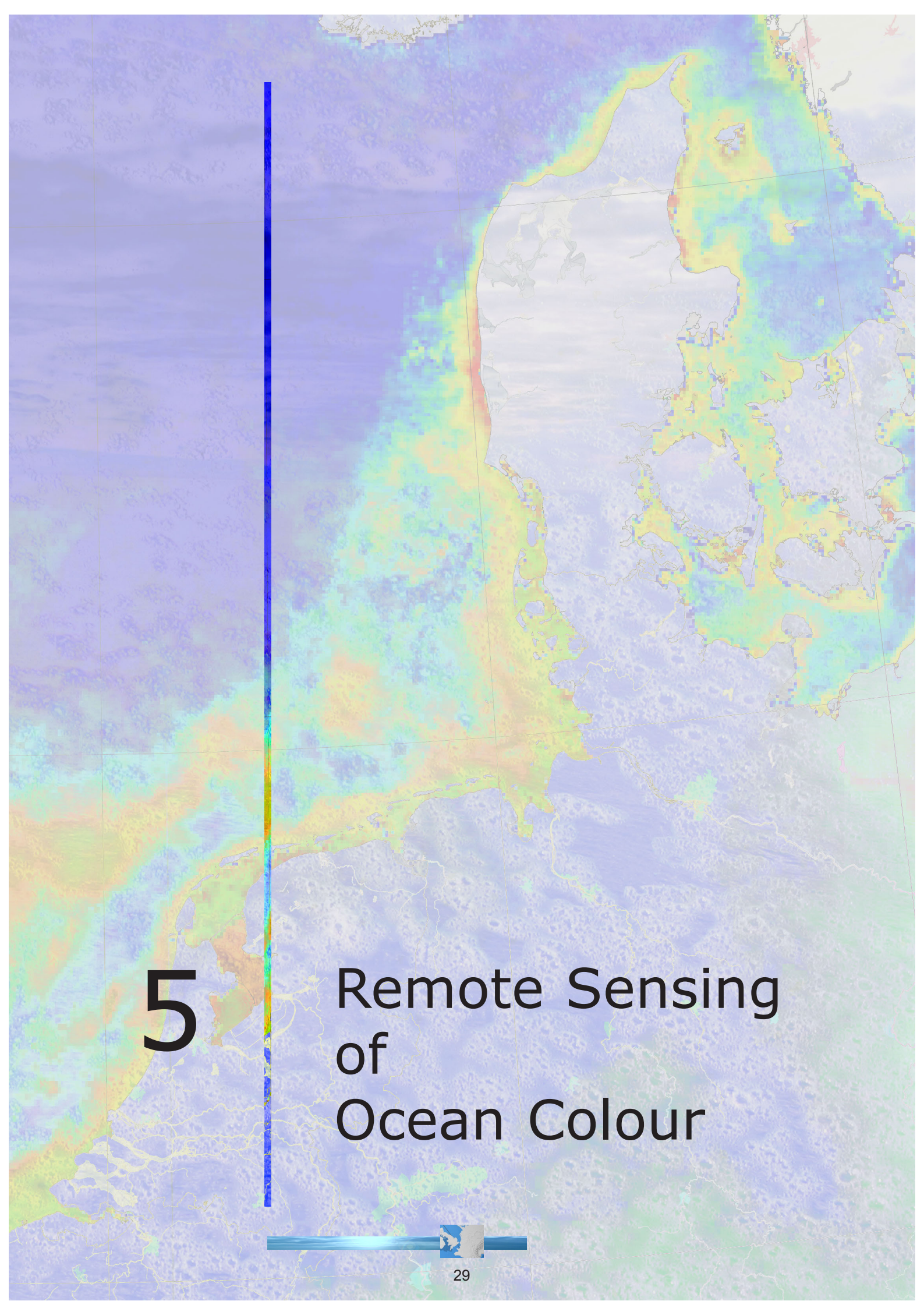
MERIS Spectral Bands

Nr.	Band centre (nm)	Bandwidth (nm)	Potential Applications
1	412.7	10	Yellow substance, turbidity
2	442.6	10	Chlorophyll absorption maximum
3	489.9	10	Chlorophyll, other pigments
4	509.8	10	Turbidity, suspended sediment, red tides
5	559.7	10	Chlorophyll reference, suspended sediment
6	619.6	10	Suspended sediment
7	664.6	10	Chlorophyll absorption
8	680.8	7.5	Chlorophyll fluorescence
9	708.3	10	Atmospheric correction, red edge
10	753.4	7.5	Oxygen absorption reference
11	760.3	3.75	Oxygen absorption R-branch
12	778.4	15	Aerosols, vegetation
13	864.9	20	Aerosols corrections over ocean
14	884.9	10	Water vapour absorption reference
15	900.0	10	Water vapour absorption, vegetation



Artist impression of Envisat (<http://envisat.esa.int/instruments/meris/>)





5

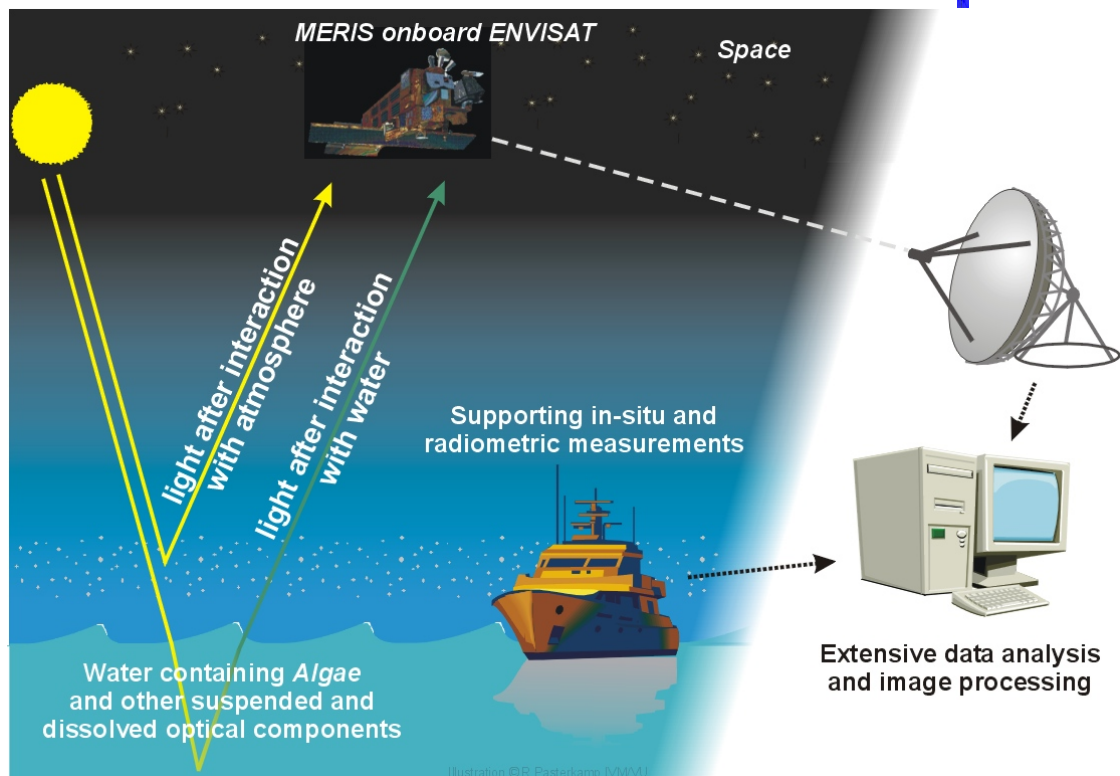
Remote Sensing of Ocean Colour

Passive Remote Sensing of Ocean Colour

There are numerous textbooks on the remote sensing of water quality. For the explanation of the process we quote:

IOCCG Report No. 3: Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters Edited by: Shubha Sathyendranath (Bedford Institute of Oceanography, Canada). (http://www.ioccg.org/reports_ioccg.html).

Passive remote sensing of ocean colour is based on the analysis of the solar radiance spectrum which is backscattered by the water and its constituents. Due to absorption and scattering processes the solar radiance, which travels into the sea, is modified in its spectral composition. A small fraction, around 1%, is backscattered back to the sky and thus can be monitored by a sensor mounted on an aircraft or earth observation satellite. Due to the optical properties of pure water, only the visible part of the spectrum in the range 400 - 700 nm can be used. Above 700 nm the high absorption coefficient of pure water makes the water nearly black except for conditions with high suspended particle concentrations. Thus, the red and near infrared part of the spectrum is used to determine the effect of atmosphere on the signal. In general, photons from the sun can follow various pathways before they reach the remote detector.



We get the following main contributors to the remotely-sensed signal:

- Light reaching the sensor after scattering of photons by the atmosphere;
- Light reaching the sensor after specular reflection of direct sunlight at the sea surface;
- Light upwelling from the sea surface after backscattering in water.

Note that the light upwelling from the sea surface would be attenuated on its journey from the sea surface to the sensor, due to absorption and scattering by the intervening atmosphere.



Only the upwelling light from the sea surface carries useful information on the water body. This upwelling component from the water has to be processed to evaluate what the water-leaving component would have been if there were no atmosphere in between the sensor and the water body. Since the contribution by the atmosphere to the radiance, which is captured by the satellite, can surmount 99% of the signal, techniques for atmospheric correction form a very important and critical component of remote sensing of ocean colour.

Several factors influence the water-leaving signal. Direct sun light and scattered sky light that penetrate the sea surface may be absorbed or scattered by the water molecules, or by the various suspended and dissolved materials present in the water.

In shallow, clear waters, a significant part of the light from the sun may reach the bottom, and be reflected from it. Some of the scattered and reflected photons eventually find their way to the remote sensor.

Remote sensing involves analyses of the variations in magnitude and spectral quality of the water-leaving radiation to derive quantitative information on the type of substances present in the water and their concentrations. Clearly, this has to be based on a sound understanding of the optical properties of the medium, and of the optical processes in the medium.

When we analyse the optical properties of this medium, we need to distinguish the effect of water itself on the light field from the effects of the dissolved and suspended matter that are present in the water.

It is recognised that several substances influence the optical properties of natural bodies of water. From an optical, perspective there are three main components, in addition to pure water itself:

-Phytoplankton: This component is characterized by their pigments, which are used for photosynthesis. The pigments with Chlorophyll-*a* as the dominant component cause a characteristic absorption spectrum, which, although variable, is different from that of the other components. The concentration of phytoplankton is expressed as the concentration of Chlorophyll-*a*, which in the North Sea is in the range of a few micrograms per liter during the summer season

-Suspended matter (inorganic): Even though microscopic organisms are also "suspended" material, we use this term here to represent only suspended material of inorganic nature.

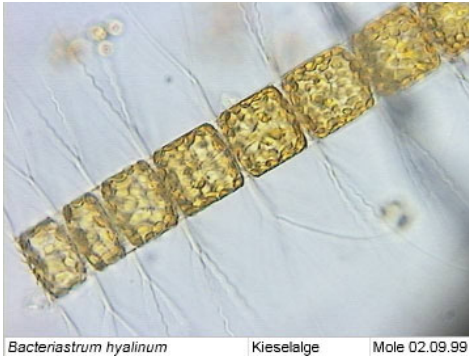
-Yellow substance (also called CDOM, colored dissolved organic material): These are coloured, dissolved, organic substances. One can take this component to also include "detrital" particulate material, which generally has absorption characteristics similar to yellow substance.

Phytoplankton:

A large variety of phytoplankton species, with characteristic sizes, shapes and physiological properties, are known to exist in the aquatic environment, and their species composition and concentration can change with time and space.

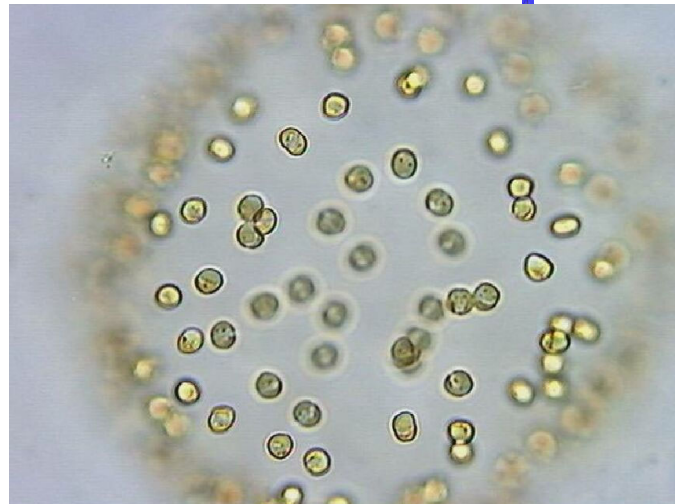
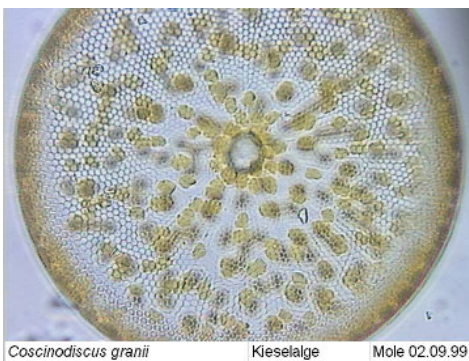
The concentration of the main phytoplankton pigment, Chlorophyll-*a*, is often taken as an index of phytoplankton biomass. However, it is important to recognise that Chlorophyll-*a* is accompanied by a number of auxiliary pigments in the phytoplankton cells.

The pigment composition of a water sample can vary with the community structure of the phytoplankton population in the sample, as well as with the physiological state of the cells (e.g., photoadaptation and nutritional status).



Some microscope images of phytoplankton incl. *Phaeocystis* (large photo)

Photo's taken by Marion Rademaker



Suspended matter

In this somewhat loose category we include all inorganic particulate material that is not included in the phytoplankton component. We measure this quantity as the dry weight of all material in the water sample which does not pass a filter with a pore size of about 0.7 micrometer. Thus, also the organic material is measured.

In shallow coastal and inland water bodies, wave and current action can bring bottom sediments into suspension, modifying significantly the colour of the oceans.

It is important to recognise that the term "suspended matter" does not apply to a single type of material, but to a whole family of materials with their own individual characteristics.

Yellow substance

Yellow substance, variously called "gelbstoff", "coloured, dissolved organic matter" (CDOM) or "gilvin", are a group of organic, dissolved substances, consisting of humic and fulvic acids. They may have a local origin, for example from the degradation of phytoplankton cells and other organic particles, or they may be advected to a locality from a distant source.



The main source for the high yellow substance concentrations in the coastal waters of the North Sea are rivers transporting high amounts of humic substances into the sea.

The absorption properties of yellow substance are also known to be somewhat variable.

Bottom effect

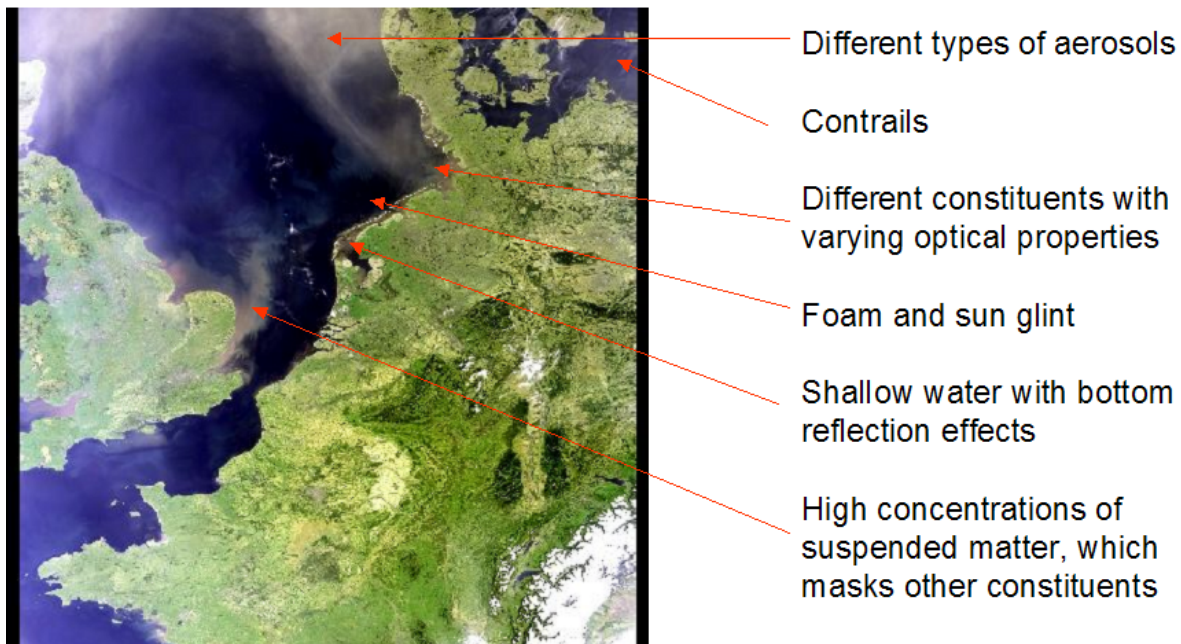
In addition to these three types of substances present in the water column, light reflected by the bottom of a water body can also influence ocean colour, provided the water is sufficiently shallow and clear.

The influence of the bottom on the colour of water can vary with the depth of the water body, the clarity of the water, the type of substances present in the water, and the type and colour of the bottom.

The bottom may be rocky or sandy, and may or may not be covered, partially or fully, by a variety of benthic organisms (e.g., algae, molluscs). All of these factors will influence the manner in which bottom effects are manifested in the colour of the water, as seen by a remote sensor.

Areas, where the bottom may have a significant influence on ocean colour remote sensing have to be excluded or masked out.

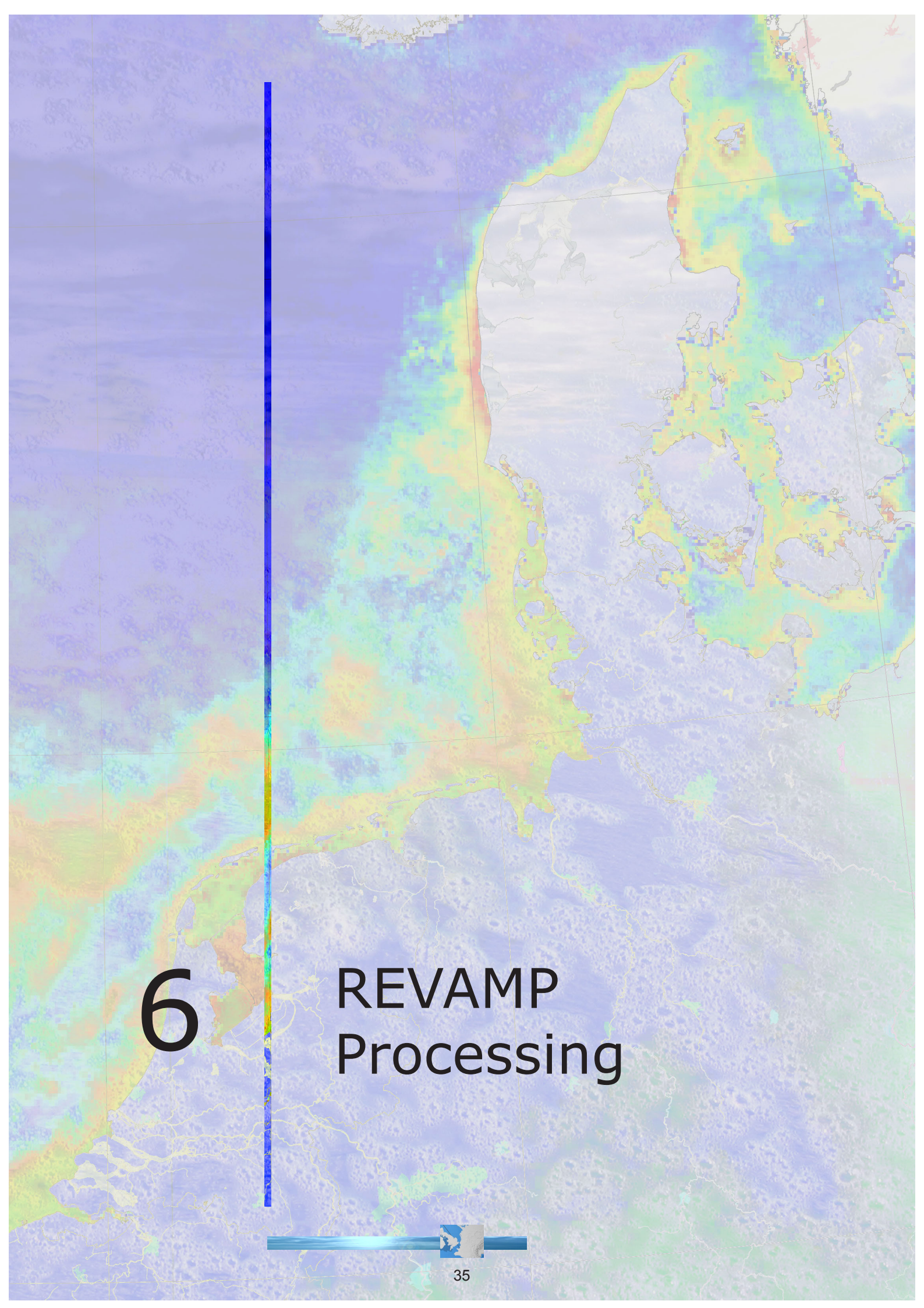
The Challenge of Case 2 Water Remote Sensing



MERIS RR 16.4.2003 full swath

Well-recognized limitations of satellite remote sensing are interference by clouds, relatively coarse spatial resolution (for coastal processes), and discrete observation periods. Therefore the scope of a remote sensing procedure is restricted to certain conditions. The technique cannot be applied with the same quality under all conditions. A careful examination of possible errors is always necessary.





6

REVAMP Processing

From MERIS reflectance image to REVAMP Chlorophyll-*a* maps

Step 1: The processing of water leaving radiance reflectances, which is a standard MERIS product provided by ESA, to Chlorophyll-*a* concentrations is done using the REVAMP Chlorophyll-*a* algorithm coded in the REVAMP MERIS processor.

Together with Chlorophyll-*a*, a quality measure of the Chlorophyll-*a* concentration is calculated (see pages 11 and 12 of this book) for every image pixel.

Step 2: The individual REVAMP Chlorophyll-*a* and quality images are aggregated in time and space to obtain monthly and seasonal binned products of the Median and Maximum Chlorophyll-*a*, the number of counts per bin and the mean relative error per bin.

Step 3: The products are projected into the same projection, UTM Zone 31, and tailored to the same area. A unique colour scale is applied to make the Chlorophyll-*a* maps easily comparable.

Step 4: The final maps are generated in GIS and DTP software in a standard lay-out with a graticule and legend.

Binning Procedure:

Following the conclusions of the User Requirements Surveys, this REVAMP Chlorophyll-*a* Atlas of the North Sea mostly contains maps that are based on an aggregation of individual MERIS scenes both in time and space. The "L3-processor" included in the BEAM3.1 software has been used to aggregate the individual Chlorophyll-*a* scenes to e.g. monthly composites.

Finally, a total number of **450** individual MERIS scenes for 2003 have been used for the aggregation. They have been binned into 10 monthly maps, 4 seasonal maps and one yearly map of the Chlorophyll-*a* concentration. For each month approximately 35-45 REVAMP Chlorophyll-*a* maps were used. An output resolution of 2 km was chosen.

Pixels that were of low quality according to the standard MERIS flags (PCD1_13, INVALID etc.) were excluded from processing. Specifically, these were the flags indicating that:

- 1) An invalid pixel (MERIS L2 invalid flag, raised by the presence of e.g. clouds, sunglint or land)
- 2) A pixel where the atmospheric correction has failed (MERIS L2 PCD_1_13 flag) or
- 3) The calculation of the REVAMP Chlorophyll-*a* indicated out of range values (REVAMP LOW_CHL and HIGH_CHL flags)



The Product Confidence Flag 1-13 (PCD_1_13) is a binary value, available for every pixel in a MERIS Level 2 product. It indicates that the atmospheric correction process has reported a problem, and that the water leaving radiance reflectance value should be excluded from further processing.

The conditions to raise the PCD_1_13 over water are the following:

- the input to the atmospheric correction is out-of-range (e.g. saturation)
- the output of the atmospheric correction is out-of-range
- one of the surface reflectances of bands 1 - 9 is negative
- the pixel is in uncorrectable sunglint
- the pixel is a high altitude inland water
- the wind speed was too high (white caps risk)
- the atmosphere is too turbid (residual clouds, partly cloudy pixel, cirrus clouds, thick aerosols)
- ice is present
- it was not possible to detect a proper aerosol model
- in Case 1 waters: the surface reflectance in a band 4 deviates significantly from a climatological value

For this Atlas the median and maximum Chlorophyll-a values have been calculated. For each pixel in the aggregated image (bin) the processor calculates the statistics of the potential 35-45 values of the input scenes. In reality, however, the scenes do not always cover the whole area of the North Sea, and the flags mask out pixels in each of the scenes so that fewer values for each bin are available. In the event that there are no pixels available for the bin, this is depicted as a white area in the composite map.

The maps of the winters are excluded from the Atlas because of the low number of suitable images (insufficient light, cloud coverage) mainly due to increased winter cloudiness, but also due to limitations caused by limited light and wind conditions. Therefore you will find the monthly maps from March until October in this book.

Seasonal averages are based on the following time windows used in the binning process:

Spring:	15 February	-	14 May
Summer:	15 May	-	14 August
Autumn:	15 August	-	14 November
Yearly:	15 February	-	14 November

Note that the winter months were excluded from the yearly products.

Because in general the lowest Chlorophyll-a values are found during winter, this omission may bias the yearly median value towards higher values, as compared to the 'true' yearly median. The yearly maximum maps are probably not affected by this.



Details of The binning procedure

The Level 3 Binning applied to the REVAMP Level 2 Chlorophyll-a data has been performed with the BEAM binning tool and is based on the NASA SeaWiFS binning algorithm as described in: "Level 3 SeaWiFS Data Products: Spatial and Temporal Binning Algorithms" J.W.Campbell, J.M. Blaisdell, and M.Darzi , NASA Technical Memorandum 104566, Vol.32.

The binning process resamples every input pixel (REVAMP Chlorophyll-a) in a bin on an equal area grid (spatial binning). This spatial bin database includes for every bin the sum, square of sums and counts (MLE algorithm) or minimum and maximum values (MinMax algorithm).

The spatial bin databases of the individual input products are then integrated in a temporal bin database, whereby a weighting according to the number of input values can be applied.

After integrating all products of the averaging period a final step is applied in which the averages are calculated from the sums and a map projection is applied in order to generate a displayable image product.

The Maximum Likelihood Algorithm (MLE) aggregation algorithm provides an estimation of the Median for a log-normal distribution. The binning process is as follows:

In the following equation, the index k denotes an input scene. The index i denotes a pixel which falls into a bin j of the binning database due to its geolocation. $i=1..n_{k,j}$ are all those pixel of the input scene k , which fall into bin j . The temporal binning algorithm sums up all measurements $X_{k,i,j}$ to the following intermediate variables:

$$S_{1,k,j} = n_{k,j}^{(w-1)} \sum_i \ln(X_{k,i,j})$$

$$S_{2,k,j} = n_{k,j}^{(w-1)} \sum_i \ln^2(X_{k,i,j})$$

where w is the weighting coefficient specified for the processing and $n_{k,j}$ is the number of measurements of a scene k of a specific bin j . Additionally, the number of measurements $n_{k,j}$ and the weight w are saved in the bin database.

The temporal binning just sums up these "per scene" intermediate variables to the final bin database:

$$SUM_{1,j} = \sum_k S_{1,k,j}$$

$$SUM_{2,j} = \sum_k S_{2,k,j}$$

$$N_j = \sum_k n_{k,j}$$

$$W_j = \sum_k n_{k,j}^w$$



The final process converts the variables stored in the temporal bin database to the final L3 variables according to:

First calculate two intermediate values:

$$m_j = \frac{SUM_{1,j}}{W_j}$$

$$s_j^2 = \frac{SUM_{2,j}}{W_j} - m_j^2$$

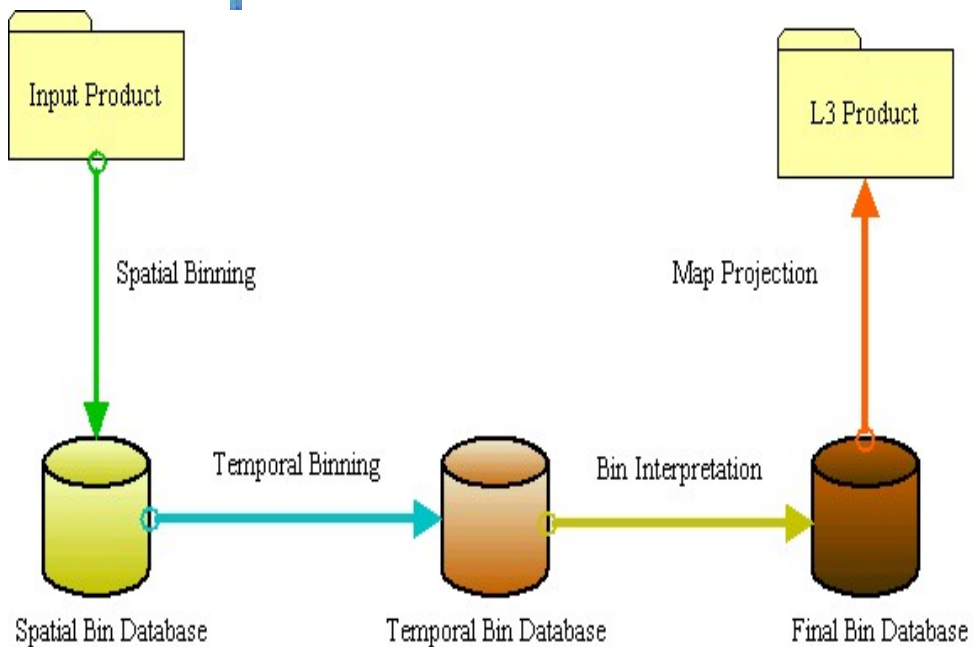
Then compose the final variables MEAN, SIGMA, MEDIAN and MODE:

$$MEAN_j = e^{(m_j + 0.5 \cdot s_j^2)}$$

$$SIGMA_j = MEAN_j \cdot \sqrt{e^{s_j^2} - 1}$$

$$MEDIAN_j = e^{(m_j)}$$

$$MODE_j = e^{(m_j - s_j^2)}$$



Details of the relative error calculation method

The REVAMP algorithm calculates a measure of the absolute standard error in Chlorophyll-a per pixel.

In this atlas the relative error is shown, which is calculated as the absolute standard error divided by the absolute Chlorophyll-a value per pixel.

The MLE aggregation algorithm is used to calculate the median relative error for each binning period (monthly, seasonal, yearly).

This value is an indication of the average uncertainty for an individual image per pixel for the binning period.

It does not reflect the natural temporal variation (expressed as e.g. the variance) of Chlorophyll-a, which, in general, is much bigger).

Counts images

The exact number of observations for each bin has been registered in "count-images".

Count images were calculated simultaneously with the monthly, seasonal and yearly median and maximum Chlorophyll-a maps to give an impression of the data density and, hence, an approximation of the inherent quality of the binned maps.

Especially the calculation of the "true" median value per bin requires a significant number of samples.

Due to cloudiness and other factors mentioned above, the number of observations per bin can, occasionally, be quite low on a monthly basis.

This is one of the reasons that a bin size larger than the original pixel size was chosen (namely 4 km²) in order to improve the statistics for each bin.

On the next pages we will show subsequently

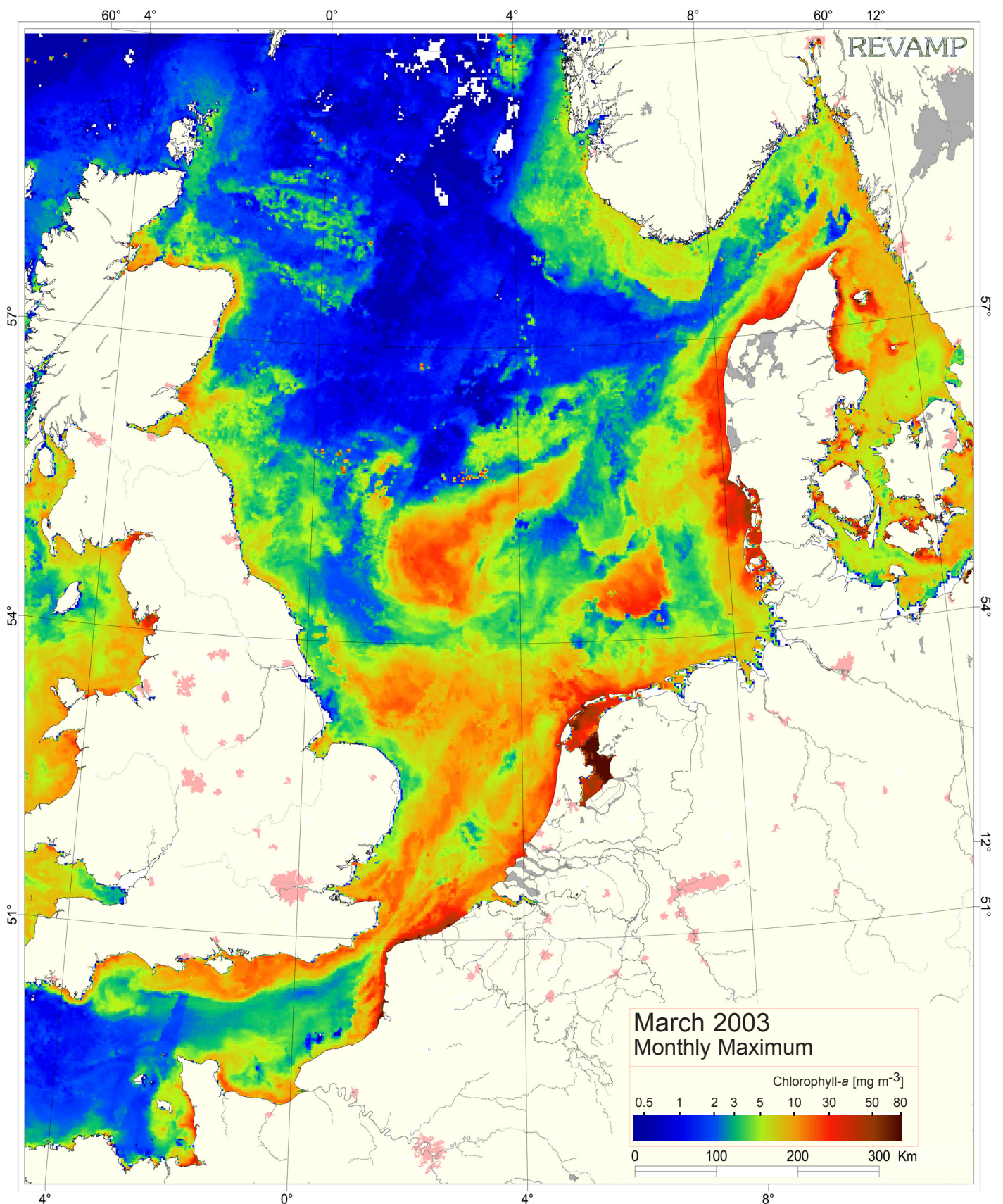
- 1) Maximum and Median image per month and per season
- 2) The monthly counts images
- 3) The monthly mean relative error images
- 4) Monthly dynamics of Chlorophyll-a for a number of sub-regions.



7

Monthly Chlorophyll-*a* Median and Maximum maps

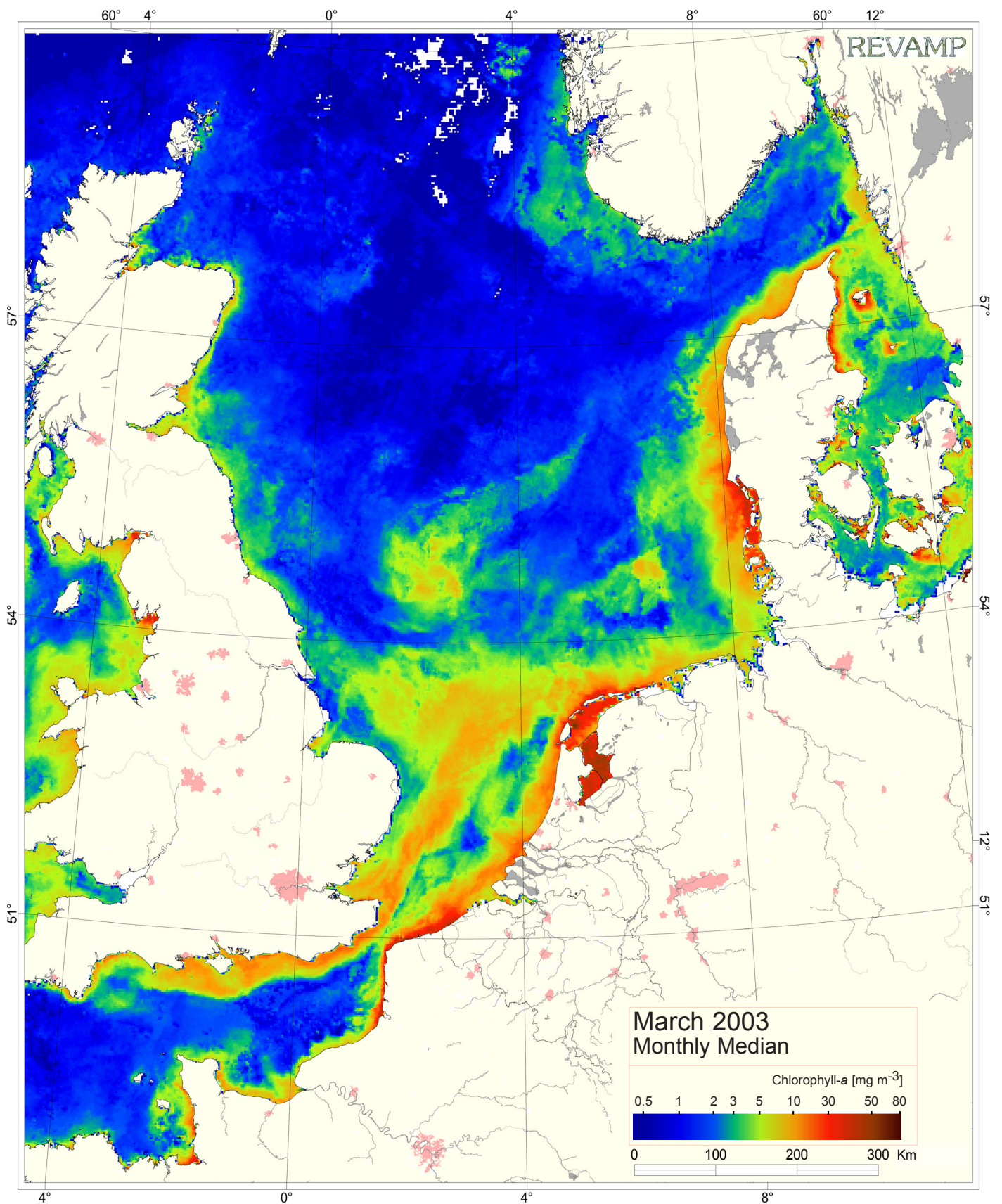




March 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The March 2003 Maximum Chlorophyll-a image by its nature displays more events and features from the individual scenes than the corresponding median image. The algae bloom areas show up stronger, and with higher concentration values. The March bloom(s) for instance in Skagerrak have been confirmed by in-situ measurements (ferry-box) as diatoms with increasing concentrations towards the Norwegian coast in the middle of March. By the end of March concentrations in the order of 10-20 mg m^{-3} were confirmed toward the coast on the Danish side.

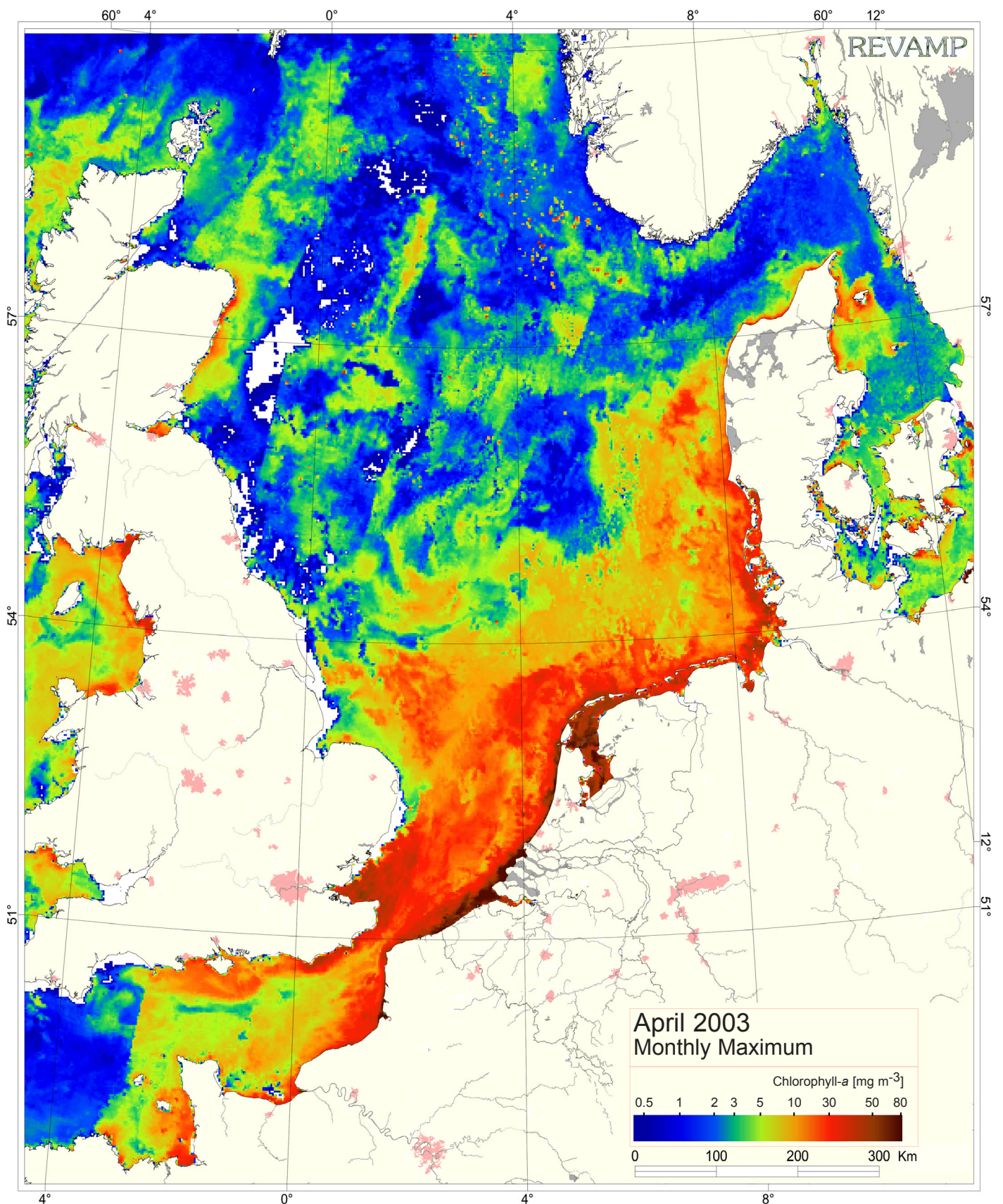




March 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The March 2003 median Chlorophyll-a image shows that spring algae blooming has started in several areas; along the West-coasts of Belgium, Holland and Denmark plus along the South-East coast of the UK with concentrations above 10 mg m^{-3} . Even in the Skagerrak towards the Swedish and Norwegian coasts and in the central North Sea by the Dogger bank concentration values up to $5\text{--}7 \text{ mg m}^{-3}$ are seen, which is an increase as compared to the normally lower values in these regions. Often the spring starts already in late February in Northern North Sea, Skagerrak and Kattegat.

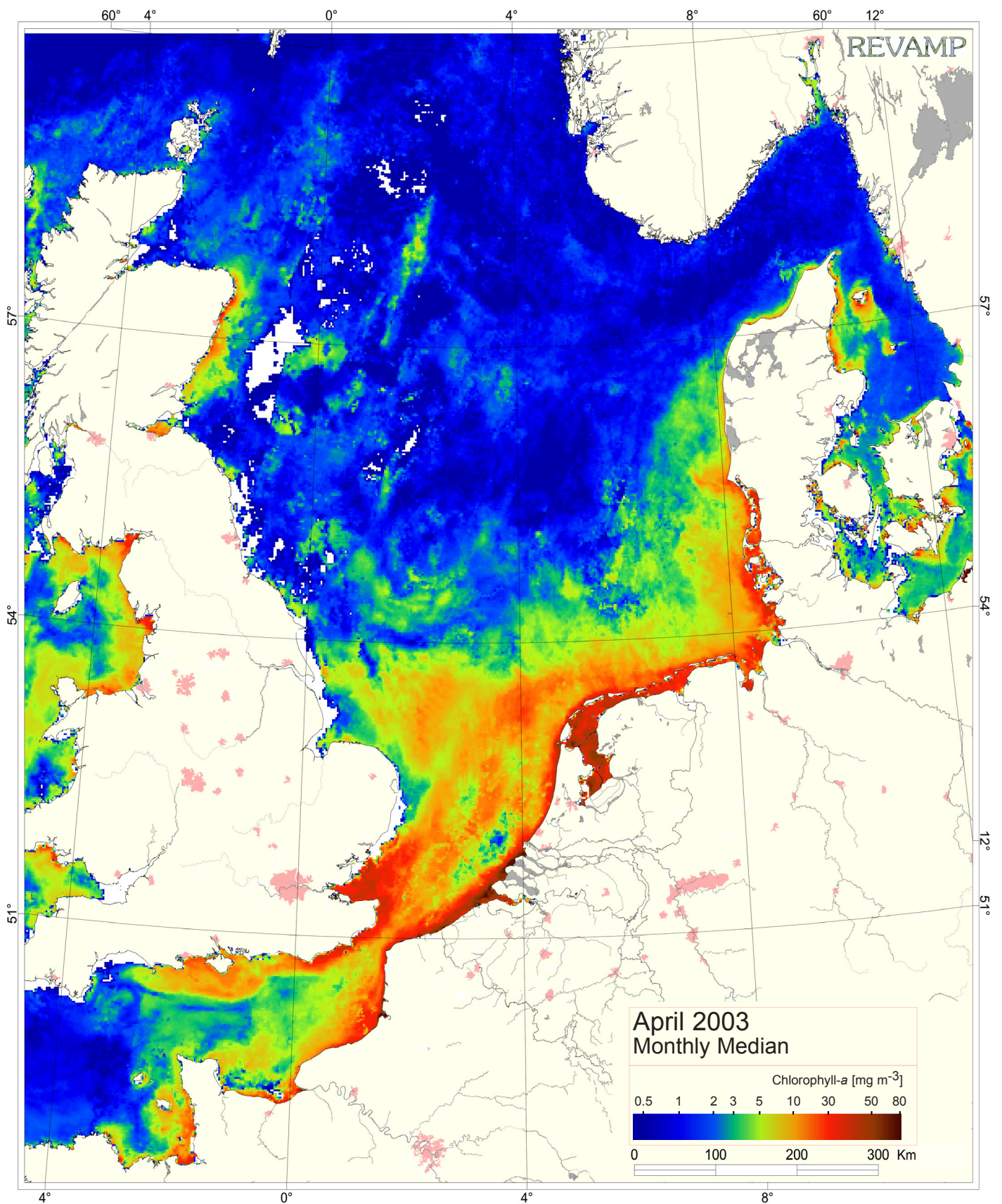




April 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The April 2003 maximum Chlorophyll-a image shows, like the March maximum, larger concentrations and more features than the median. In Belgium coastal water the maximum spring Chlorophyll-a concentration normally arrives in April, which is confirmed here by MERIS. The blooming activity is also extending further towards the South-West, and into the Westernmost part of the English Channel. Also the Frisian Front has intensive activity. The Central-North North Sea also features several small inhomogeneous areas with increased Chlorophyll-a.

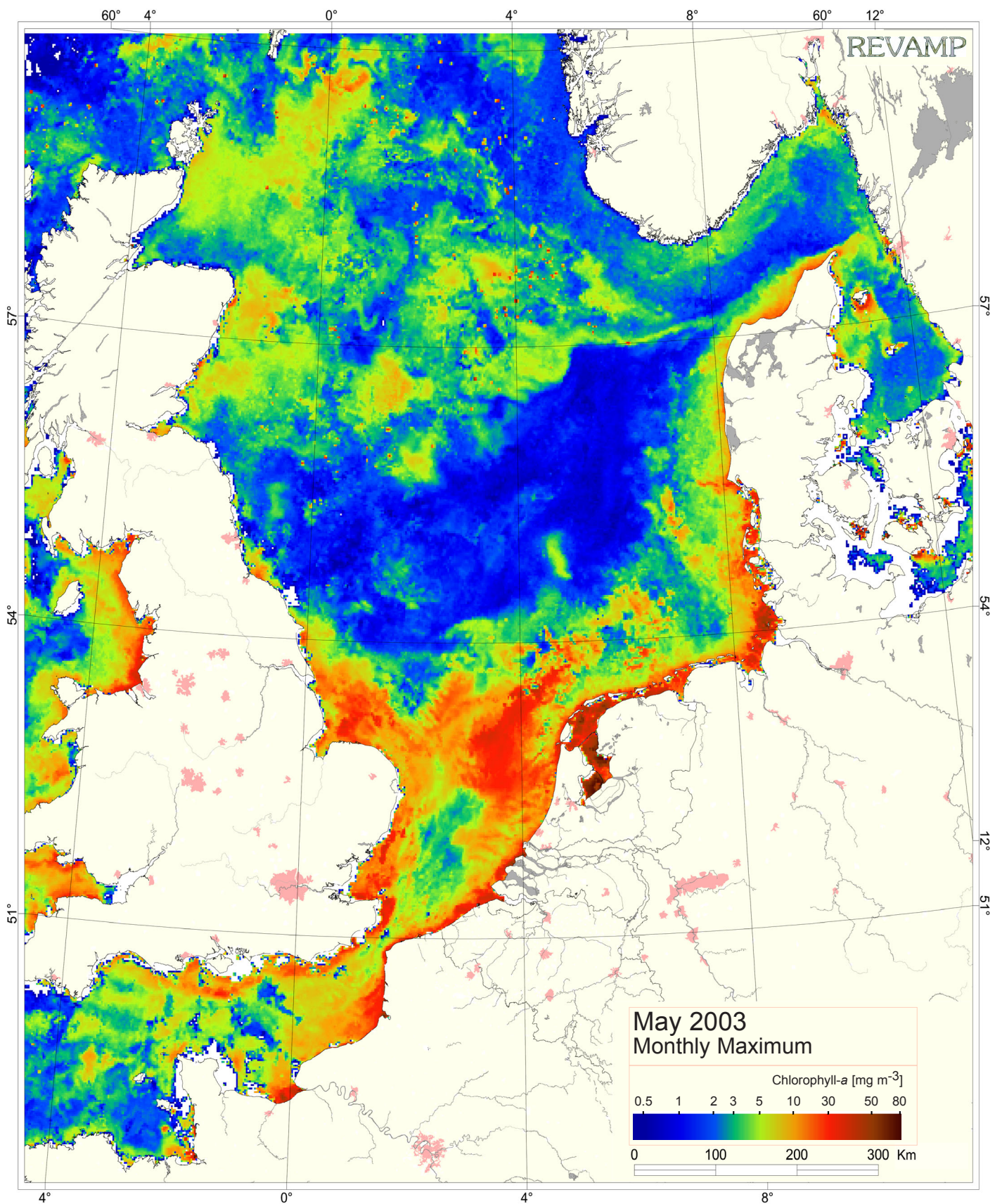




April 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The April 2003 median Chlorophyll-a image shows larger concentrations along the Belgian coast, in the German Bight and in the Thames Estuary compared to the March image. In contrast, lower concentrations are seen central North Sea by the Dogger bank, in Skagerrak and in Kattegat indicating that the blooming here dramatically decreased, probably having used up most available nutrients. In the Southern part the blooming is still increasing with nutrients still readily available.

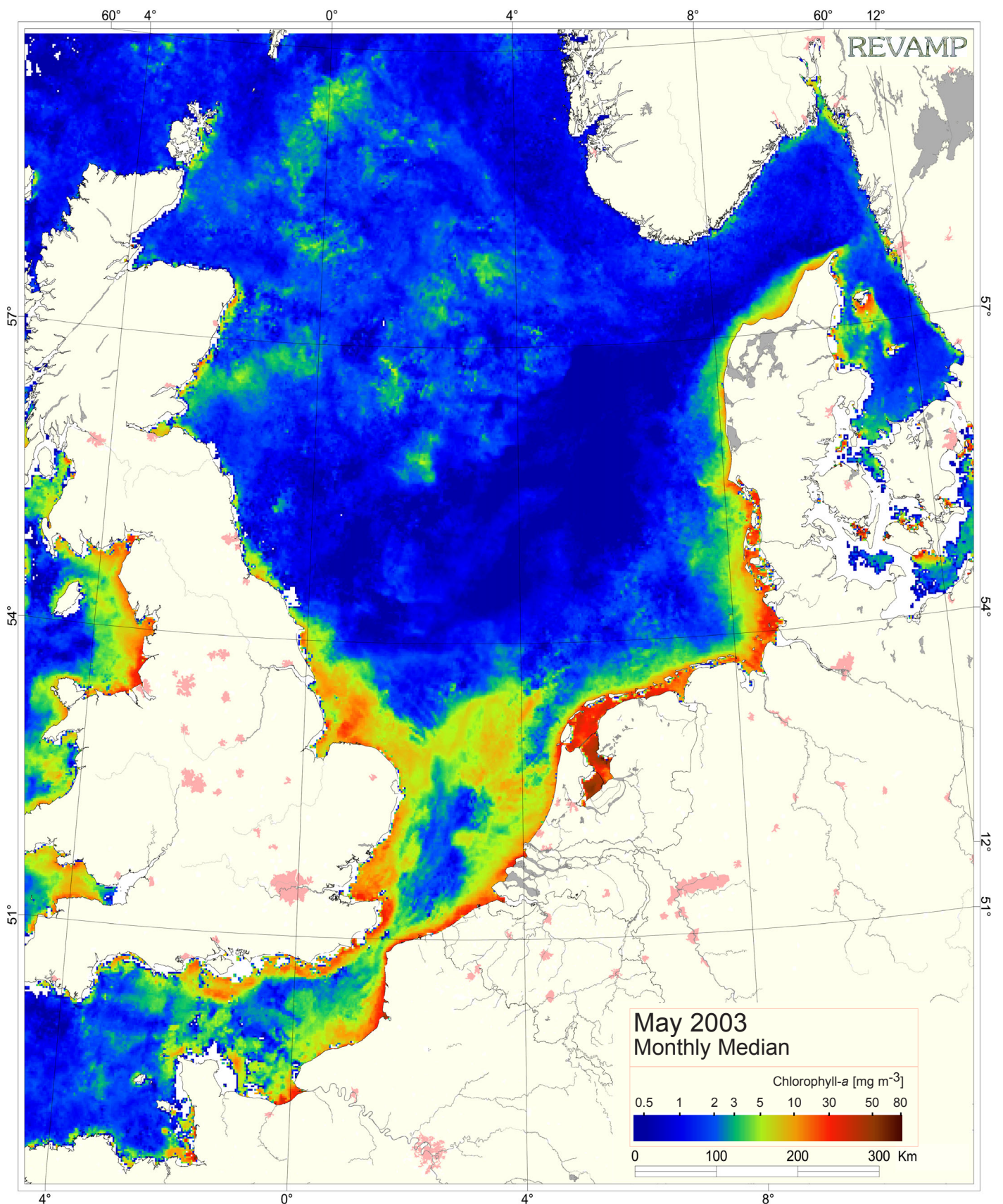




May 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The May 2003 maximum Chlorophyll-a image shows as mentioned in the text for the May median image, a pronounced blooming area in the Central-Northern North Sea stretching all the way from the UK North-East coast to the Danish North-West coast into the Skagerrak. The bloom extension is much influenced by the bathymetry and does not extend into the Norwegian Trench area. Here a different bloom is seen towards the Norwegian coast, which was confirmed in-situ to be of the species *Pseudo-Nitzschia Pseudodelicatissima*.

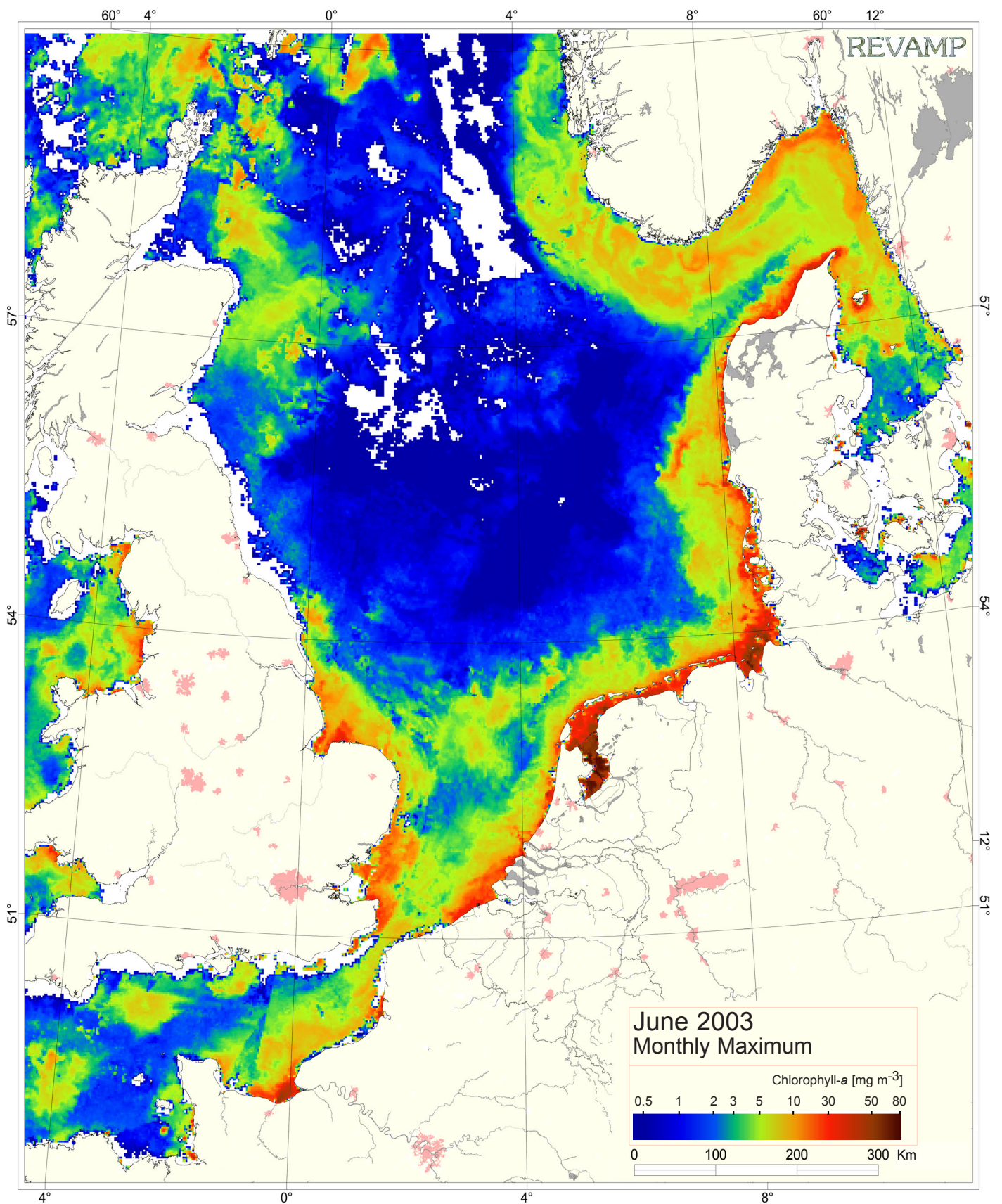




May 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The May 2003 median Chlorophyll-a image shows a marked decrease in Chlorophyll-a in all areas compared to the March and April images. A new blooming area on the UK East coast, by The Wash, is also seen. The still high values in the Danish and German Wadden Sea (on the eastern side of the barrier islands) are probably overestimated due to bottom reflections in very shallow waters (see also explanation in Chapter 11). Indications of slightly increased concentrations in the Central-North North Sea are seen, but are much more evident in the maximum image.

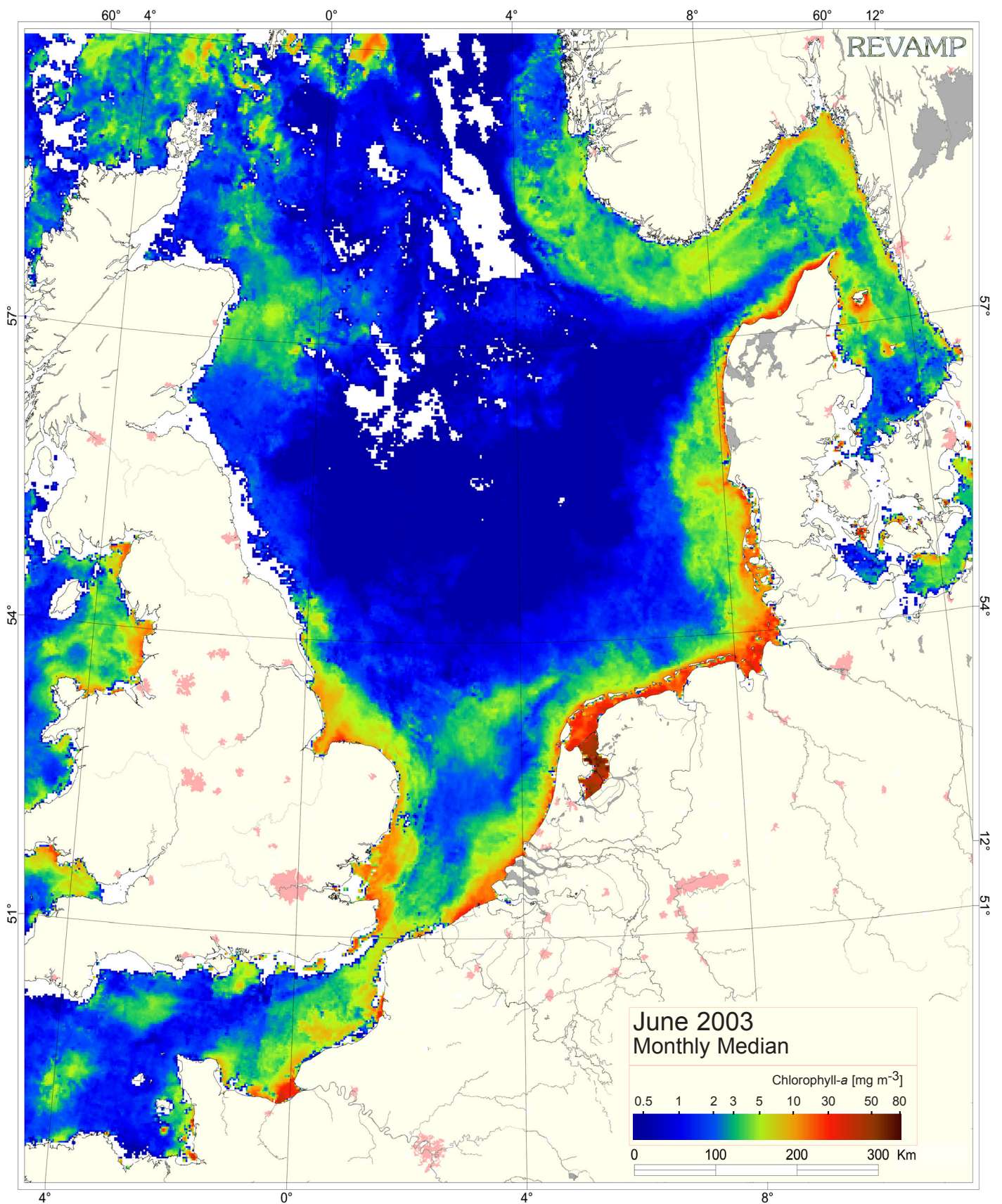




June 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The June 2003 maximum Chlorophyll-a image shows mainly the same features as the median image but with stronger concentrations in the NE North Sea, Skagerrak, along the Danish West Coast, in the German Bight and in the English Channel and Thames Estuary but also to some extent along the Dutch and Belgium coasts and by the Dogger Bank. Much of the blooming features at and around Horn's Reef (55.5°N, 8°E) are due to suspended sediments so the true Chlorophyll-a concentrations in the region are in fact lower.

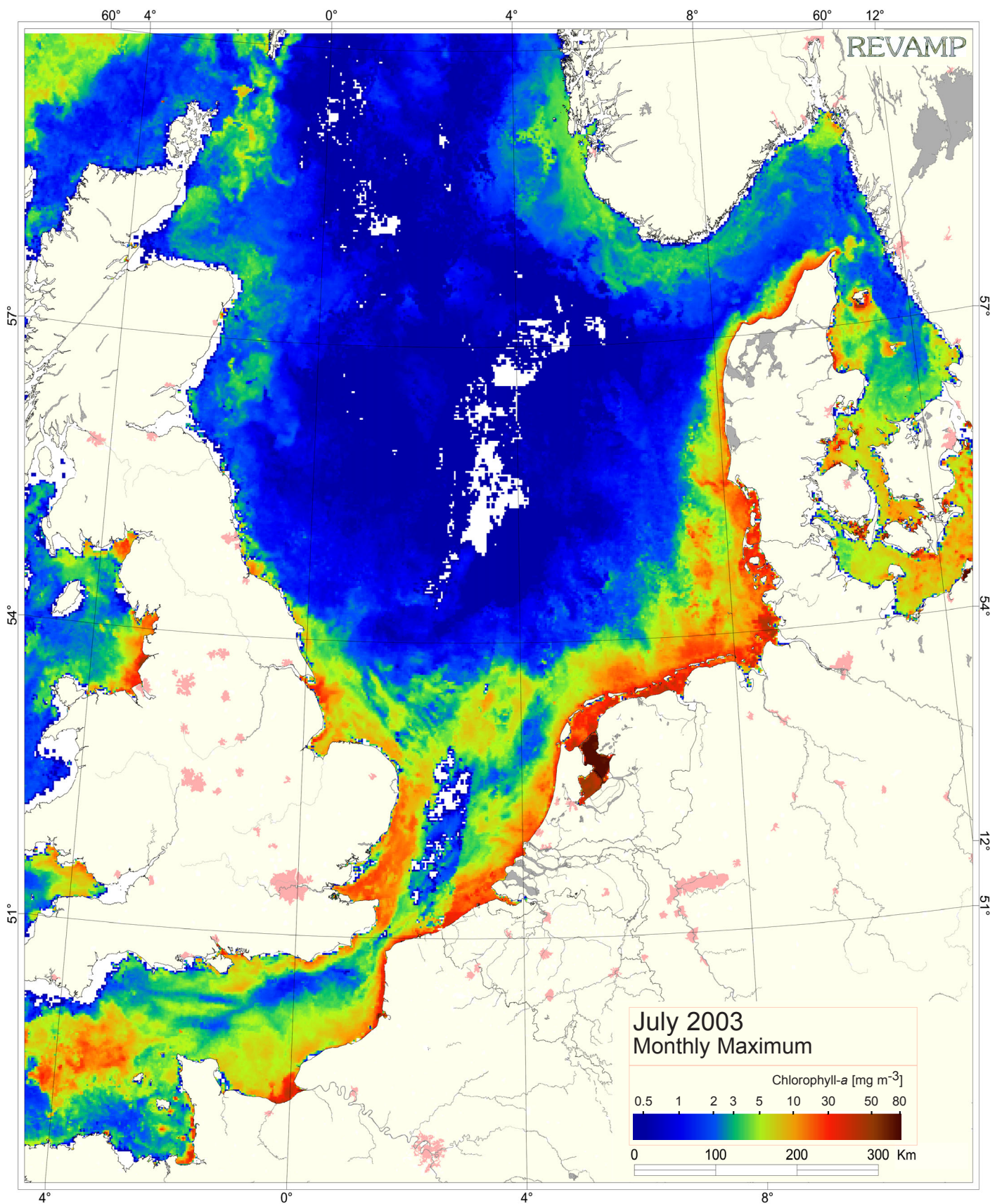




June 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The June 2003 median Chlorophyll-*a* image shows a continued and increased blooming activity in the Skagerrak area within Norwegian Trench region, which was confirmed as diatoms with 3 dominant species. High concentrations are also found in Kattegat, on the Danish West Coast, particular in the Jammer Bay in the Skagerrak. Also, the Wash area on the UK East coast is still showing increased values of Chlorophyll-*a*. A pronounced blooming is occurring in the North-Westernmost part of the North Sea by the Shetland and Orkney Islands.

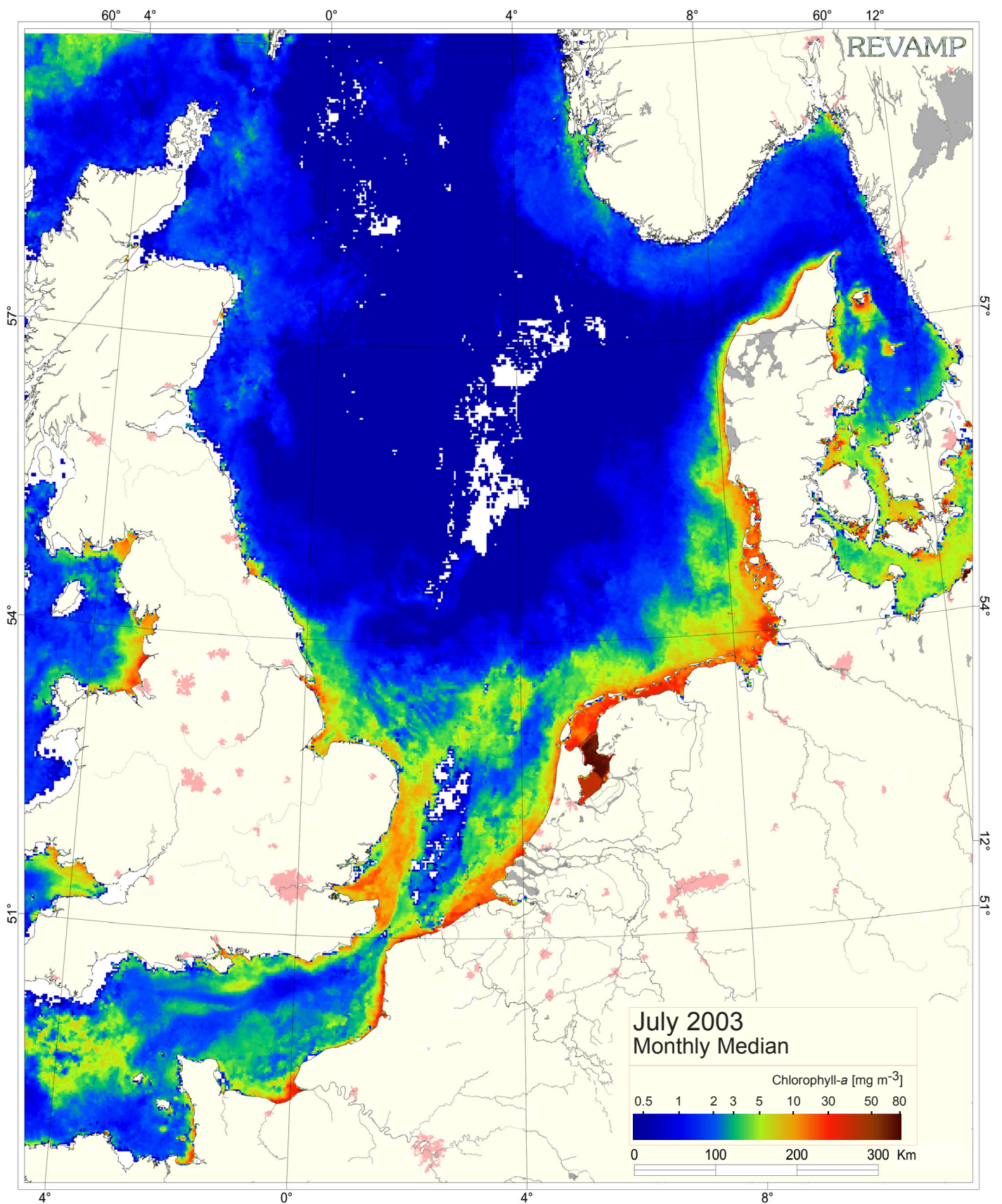




July 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The July 2003 maximum Chlorophyll-a image shows more feature than the median image with for instance small blooming events in along the Norwegian coast in Skagerrak, in the North-Easternmost corner of the image (North of Scotland and West of the Shetland - and Orkney Islands). Also a pronounced bloom is seem in the Western part of English Channel. This has been confirmed by in-situ measurements to be a *Karenia Mikimotoi* bloom with Chlorophyll-a concentrations up to 50 mg m^{-3} .

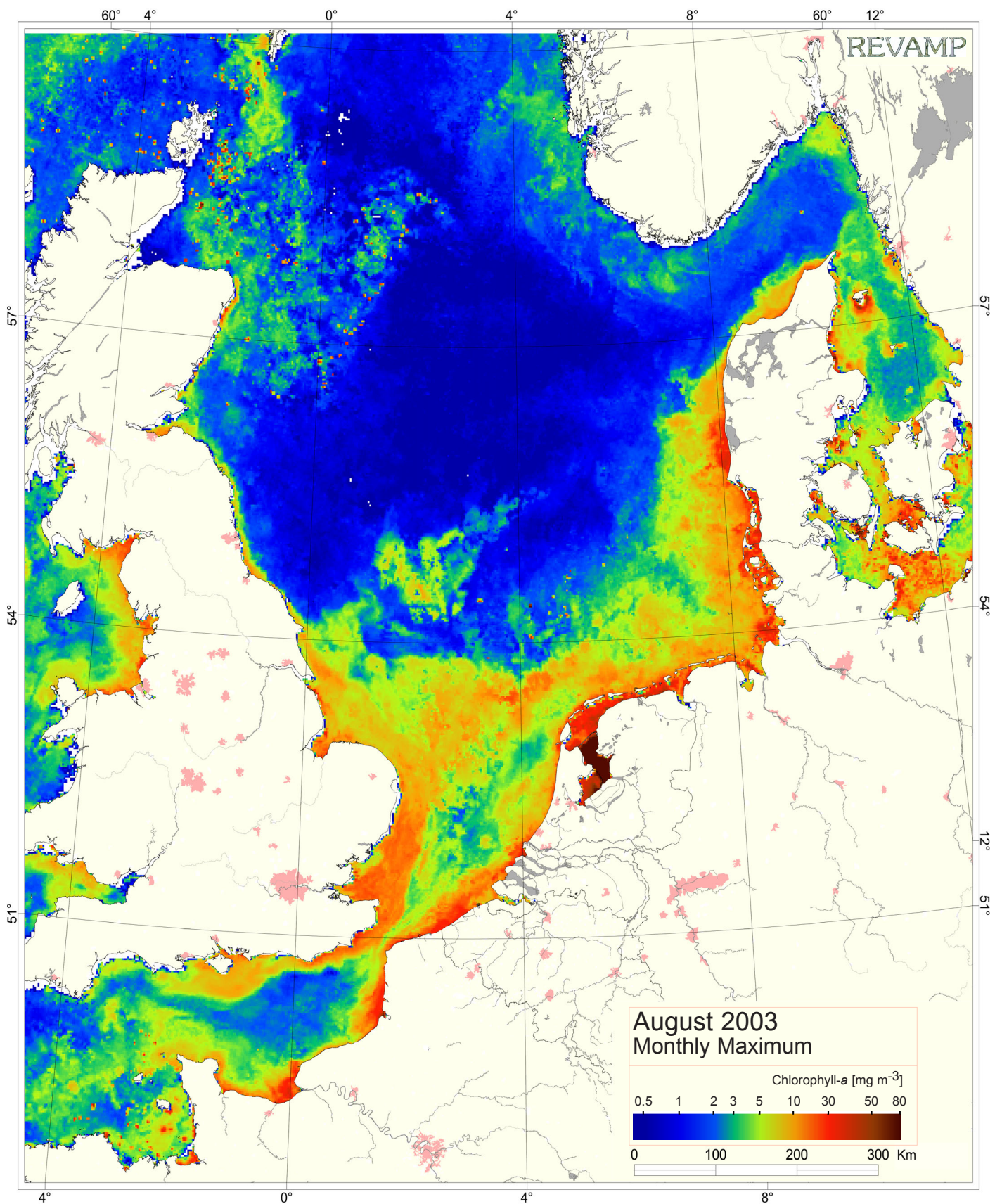




July 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The July 2003 median Chlorophyll-a image generally shows decreased concentrations as compared to June. This is most pronounced in Northern part of the image, the Scottish coast, the Skagerrak, the Oslo Fjord and the Kattegat. Other areas like the German Bight and the Dutch coastal zone even have minor increases as compared to July.

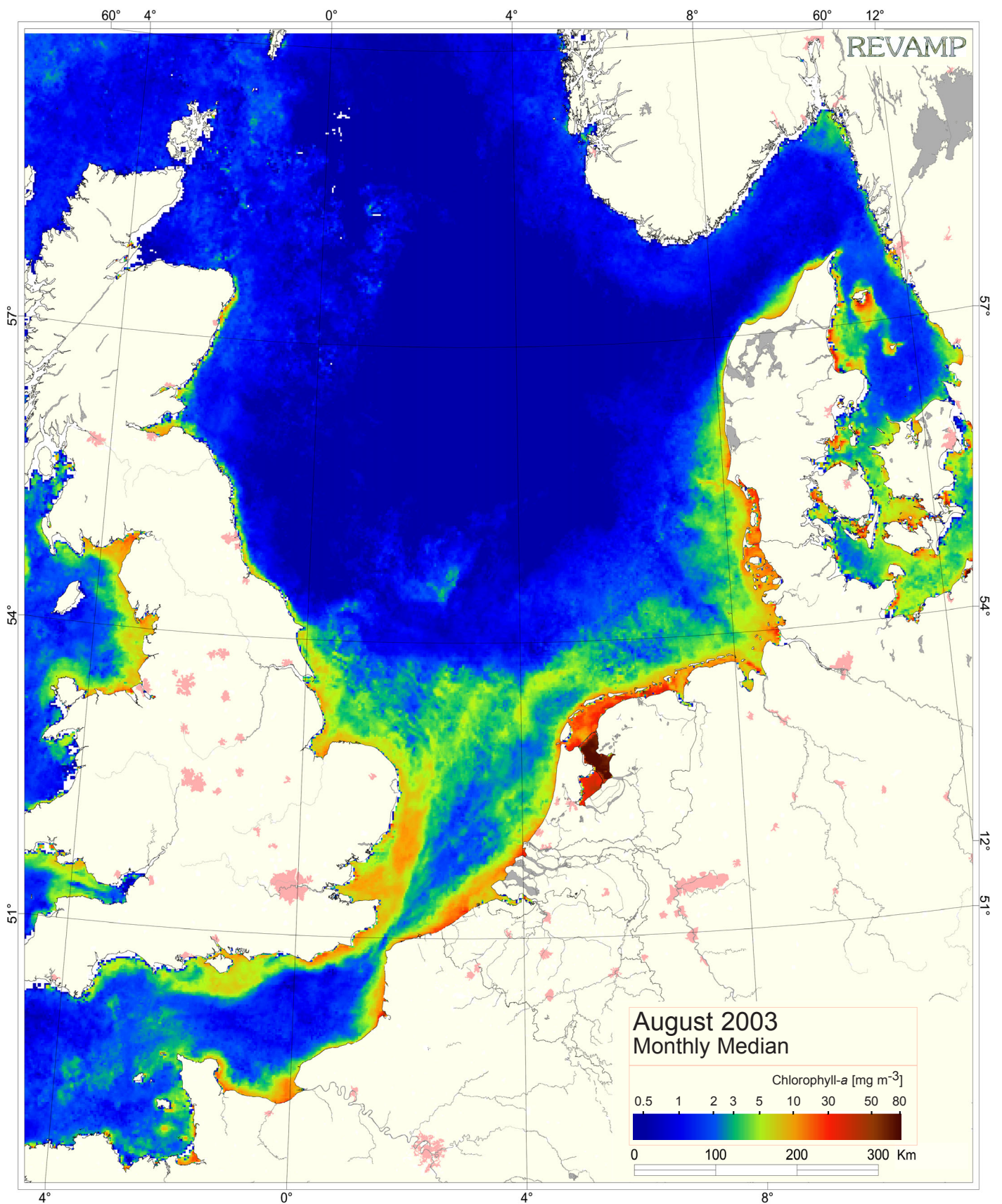




August 2003 Maximum REVAMP Chlorophyll-*a* [mg m^{-3}]

The August 2003 maximum Chlorophyll-*a* image shows indications of small bloom events in the North-Easternmost quarter of the image. The red-orange dots in this area are artefacts and not real Chlorophyll-*a* concentrations mostly due to cloud-edges which were not masked out from the processing. Also a bloom at the Dogger Bank can be seen near the central North Sea. A strong blooming is indicated at the Danish West coast just north of Horn's Reef with concentration up to 30 mg m^{-3} which is rather extreme for this area.

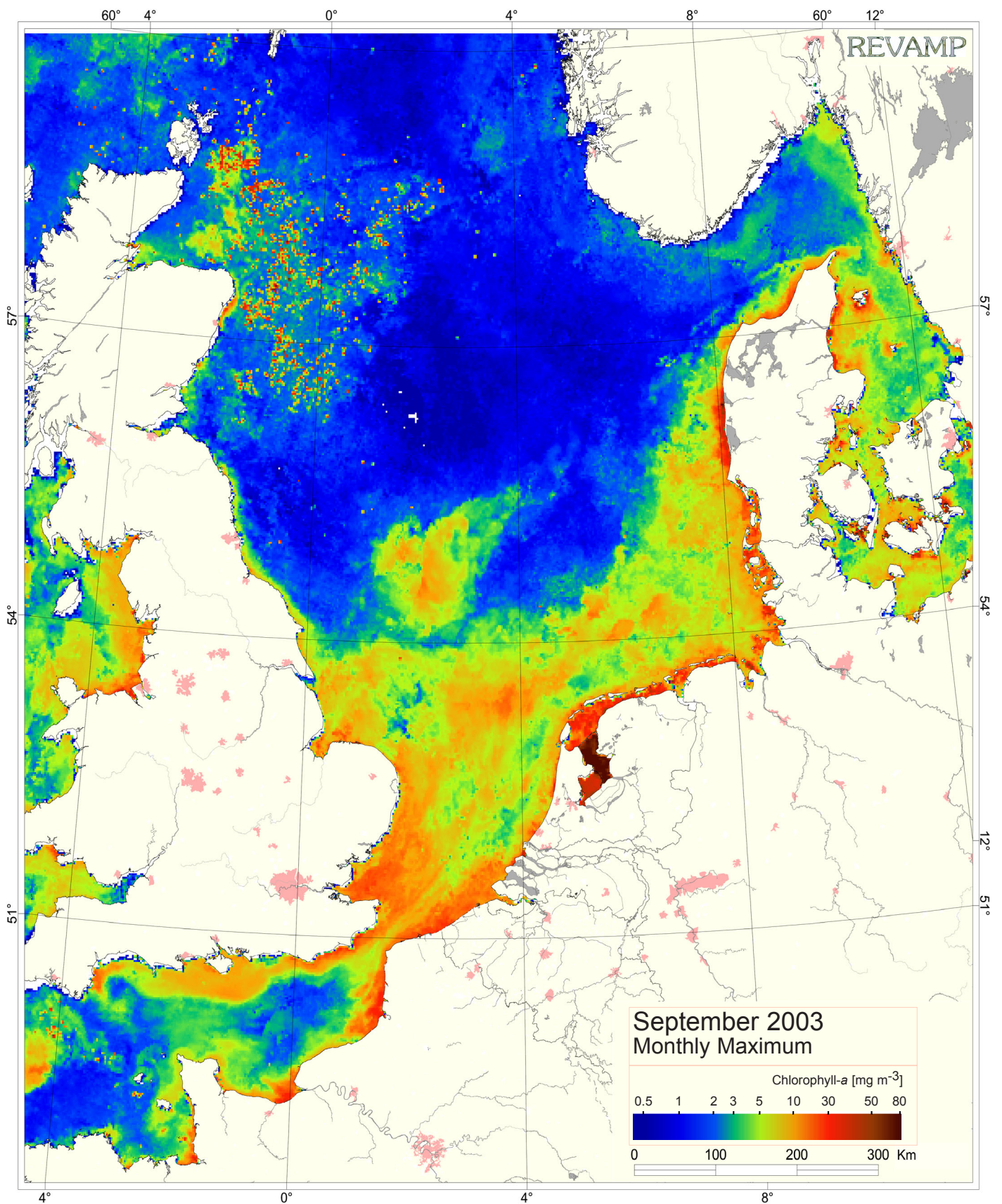




August 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The August 2003 median Chlorophyll-a image is remarkably similar to the July median. Close examination does however reveal small differences where concentrations in the German Bight, along the Dutch and Belgium coasts have decreased slightly. In the Northern English Channel the concentrations are very similar but the distribution pattern is different in August as compared to July.

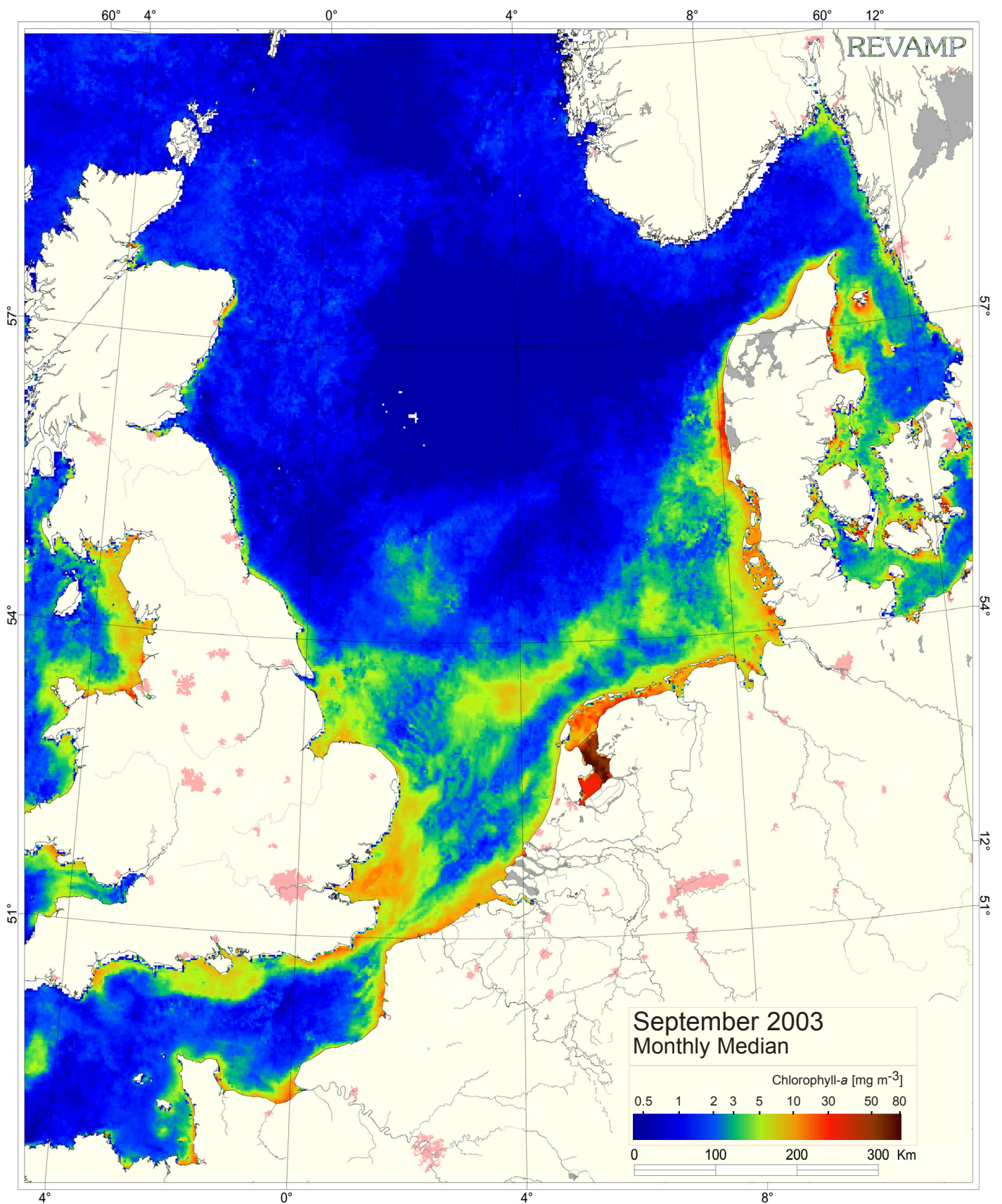




September 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The September 2003 maximum Chlorophyll-a image shows that increased concentrations during the month were found in many areas. An intense blooming occurred around the Dogger Bank (approx. 55°N , 3°E). Intensive blooming also occurred on the Southern UK coast, at the French and Belgium coasts, and as indicated in the median image by the Frisian frontal zone. Substantial blooming occurred in all the waters between the UK South-East coast and the Dutch and German Coasts. Blooming events, although with lower concentrations happened in the NW North Sea and in Eastern Skagerrak.

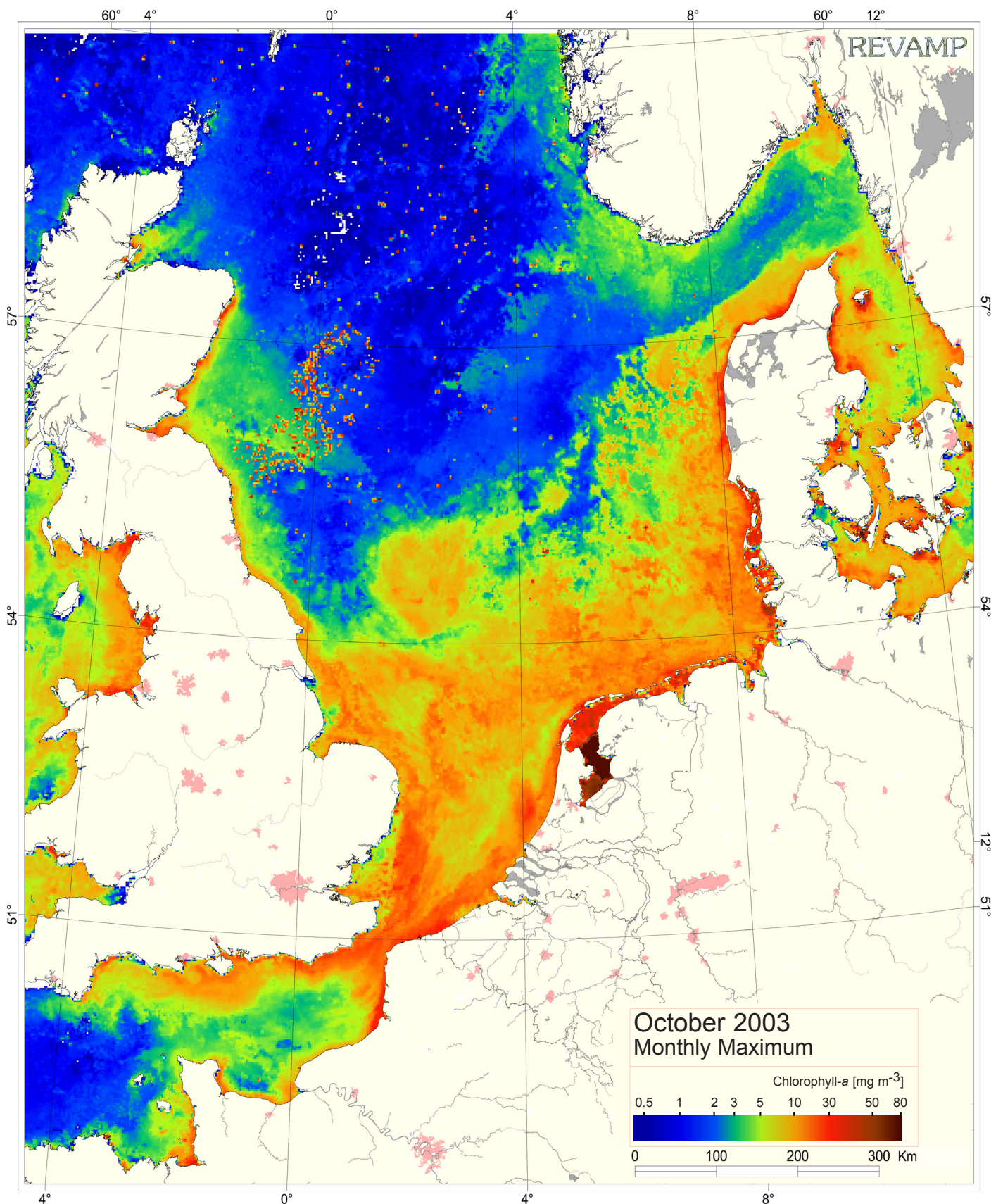




September 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The September 2003 median Chlorophyll-a image is quite similar to the July 2003 median image: normal and low concentrations in the central North Sea and in the upper half of the North Sea, Skagerrak and Kattegat, but also in much of the English Channel area. Slight increased concentrations compared to July are found along the Danish West coast, outer German Bight and off-shore Dutch and English waters by the Frisian Frontal Zone. Blooms are also still occurring in Belgium coastal Water and near the Thames Estuary.

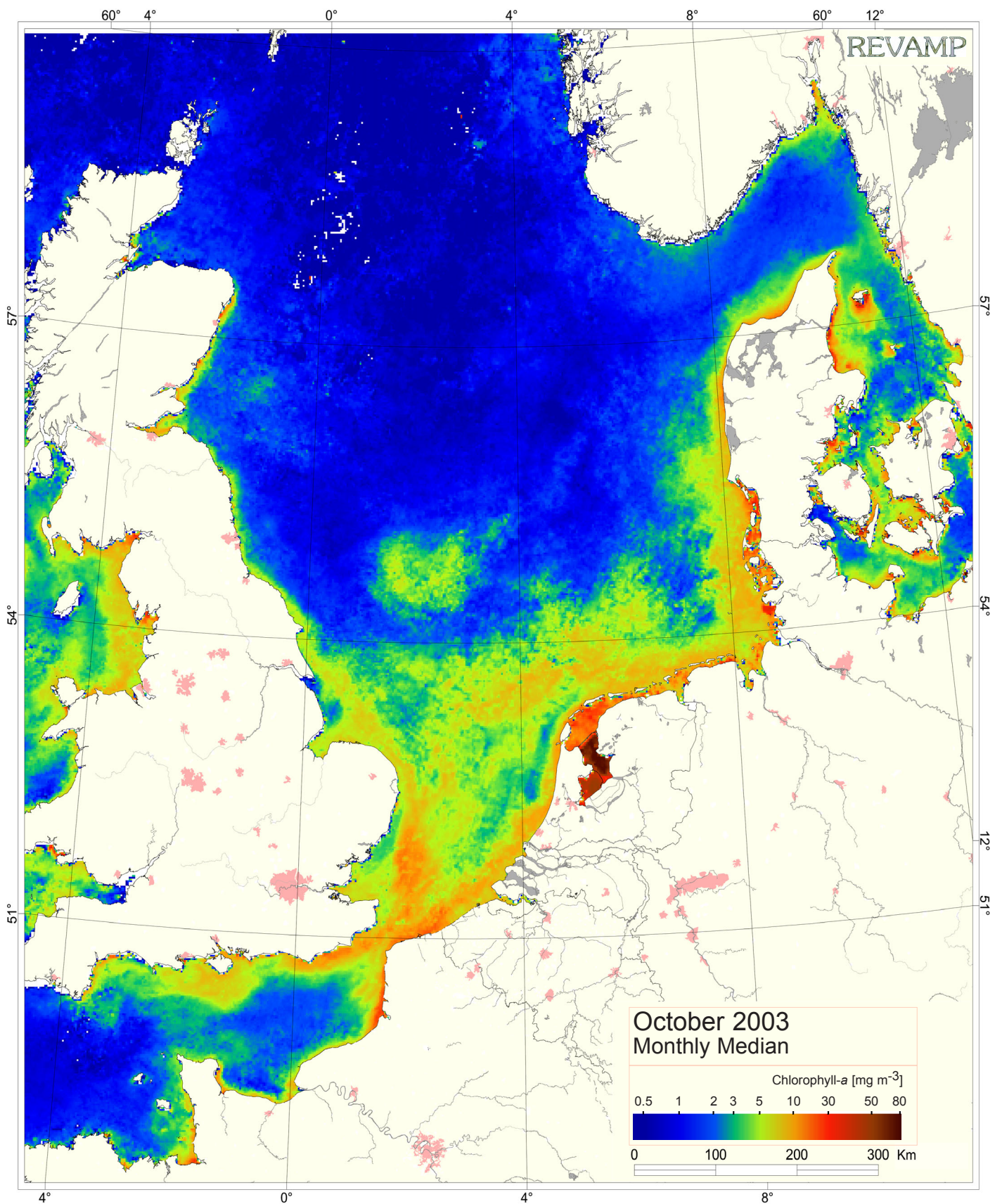




October 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The October 2003 maximum Chlorophyll-a image confirms the intense blooming almost everywhere in the North Sea. In the Danish and Norwegian waters it is quite common that the autumn blooming happens in late September or first half of October, so the events shown are quite realistic, and for instance confirmed to be diatom in Skagerrak, although concentrations may generally be overestimated in the map. Some artificial red-orange dots are again seen in the Northern part of the North Sea.

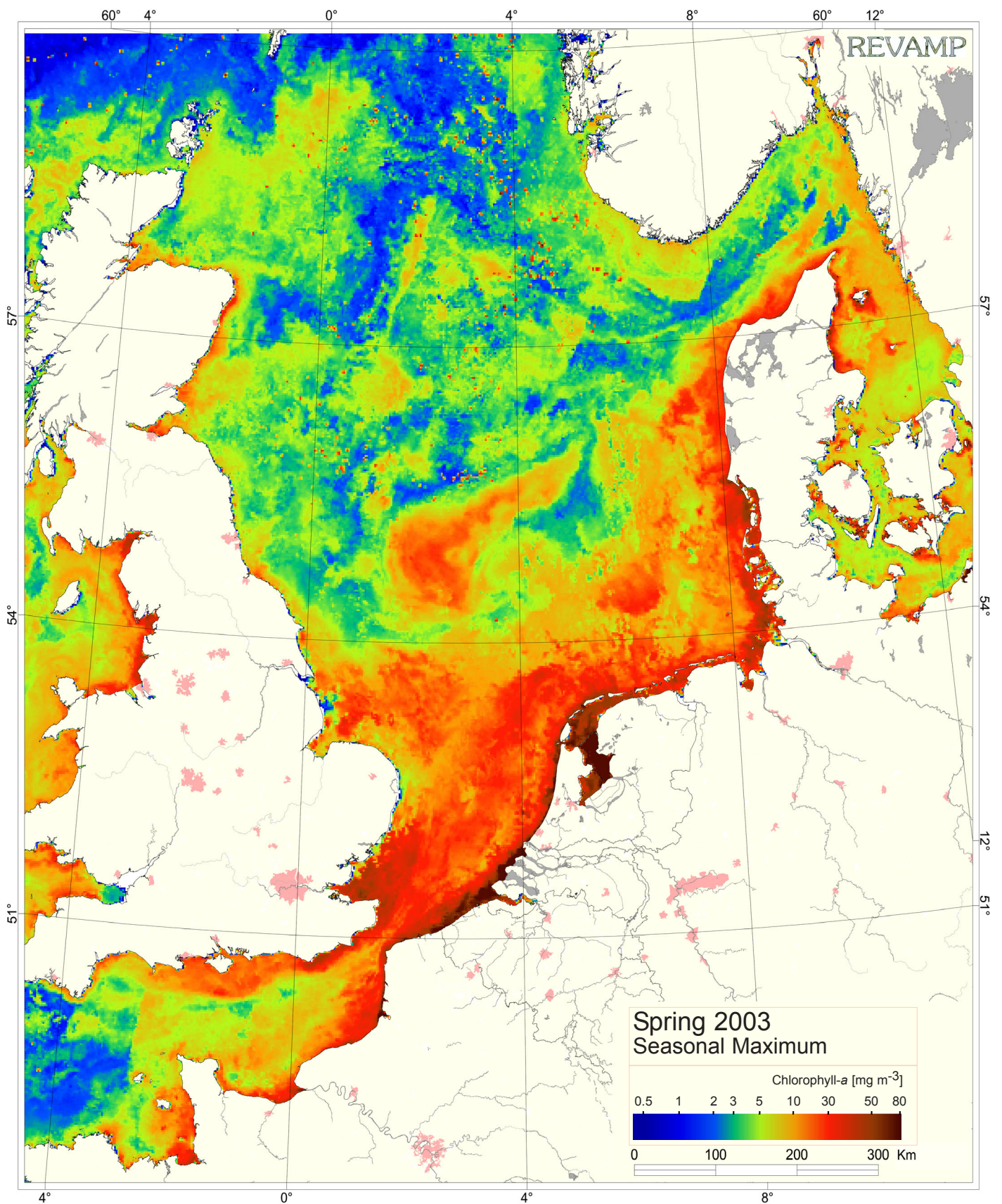




October 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The October 2003 median Chlorophyll-a image generally shows higher concentrations than in September and higher than what is normally expected during this month. It should be noted that 2003 was an exceptionally warm year with summer temperatures well above average, so this may be part of the reason. On the other hand some validation points indicate that the Chlorophyll-a algorithm may have a general tendency to overestimate Chlorophyll-a during the winter month.

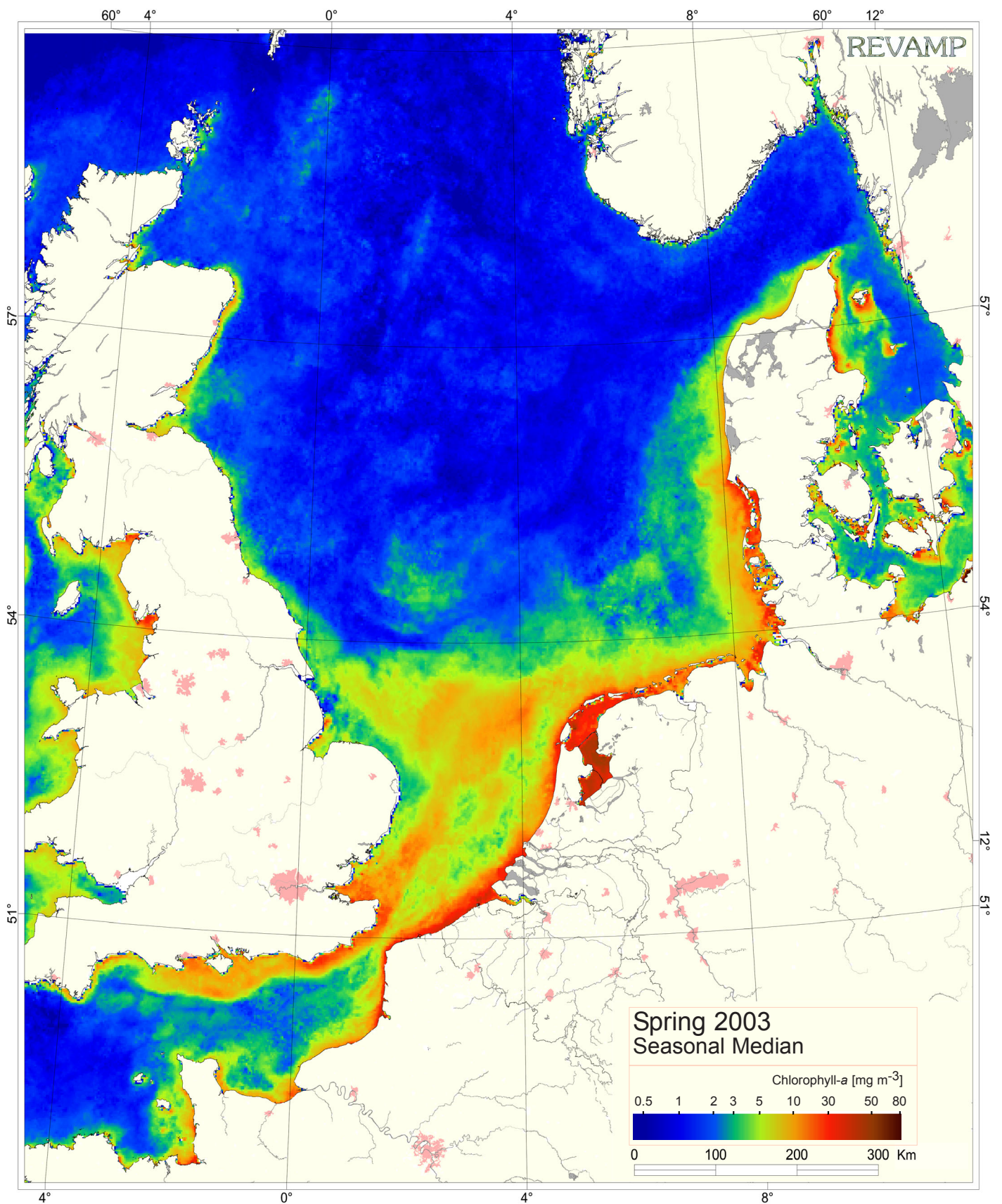




Spring 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The Spring 2003 maximum Chlorophyll-a image shows that blooming features and events have taken place nearly everywhere in the North Sea with varying degrees of concentration-increases. Strongest blooming features are seen at the Dogger Bank, along the Danish West Coast, in the German Bight and in all Belgian and Dutch waters (not just the coastal zones), and in the Southern and South-Eastern UK waters.

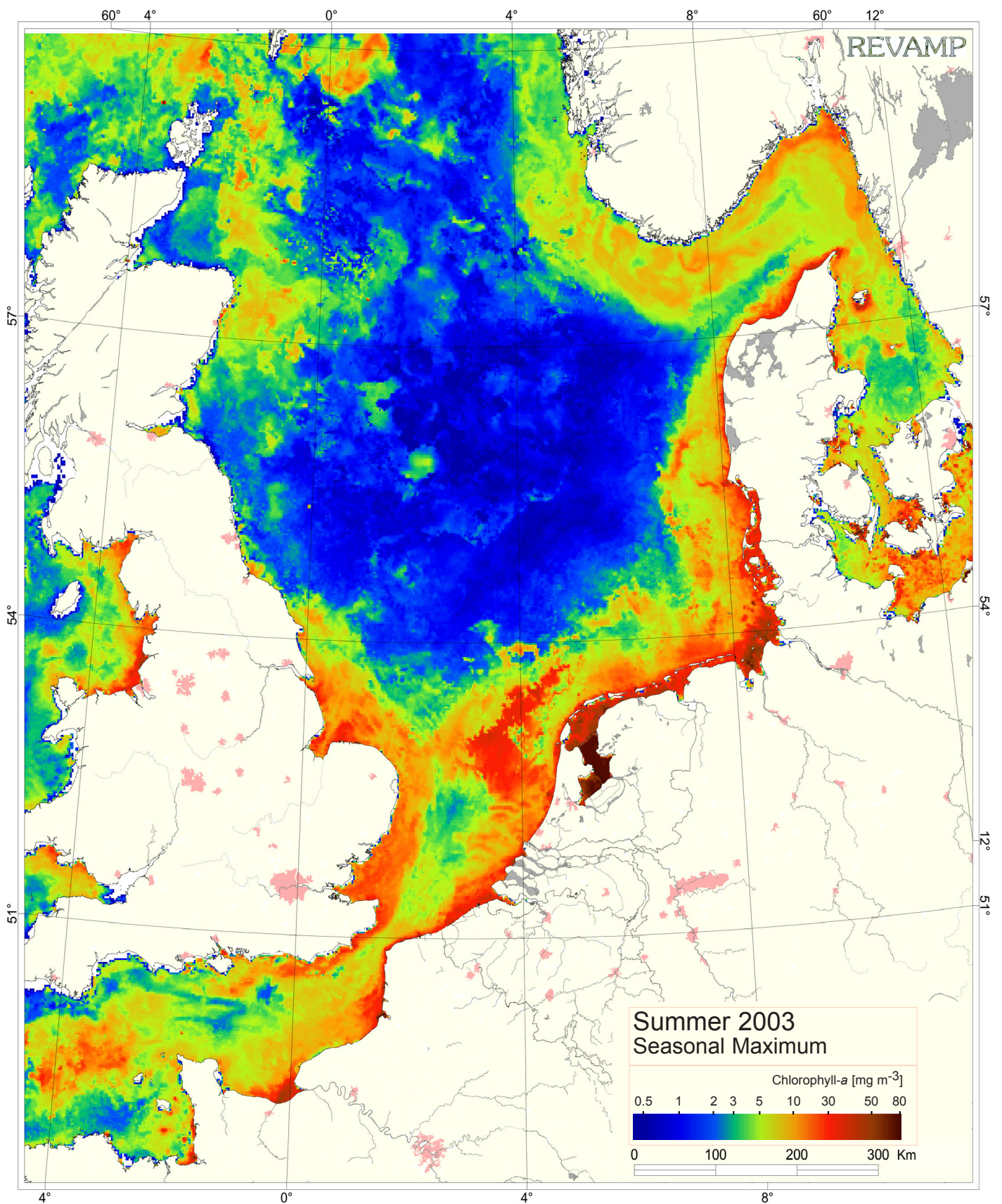




Spring 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The Spring 2003 Median Chlorophyll-a image summarises the MERIS scenes from the period 15. February - 15. May 2003. Concentrations in the Northern half of the North Sea and in the central North Sea and in the Westernmost part of the English Channel are in the range 0 - 3 mg m^{-3} , except along Danish and UK coasts. In the Southern North Sea off-shore waters generally have spring concentrations in range 3-15 mg m^{-3} , while coastal areas may have very high Chlorophyll-a concentrations >30 mg m^{-3} .

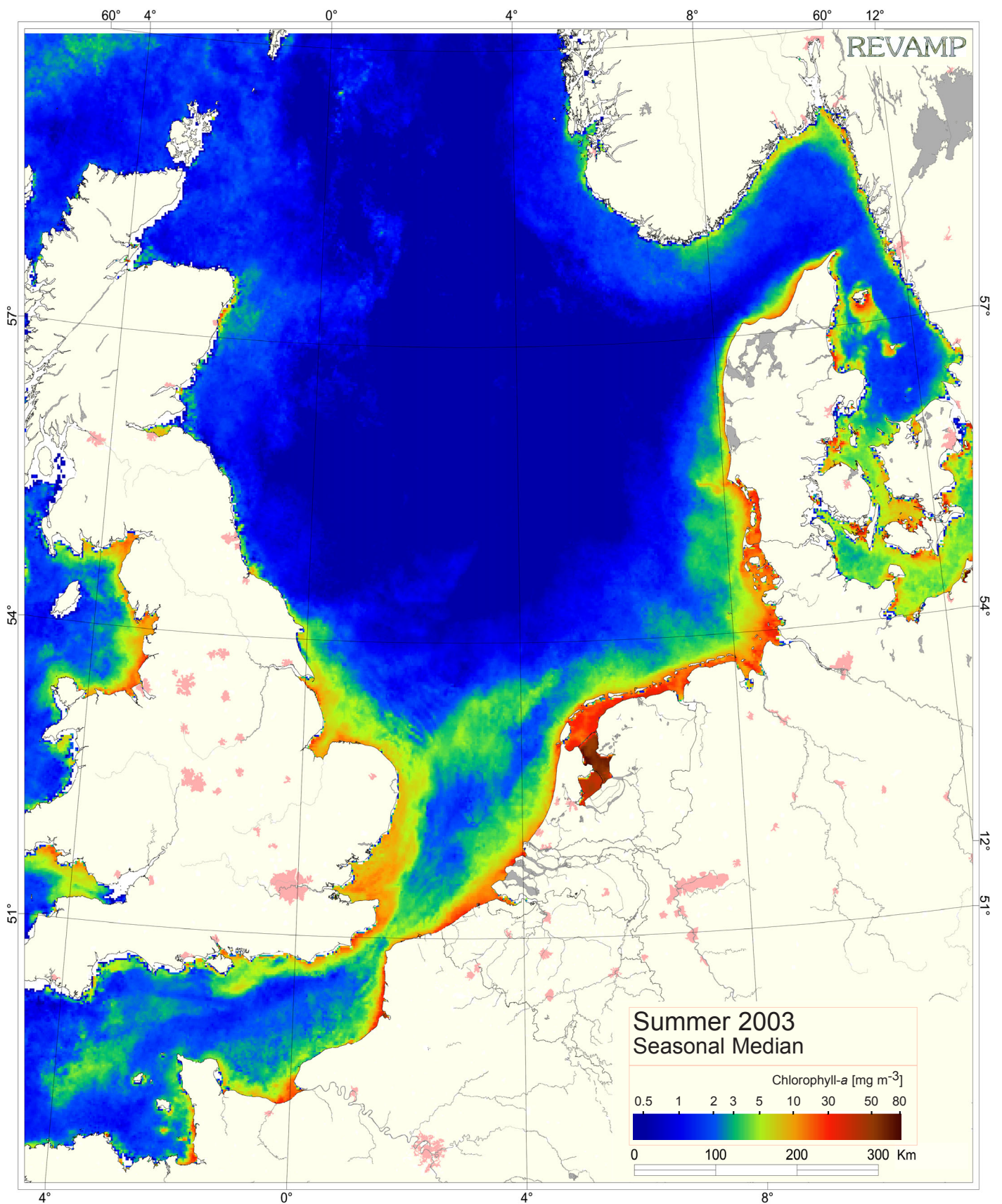




Summer 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The Summer 2003 maximum Chlorophyll-a image, covering the period 15. May - 15. August, shows many of the same features as the spring maximum did with blooming over much of the North Sea, but not quite as strong as during spring, and also with the pronounced difference that the central North Sea does not show significant high peaks in Chlorophyll-a concentration during the summer

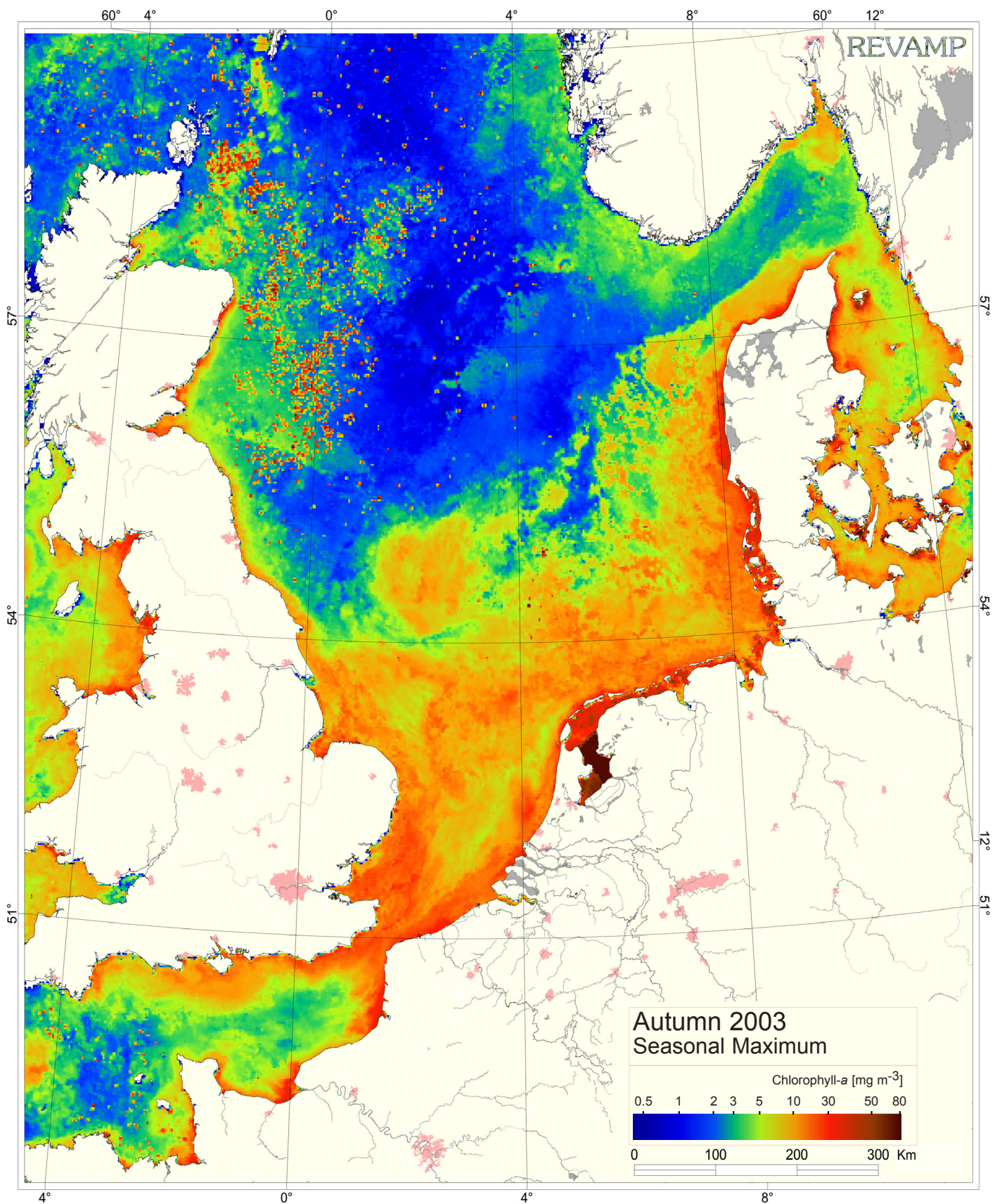




Summer 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The Summer 2003 median Chlorophyll-a image shows the same overall tendencies as the spring median image, but concentrations are generally lower than in the spring image. This is seen along the Danish West-coast and in the whole upper English Channel area between UK and Holland/Belgium. Also the clear water area in the Westernmost English Channel has extended towards east as compared to the spring image. One exception to the general trend are the Norwegian coastal waters which have increased concentrations as compared to the spring image.

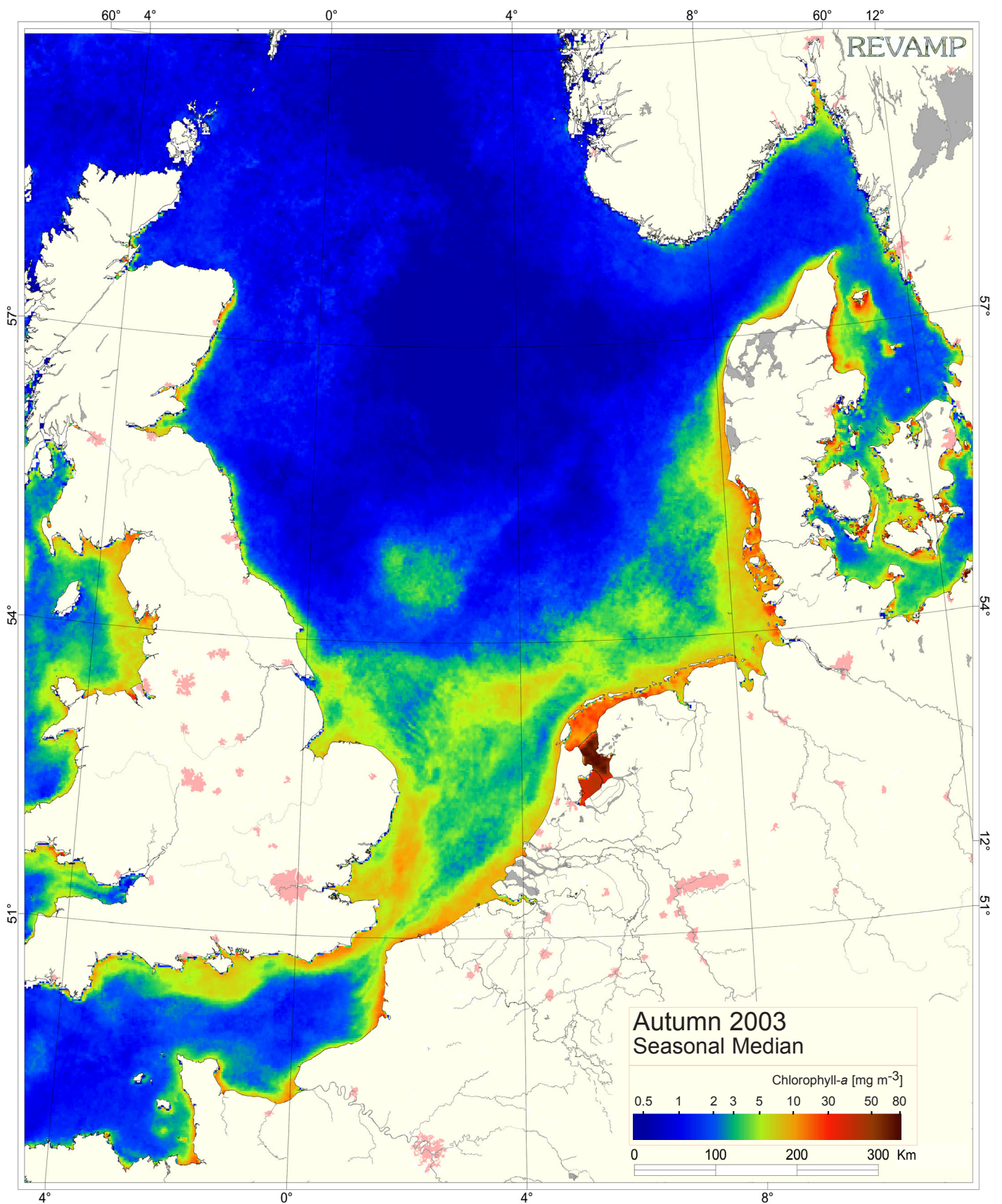




Autumn 2003 Maximum REVAMP Chlorophyll-a [mg m^{-3}]

The Autumn 2003 Maximum Chlorophyll-a image shows that the autumn maximum Chlorophyll-a values are higher than the summer maximum values in many places, for instance in the Southern half of the North Sea, although the values along most of coasts are more at the same level as during the summer. In the North-Eastern North Sea and in Skagerrak the opposite trend is seen with slightly lower autumn concentrations.

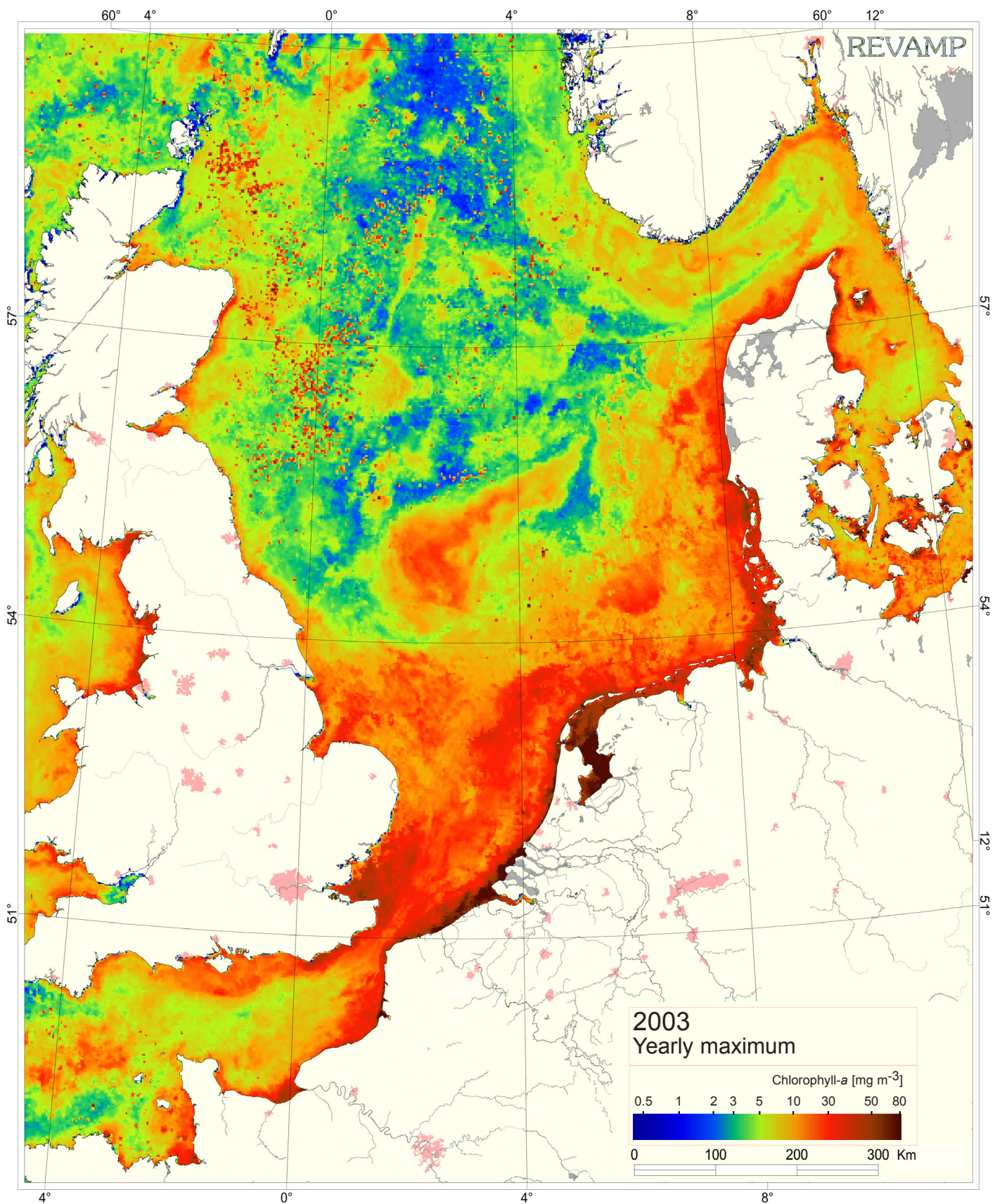




Autumn 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The Autumn 2003 Median Chlorophyll-a image summarises the MERIS scenes from the period 15. August - 15. November 2003. It displays many of the same features as very often seen both in the spring median image and the summer median image. In terms of concentrations, the autumn seems to be intermediate as compared to the spring and summer.

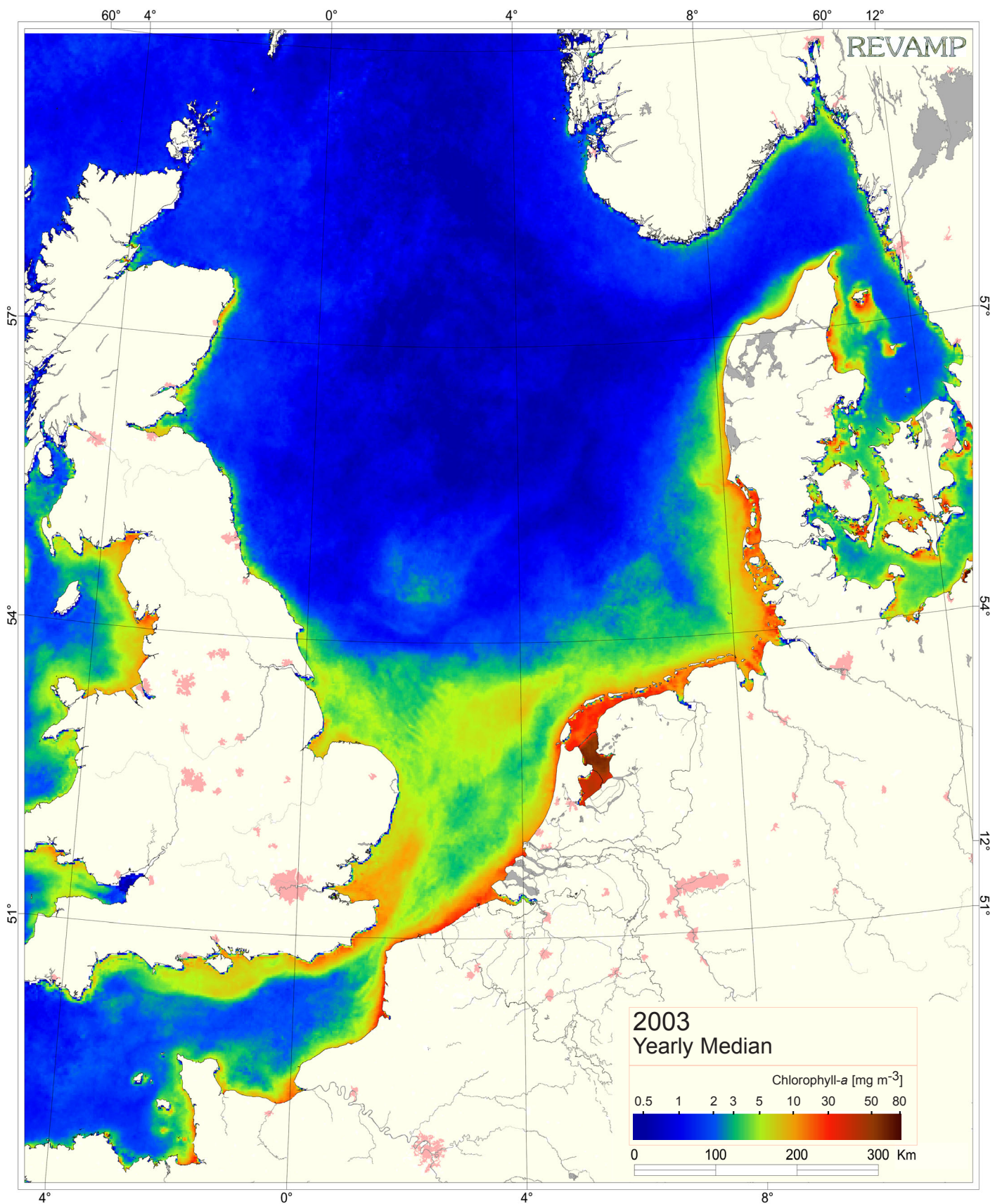




Spring+Summer+Autumn 2003 Maximum REVAMP Chlorophyll-*a* [mg m^{-3}]

The Yearly 2003 maximum Chlorophyll-*a* image shows in general that the maximum Chlorophyll-*a* concentrations in the non-problematic areas (with limited eutrophication) may reach a maximum of 10 mg m^{-3} during the year, while the problematic areas (with more eutrophication) may reach concentrations above 30 mg m^{-3} .



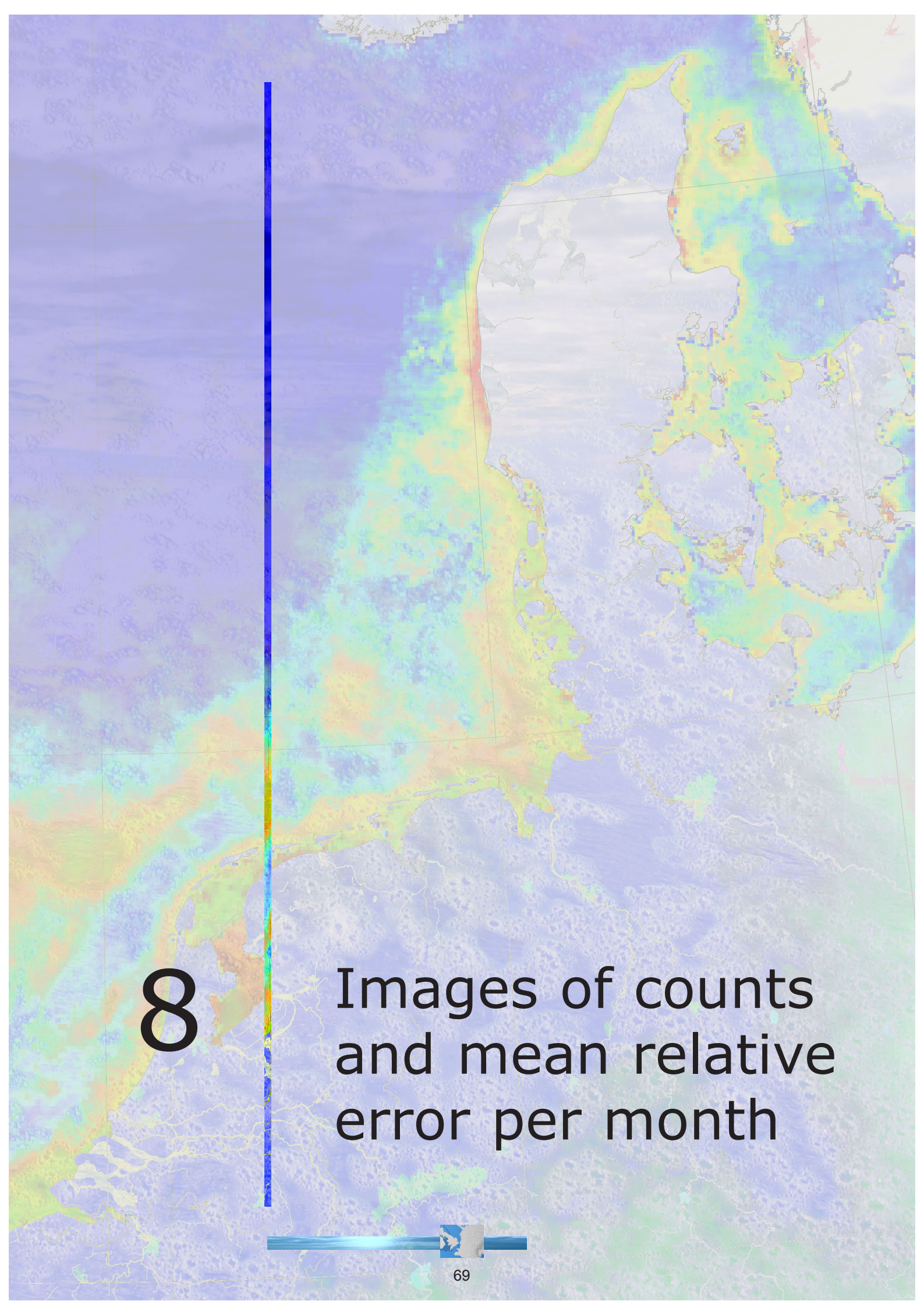


Spring+Summer+Autumn 2003 Median REVAMP Chlorophyll-a [mg m^{-3}]

The Yearly 2003 median Chlorophyll-a image summarises the MERIS scenes from the period 15. February - 15. November 2003. The Winter season was not processed since the remaining scenes from mainly January and December were too few and heavily cloud-covered. The yearly median displays that the overall picture is: low Chlorophyll-a concentrations in the Northern half of the North except along the Norwegian Skagerrak coast, the Danish West-coast and the UK North-East coast, while the southern half of the North Sea has high Chlorophyll-a values and potentially more eutrophication problems.

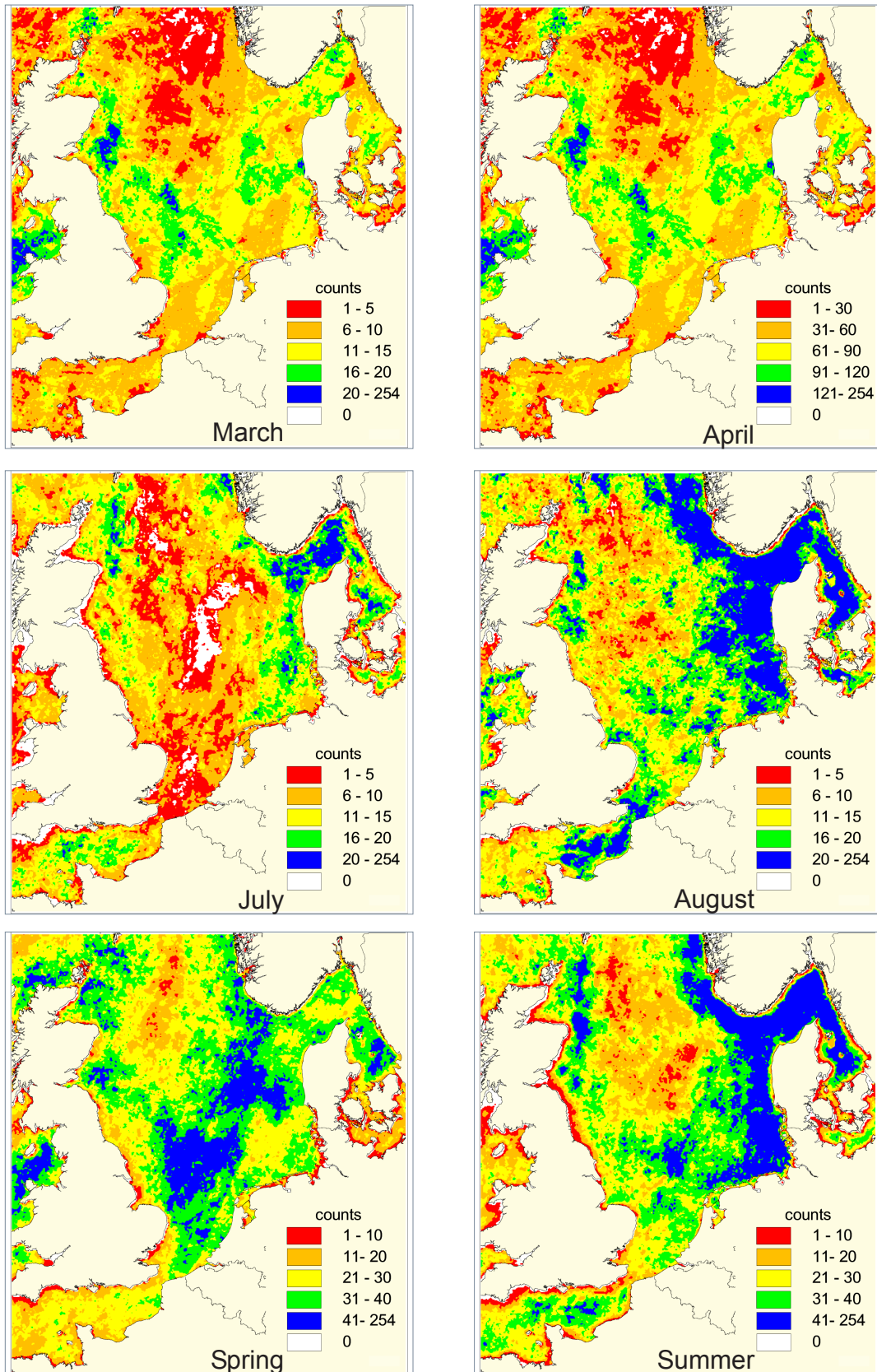






8

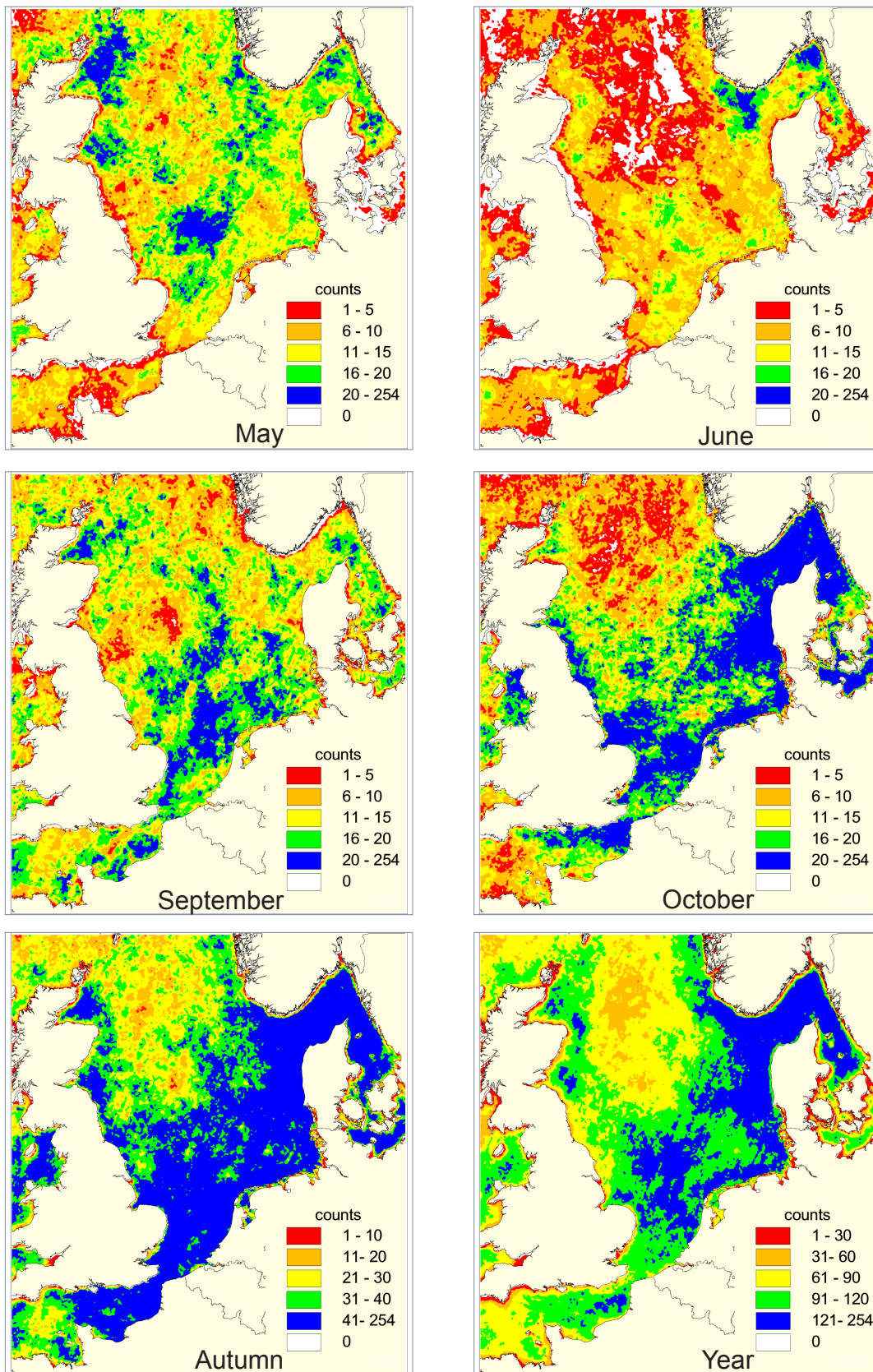
Images of counts
and mean relative
error per month



The number of counts indicates the number of suitable MERIS scene pixels for the binning period and within the binning spatial window extent.

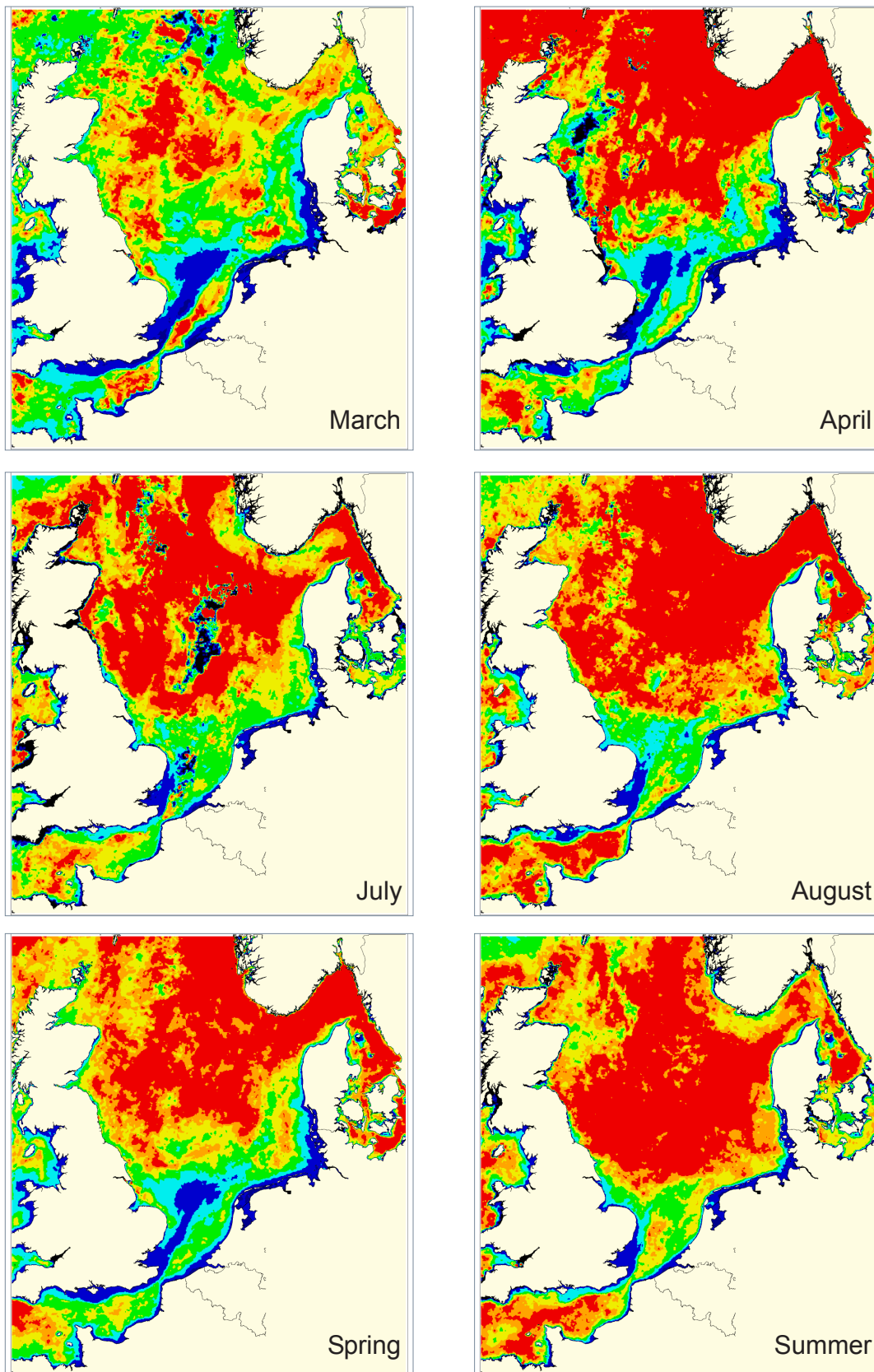
There is a general tendency to have more counts in the area extending from the Skagerrak towards the English Channel. It may be that the number of MERIS strips is significantly higher in this area due to some reason.





The Northern Central North Sea features persistent areas with very low counts. This has probably to do with persistent cloud cover. Autumn was the clearest season.





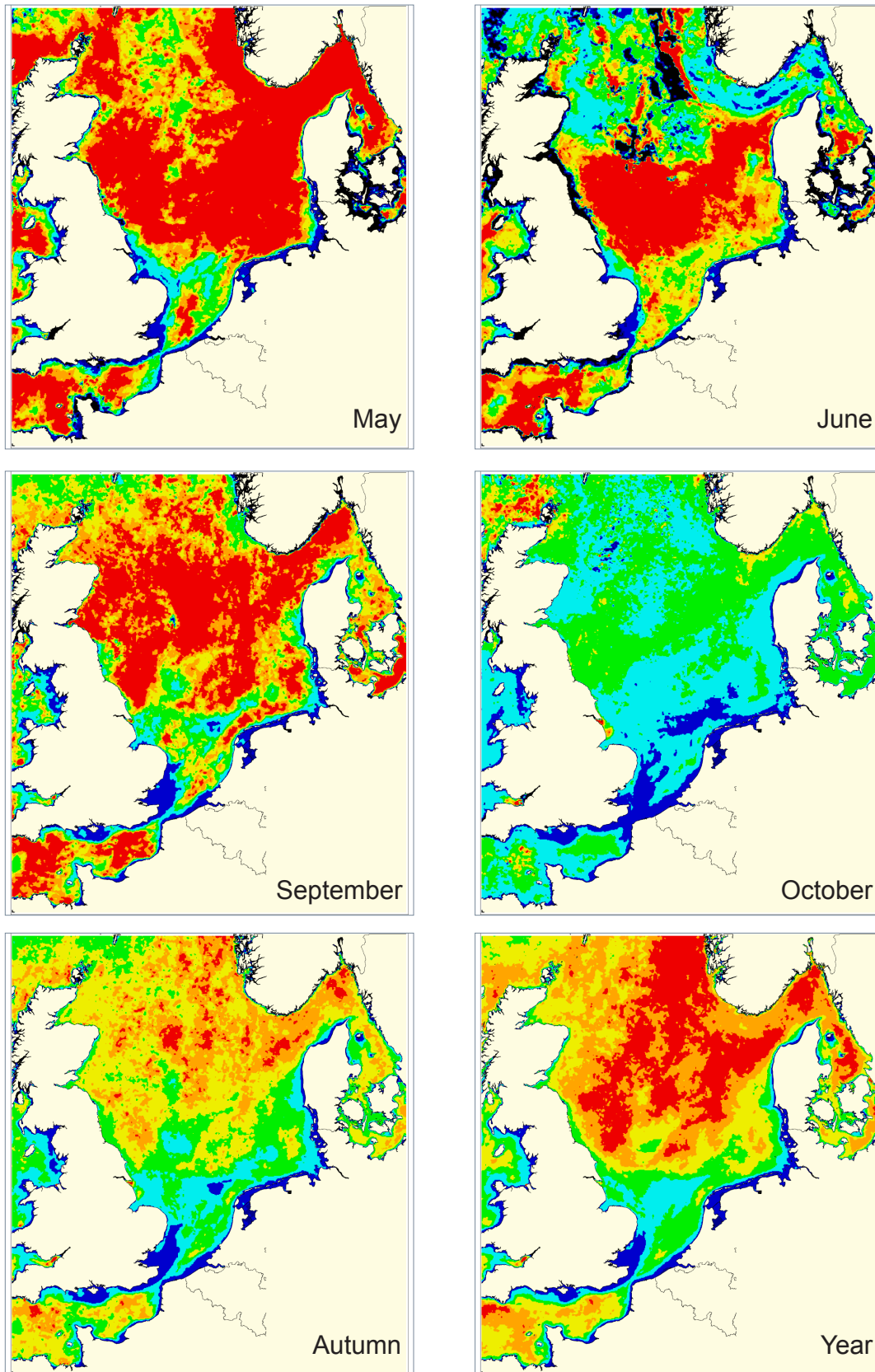
Median
Relative
Error [%]

no data
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
> 60

The median relative error is a combined indicator of the variability of chlorophyll-a within a bin due to natural variability during the binning period and due to uncertainties in the processing.

As expected we find the highest values in areas with low overall chlorophyll-a values.





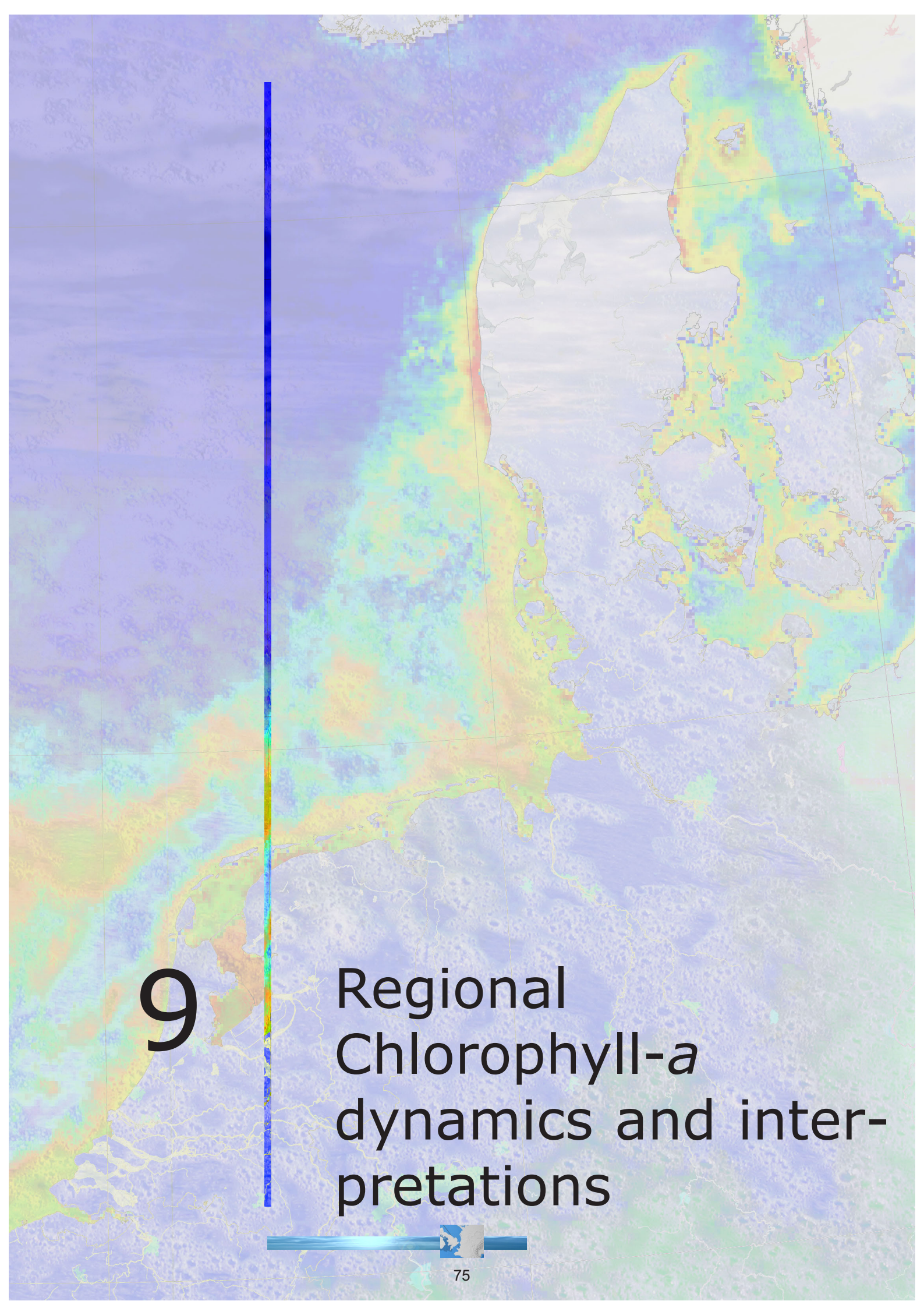
Median
Relative
Error [%]

no data
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
> 60

It is interesting to observe that the median relative error is lowest in areas with probably a high suspended sediment concentration. This indicates to the fact that these spectra have very good signal to noise ratios due to high reflectances.







9

Regional Chlorophyll-*a* dynamics and inter- pretations



German Bight Chlorophyll-a dynamics

The Wadden Sea along the coastline of the Netherlands, Germany and Denmark generally is very shallow and periodically falls dry. Due to strong tidal currents the water has a high sediment load. Optically derived data in this area have to be interpreted with care.

The spring bloom in the German Bight starts in March and is fully developed in April. At this time we find the highest Chlorophyll-a concentrations of the year. The bloom increases especially in the southern German Bight along the Dutch/German coast due to the high nutrient input into the coastal current from the major rivers. This can be at least partly verified by validation cruises taken end of April 2003 along Schiermonikoog to Borkum.

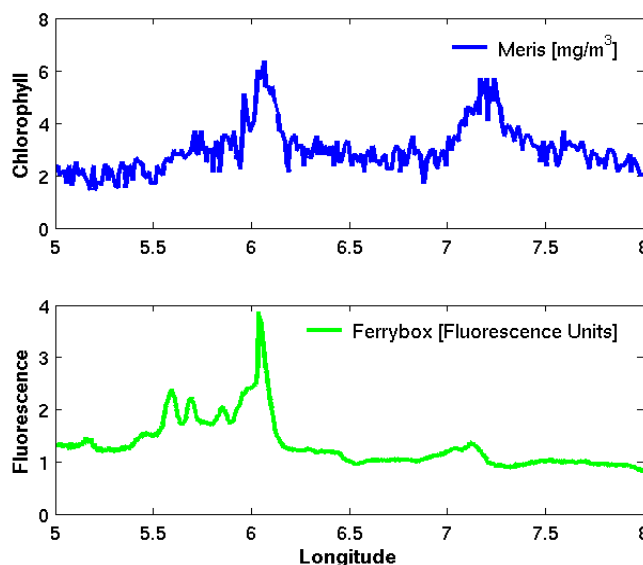
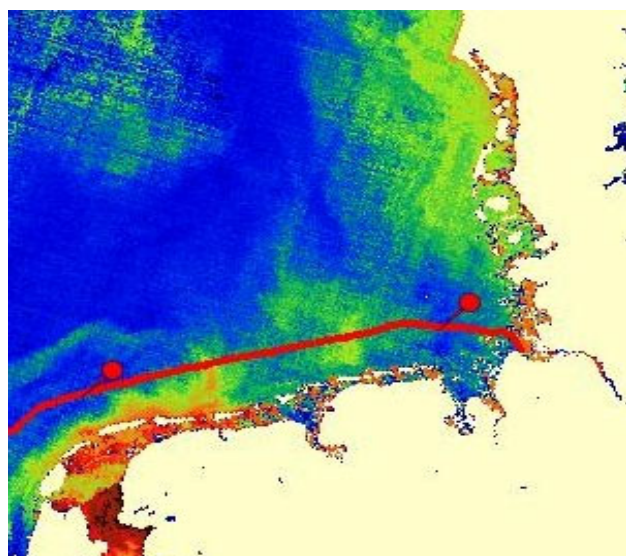
In May and June Chlorophyll-a concentrations declined in the outer German Bight. Strong gradients from the coast towards the open sea are visible. One has to be careful with the interpretation of high concentrations along the shoreline from Texel to Esbjerg. The backscattered radiation is presumably highly influenced by suspended matter as stated above.

In August Chlorophyll-a concentrations are increasing again. The values in the inner German Bight are in agreement with in situ measurements.

In September a second or autumn bloom seems to develop in the German Bight.

Exceptional high values can be detected for October which may be a result of the warm summer in 2003.

Comparison of Chlorophyll-a measurements from space with measurements of in situ fluorescence. Fluorescence is a good measure for Chlorophyll-a concentration as long as species and conditions of the algae do not vary too much.



The left figure shows Chlorophyll-a concentrations derived from MERIS data on November 6th 2003. The red line indicates the track of the ferry from Cuxhaven to Harwich. The ferry crosses two areas with high Chlorophyll-a concentrations.

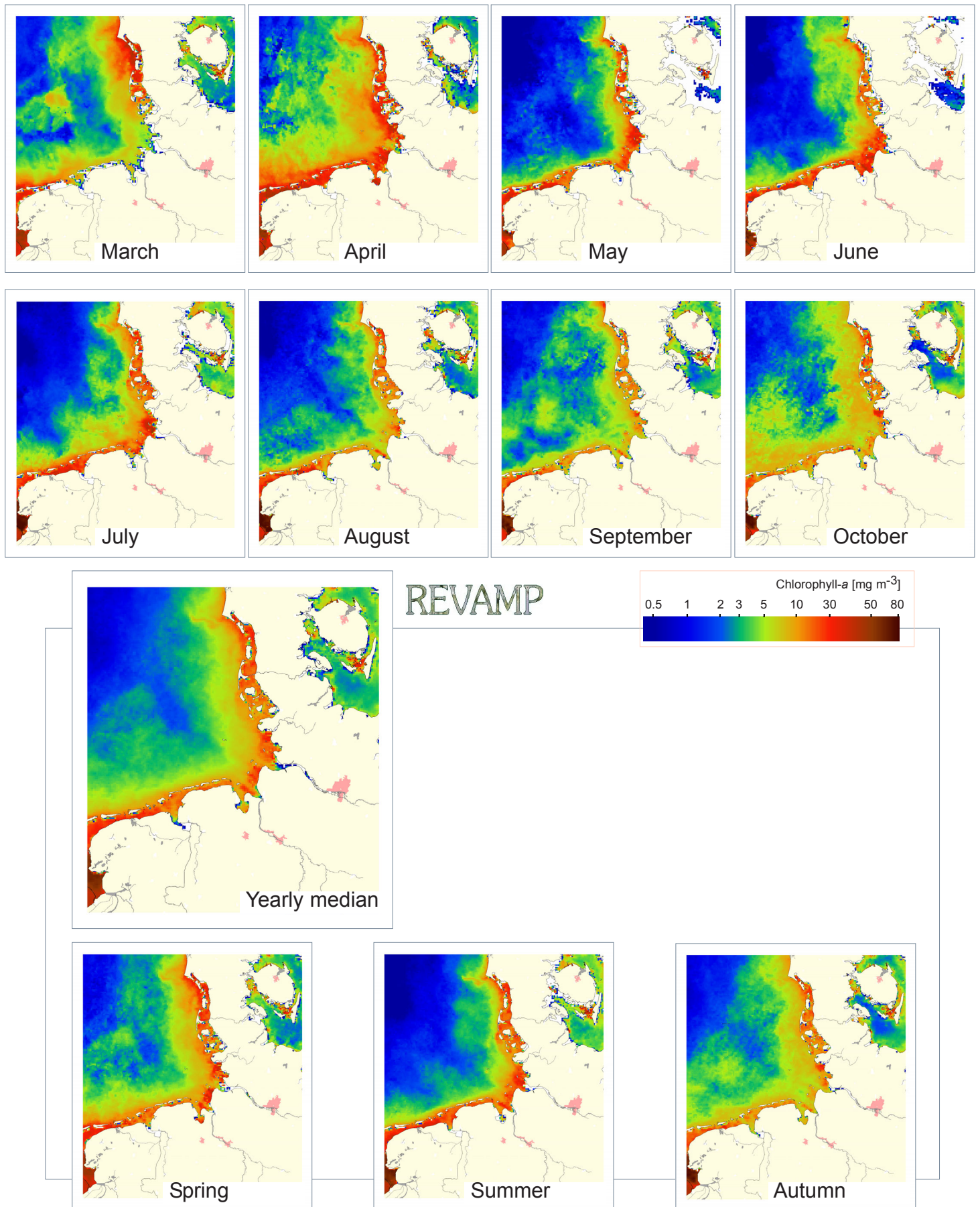
In the right lower figure the in situ fluorescence of phytoplankton Chlorophyll-a along the ferry transect is plotted between the two markers at 5° and 8°E. It is measured by an automatic measurement system (ferrybox), which is installed on the ferry boat.

These data are compared with MERIS Chlorophyll-a concentrations as seen from space six to nine hours earlier (upper right panel). The structures are in good agreement and the two peaks are clearly visible. The less pronounced right peak in the ferrybox fluorescence may be due to different algae species and/or water depth. The ferrybox is supplied with water from a depth of 5 meters.

The absolute values differ because the uncalibrated in situ fluorescence provides only a relative Chlorophyll-a concentration.



GERMAN BIGHT: 2003 monthly, seasonal and yearly median Chlorophyll-a concentrations from MERIS



Danish Waters / Kattegat

Bathymetry plays an important role on the MERIS reflectance spectra in areas with very shallow waters below, say 15-20 meters in the North Sea region, depending on water clarity. For instance in Kattegat there is a large area near the two major islands: Anholt and Læsø and to the West off these all the way to the Jutland coast, where depths are generally between 3-10 meters. In combination with a quite bright sand-bottom in most places this greatly enhances the signal from the water surface which is received by MERIS and produces some degree of misinterpretation of the chlorophyll-a concentration in that area.

The bright sand bottoms in the Kattegat are light-green, so they will lift the entire reflectance spectra emerging from the water column inverse proportionally with depth (low depth - high reflectance lift). However, the reflectance spectrum is somewhat similar to that of suspended sediments with a reflectance peak in green (at 540-570 nm). Since the green reflectance is increased more than the blue, relatively, shallow sand bottoms will have the same effect as the primary pigment absorption peaks in the blue (440-460 nm), and hence produce overestimated Chlorophyll-a values in these areas.

The overestimation will be seasonally variable because it depends on water clarity. The lower the attenuation in the water column, the greater the bathymetry effect will be. So the algorithms for Chlorophyll-a will be the most accurate, in terms of bathymetry effect, in periods with high productivity, high turbidity and turbulent waters.

The general phytoplankton cycle in Danish waters exhibits three peaks during the year. The major peak is the spring bloom in March (sometimes even in late February). The timing of the spring bloom is a function of increased availability of light, nutrients (depending on precipitation and land run-off) and general stabilisation of water column and increased surface water temperature.

During this spring bloom nearly all available nutrients are used and the production decays during the next months even though the availability of sun-light and water temperature increases in April and May. In June there is normally a secondary peak, a small summer bloom, which is due to a maximum concentration of zoo-plankton who are living from ("grazing") the phytoplankton generated during the spring bloom.

The third peak is the autumn bloom which comes in late September or October. This bloom happens when the stratified waters built up during the summer, are broken down by increased turbulence due to the higher wind speed in the more stormy autumn weather, and unused nutrient-rich bottom water hereby is brought toward the sun-lit surface layer, where production then becomes re-boosted.

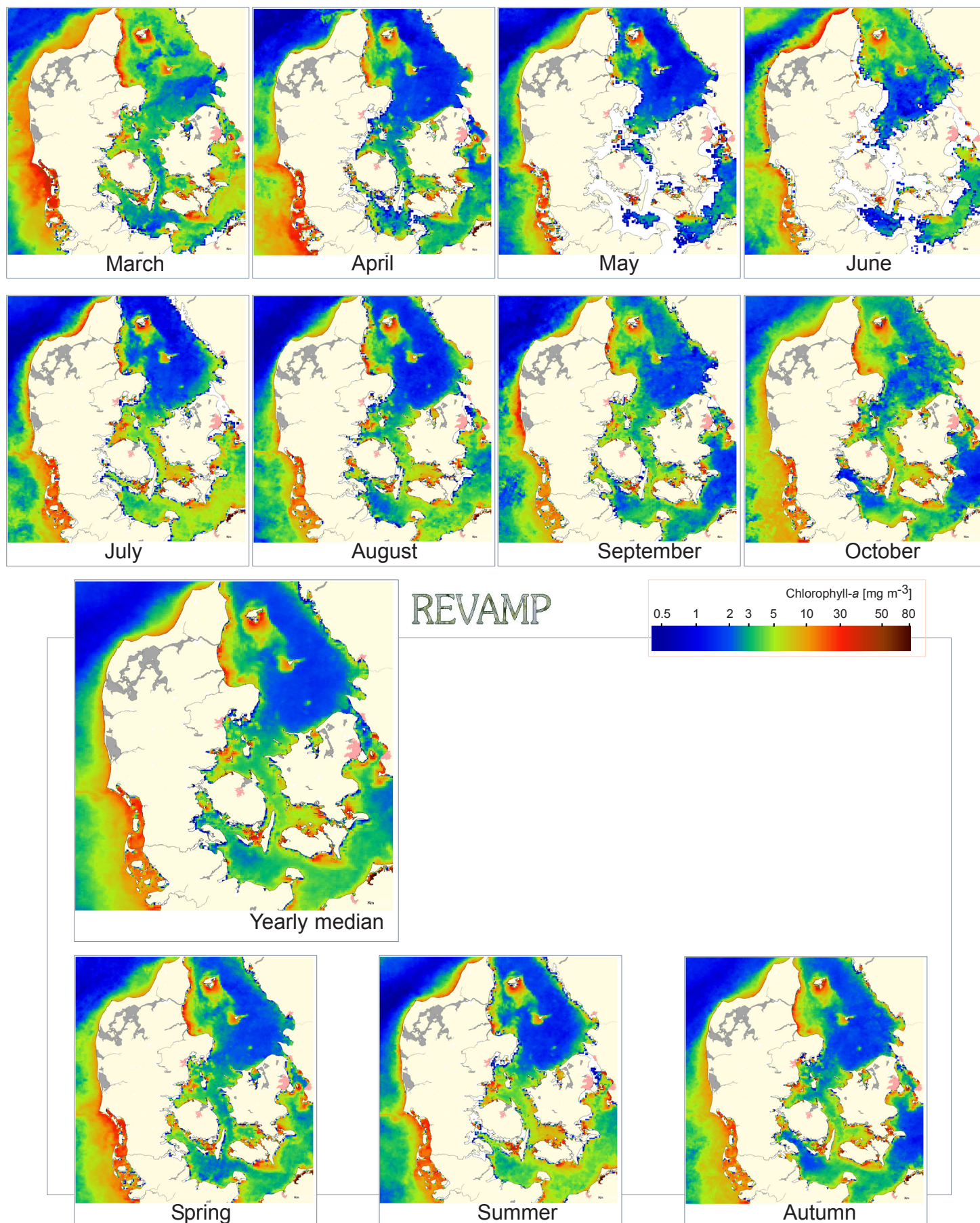
The zoom images from MERIS 2003 March - October confirm the normal cycle very nicely with March generally having the highest concentrations and June plus October the second highest monthly concentrations. In general the North Sea circulation is anticlockwise so that German Bight water, which is nutrient-rich, is transported up along the Jutland west coast much of the year. The current goes all the way along the coast to Skagerak and even spills into the Kattegat quite regularly.

In the March, April and May images the Chlorophyll-a concentrations vary along the Jutland coast with the highest concentrations towards the south in the Danish part of the Wadden Sea (10-20 mg m⁻³) and lower concentrations towards the north (3-10 mg m⁻³). This variation is directly related to the normal nutrient distribution in this area. The west-pointing "spiky" feature, nearly in the middle of the west coast, seen in almost all the monthly images, is due to a reef, Horns Rev, which has shallower water and causes increased turbulence in south-north flowing current, thus giving rise to increased Chlorophyll-a concentrations.

In the Wadden Sea south of here, the waters from the barrier islands and eastwards are very shallow and Chlorophyll-a is therefore overestimated. The same is the case in most of the Danish inner waters where the 5 km closest to the coast often has very shallow water. In western Kattegat there is also a very large area with shallow water: mostly 2- 10 m depth. The concentrations here should probably often be same as on the eastern side of Kattegat. The concentrations in the inner waters and Kattegat are normally lower than along the West Jutland coast generally ranging from 0.5 - 2 mg m⁻³, and reaching 5 - 8 mg m⁻³ during bloom periods.



Danish coastal waters: 2003 monthly, seasonal and yearly median
Chlorophyll-a concentrations from MERIS



Phytoplankton in the Skagerrak area 2003

March: In Skagerrak the springbloom of diatoms started in February and continued during March, which is reflected in the satellite image for the month. At the start of the bloom there was a numerical dominance of *Skeletonema costatum* (max. 10 mill. cells/L), but *Thalassiosira nordenskiöldii* contributed with high biomass. In the middle of March there was a culmination in the bloom in areas close to the coast, but in the open sea the bloom continued. *S. costatum* and *Chaetoceros socialis* were the dominant species in the whole area, except in the area outside Lindesnes (south end of Norway) where *T. nordenskiöldii* was found in highest number. In the end of March there was a new blooming period where *C. socialis* was the dominant species. Outside the western coast of Denmark the ichthyotoxic raphidophyce *Chattonella aff. verriculosa* was found in low concentration. The satellite image show close at the Danish coast high Chlorophyll-*a* concentration which was also registered by in situ measurements (10-20 mg m⁻³) sampled by ferrybox system in the area.

April: Early in April still there are some diatoms especially in the coastal areas. Later on this month there are low algal concentrations in the whole area with *Chaetoceros socialis* as the dominating species. At the end of the month low algal biomass dominated by flagellates was registered in the west, but near the coast in the north eastern part of Skagerrak, a small diatom bloom dominated by *Chaetoceros wighamii* took place. The image shows low concentration of Chlorophyll-*a* in the area, which is also confirmed in the in situ measurements.

May: In the central western part of Skagerrak the phytoplankton community is dominated by flagellates, while in the central eastern part there are middle concentrations of algae dominated by *Chaetoceros wighamii*, increasing towards the coast. In the middle of May a new bloom of diatoms started and at the end of the month there was a bloom dominated by *Pseudo-nitzschia calliantha* along the Norwegian coast of Skagerrak. In this period the ichthyotoxic algae *Heterosigma akashiwo* was found outside the western and northern coast of Denmark, but the algae was also found in low concentration outside Lindesnes at the Norwegian south coast. *Chattonella aff. verriculosa* occurred in low concentrations at the same locations in the beginning of May. The Chlorophyll-*a* concentration at the northern coast of Denmark was registered to be in the range of 2-3 mg m⁻³ and the satellite image also reflects higher concentrations, but sometimes the high concentrations here could be an effect of land or suspended sediments.

June: In the beginning of June the diatom bloom continued in the whole Skagerrak area. The dominating species was *Chaetoceros spp.*, *Dactyliosolen fragilissimus* and *Pseudo-nitzschia calliantha*. A week later the coccolithophoride *Emiliania huxleyi* started blooming in the middle eastern part of Skagerrak. This bloom expanded and dominated the whole Skagerrak area within the following week except for the north eastern part of Skagerrak where *Skeletonema costatum* and *Chaetoceros spp.* dominated. At the end of the month *E. huxleyi* was the dominating species in the whole area. The Chlorophyll-*a* concentration from the satellite images is relatively high in the area which probably is dominated by the *E. huxleyi* bloom. Along the coast of southern Norway the dinoflagellate genus *Ceratium* had a small bloom most of June and also diatoms accompanied the *E. huxleyi* bloom. In the beginning of the month also the satellite Chlorophyll-*a* shows good agreement with the in situ data, while during the *E. huxleyi* bloom the Chlorophyll-*a* concentration can be overestimated (see chapter 11).

July: The bloom of *Emiliania huxleyi* culminated early in July. For the rest of the month the algal biomass was low/moderate and dominated by flagellates and dinoflagellates in most of the area. In outer Oslofjord, however, moderate occurrences of diatoms were registered. The median satellite images also show low concentration, but the maximum image probably reflects the ending of the *E. huxleyi* bloom.

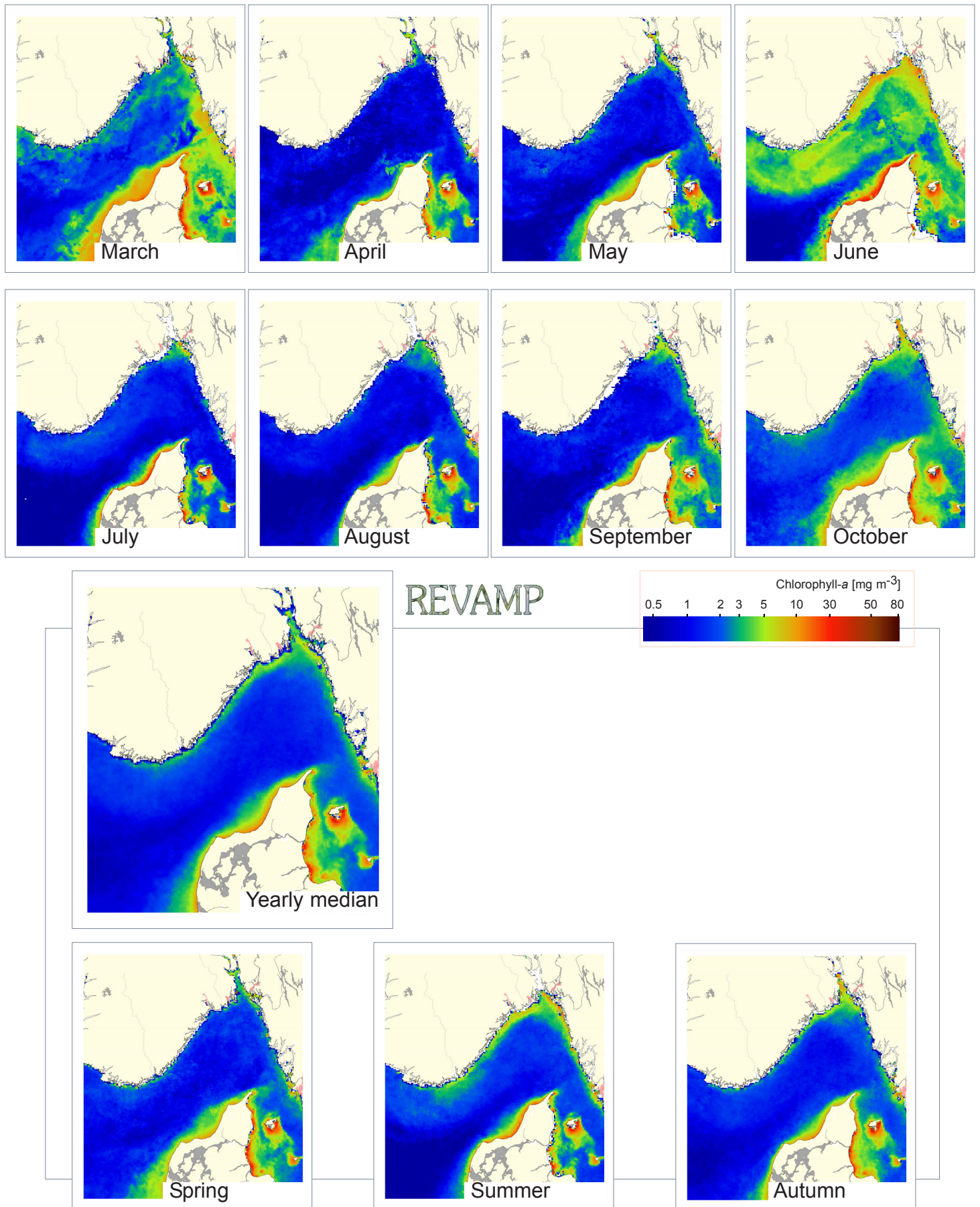
August: In August there are low concentrations of algae in the whole area except for the Outer Oslofjord area where *Chaetoceros thronsenii* was blooming which is also seen in the satellite images for the north Eastern part of Skagerrak.

September: In the first half of September the algal concentration is low in the whole area. In the second half of September the algal concentration is still low, but the biomass is now dominated by naked dinoflagellates. The satellite images show also low median values for the month.

October: At the end of October a bloom of the diatom *Pseudo-nitzschia calliantha* was registered outside Arendal (central part of Skagerrak) which is seen especially in the maximum satellite image. According to the satellite image the bloom can be extended to a larger area.



Skagerrak: 2003 monthly, seasonal and yearly median Chlorophyll-a concentrations from MERIS



English Channel

General: The satellite images shows the relative timing of the spring bloom, changes in phytoplankton biomass associated with different species in summer and the comparative decline in phytoplankton biomass in the autumn. The Chlorophyll-*a* values given in March and April for the English Channel are slightly higher than measured, and the values in July and August are slightly lower. The values given around the Isle of Wight and the Brittany Coast were also too high probably due the reflective character of the minerals found in these areas. A feature of the English Channel images is the missing data (white areas) that are found in the summer months around the south coast of England. These areas of missing data are also observed in the count images in section 7. The lack of data is most obvious in the summer images (June and July), when frequent overpasses are observed cloud free level 1 data, indicating that the product confidence flag has been raised on these images (see section 6 for details). The probable cause of this flag being raised is atmospheric correction failure due the scattering of light from adjacent highly reflecting land. The magnitude of this adjacency effect depends on the illumination conditions, the orientation of the landmass relative to the sensor, the atmospheric turbidity and the contrast between the reflection of the land and water. This effect can extend for up to 20km and is more acute at lower zenith angles (summer months), and where there is a higher contrast between the land and sea (low chlorophyll and suspended matter). The effect is however complicated by the spectral signature of the land target and the directional nature of the land reflectance.

March & April: The image shows the relative timing of the spring bloom and the transition from post winter conditions in March, to the onset of the spring bloom in April which was dominated by Diatoms (mainly *Thalassiosira spp.*) The satellite image shows a clear separation between high Chlorophyll-*a* in the eastern Channel and low Chlorophyll-*a* in the western part of the Channel which demarks the well mixed waters to the east from stratified waters to the west. From the satellite imagery however, there is no evidence of a phytoplankton bloom occurring in the western part of the channel which occurred in 2003 during early April. Chlorophyll-*a* concentrations along the South UK coast are also too high possibly due to sediment advection by long shore transport along the coast.

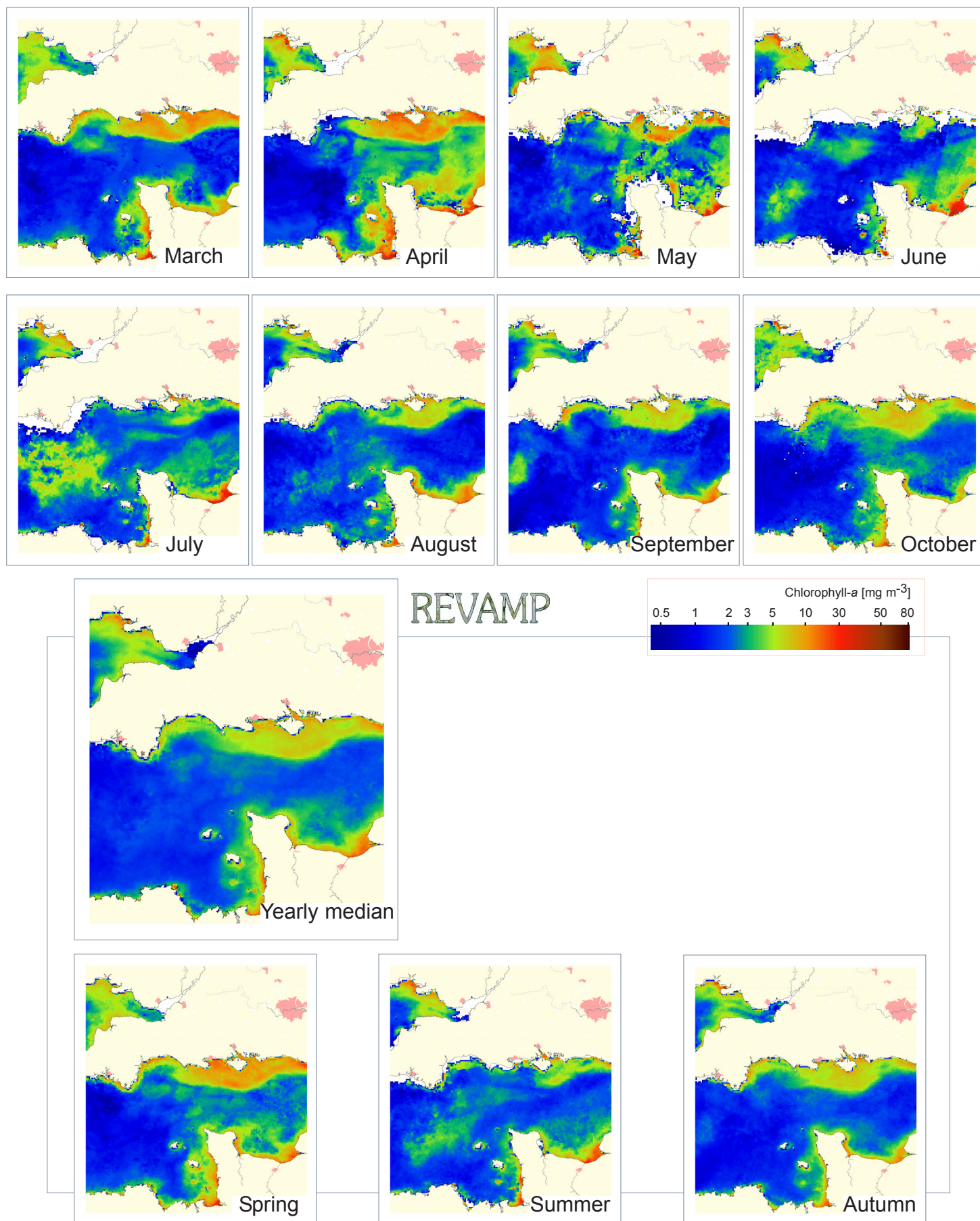
May & June: In May the spring bloom diminished and became patchier and the number of Diatoms declined and *Phaeocystis spp.* became dominant. In June there was a further decrease in Chlorophyll-*a* in the central Channel but in the western part of the Channel, the phytoplankton biomass increased towards the Brittany coast, which was the start of a *Karenia Mikimotoi* bloom.

July & August: In July the *Karenia Mikimotoi* bloom increased and on certain days reached Chlorophyll-*a* values $>50 \text{ mg m}^{-3}$. After the *Karenia Mikimotoi* bloom had subsided in August, a smaller patch of Chlorophyll-*a* was apparent ($3 - 5 \text{ mg m}^{-3}$), which was due to the Coccolithophorid, *Emiliana Huxlyii*.

September & October: In September there was a general decrease in Chlorophyll-*a* as the *Emiliana Huxlyii* bloom declined except for a small patch of phytoplankton in the western channel, which was dominated by flagellates. In October there was a further increase in flagellate biomass in the central part of the channel.



English channel: 2003 monthly, seasonal and yearly median Chlorophyll-
a concentrations from MERIS



UK Eastern Coastal Waters:

General: The satellite images reflect the spatial and temporal variation in phytoplankton biomass in all UK regions except for the North Sea southern Bight plume where the high mineral content associated with these waters has caused some contamination of the Chlorophyll-*a* signal.

March & April: The satellite composite image reflects the onset of the spring bloom in the North Sea with Chlorophyll-*a* values $>5 \text{ mg m}^{-3}$ which were dominated by *Thalassiosira* spp. in nearly all eastern UK coastal areas, except for the Wash, over the Dogger Bank and in the southern bight plume. The values reported appear to be accurate in all areas except for the southern bight plume where the values are over estimated by at least a factor of two. There is a clear demarcation between the higher Chlorophyll-*a* values in the southern North Sea and low Chlorophyll-*a* values in the northern North Sea associated with differences in bathymetry, mixing depths and temperature. In the southern North Sea, there is often an influence of warmer, more saline water entering the area through the English Channel which drive the circulation pattern in the North Sea and produce a characteristic sediment plume extending from the south eastern UK coast towards the Belgium and Dutch coasts. The spring bloom in the North Sea occurred in April, which is reflected in the satellite image although the magnitude of the bloom is greater especially in the southern bight plume. In April, the phytoplankton biomass diminished along the eastern UK coast and over the Dogger bank, but increased in patches over the central North Sea. There was also a bloom on the eastern Scottish coast was probably initiated by the transition between strong currents and tidal mixing to the seasonal thermocline which extends over most of the central and northern North Sea in response to solar heating.

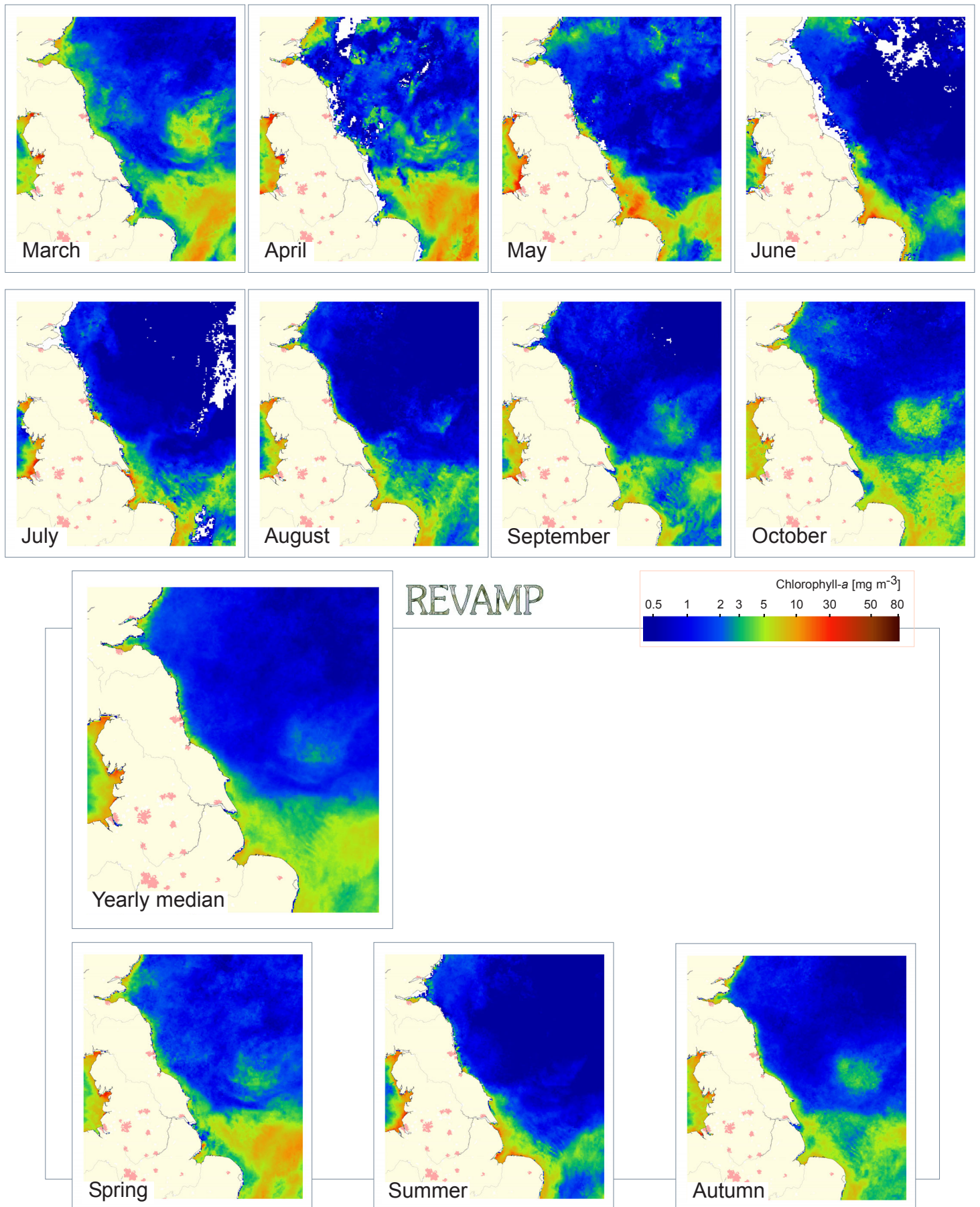
May & June: In May the phytoplankton biomass generally diminished when *Thalassiosira* spp. became less abundant and *Phaeoceros*, *Rhizoselinia* & *Psuedo-Nitzschia* became more dominant, except around the wash and East Anglia, where there was a relative increase in Chlorophyll-*a* concentrations due to increasing numbers of dinoflagellates particularly *Ceratium fusus*. In June, there was a further decrease in Chlorophyll-*a* over the North Sea except for the North East coast of Scotland where a Chlorophyll-*a* plume extends from coastal to offshore waters of the northern North Sea. The satellite values in the coastal waters off the Humber estuary and the Wash are slightly over estimated.

July & August: Chlorophyll-*a* values in southern bight plume increased but coastal Chlorophyll-*a* values decreased especially around the Wash due to increasing numbers of *Ceratium fusus*.

September & October: Chlorophyll-*a* values generally increased over the whole of the North Sea, especially in the Southern Bight Plume and over the Dogger Bank possibly associated with deeper mixing and re-suspension events in September and October when *Nitzschia seriata* dominated the phytoplankton.



UK eastern coastal waters: 2003 monthly, seasonal and yearly median
Chlorophyll-a concentrations from MERIS



Norwegian South-Western Coastal water

March: At the Southwest and West coast of Norway full spring bloom was registered in the middle of March. *Skeletonema costatum* dominated in the Southwest, while *Chaetoceros socialis* dominated in the West. Low concentrations of *Chattonella* were registered in some of the fjords of Western Norway. During the last part of March the algal biomass showed large local variations seen in the monthly median Chlorophyll-a image. In the outer area of the Southwest coast *Thalassionema nitzschioides* became a prominent species at the end of March. The satellite images show high Chlorophyll-a concentrations close to the Danish coast : this was confirmed by in situ measurements.

April: Along the west coast of Norway the algal biomass were generally low (Chlorophyll-a < 2 mg m⁻³) as seen in the image. Different types of diatoms (*Chaetoceros borealis*, *C. curvisetus*, *C. debilis*, *C. decipiens*, *Dactyliosolen fragilissimus*, *Leptocylindrus danicus*, *Cerataulina pelagica*, *Skeletonema costatum*) dominated the biomass, coinciding with a small bloom of *Phaeocystis*. At the end of the month low algal biomass dominated by flagellates was registered at the West coast of Norway, and at the Danish coast the biomass had decreased compared to March.

May: In May along the western coast of Norway the algal biomass was generally low (Chlorophyll-a < 2 mg m⁻³) and dominated by flagellates in the beginning of the month. Also in the central western part of Skagerrak the phytoplankton community is dominated by flagellates. In this period the ichthyotoxic algae *Heterosigma akashiwo* was found outside the Western and Northern coast of Denmark, but the algae was also found in low concentration outside the Norwegian Southwest coast. *Chattonella aff. verriculosa* occurred in low concentrations at the same locations in the beginning of May. The Chlorophyll-a concentration at the Northern coast of Denmark was registered to be in the range of 2-3 mg m⁻³ Chlorophyll-a, and some offshore blooms is seen in the image.

June: The algal situation in the beginning of June is much like the situation at the end of May. The general picture most of June was rather low algal biomass and flagellate dominance in West and an increasing coccolithophoride dominance of *Emiliana huxleyi* towards the South as seen in the image. At the end of June the bloom of *Emiliana huxleyi* is on the decline in the West, but is still blooming in Southwest. Diatoms became more prominent especially near Bergen. The median Chlorophyll-a image illustrates the algal situation. The coccolithophoride *Emiliana huxleyi* bloom dominated the whole Skagerrak most of the month, but along the coast of southern Norway the dinoflagellate genus *Ceratium* had a small bloom most of June and also diatoms accompanied the *E. huxleyi* bloom. In the beginning of the month also the satellite Chlorophyll-a show good agreement with the in situ data, while during the *E. huxleyi* bloom later in the month Chlorophyll-a concentration are overestimated (see chapter 11).

July: The bloom of *Emiliana huxleyi* culminated early in July and then a diatom bloom (*Skeletonema costatum*, *Chaetoceros spp.*) was registered at the West coast of Norway near Bergen. Diatoms dominated the rest of the month, but the species composition changed (*Dactyliosolen fragilissimus*, *Leptocylindrus minimus*, *L. danicus*). Further south the algal biomass fluctuated between high and rather low level during the month. At the Danish coast the algal biomass decreased further.

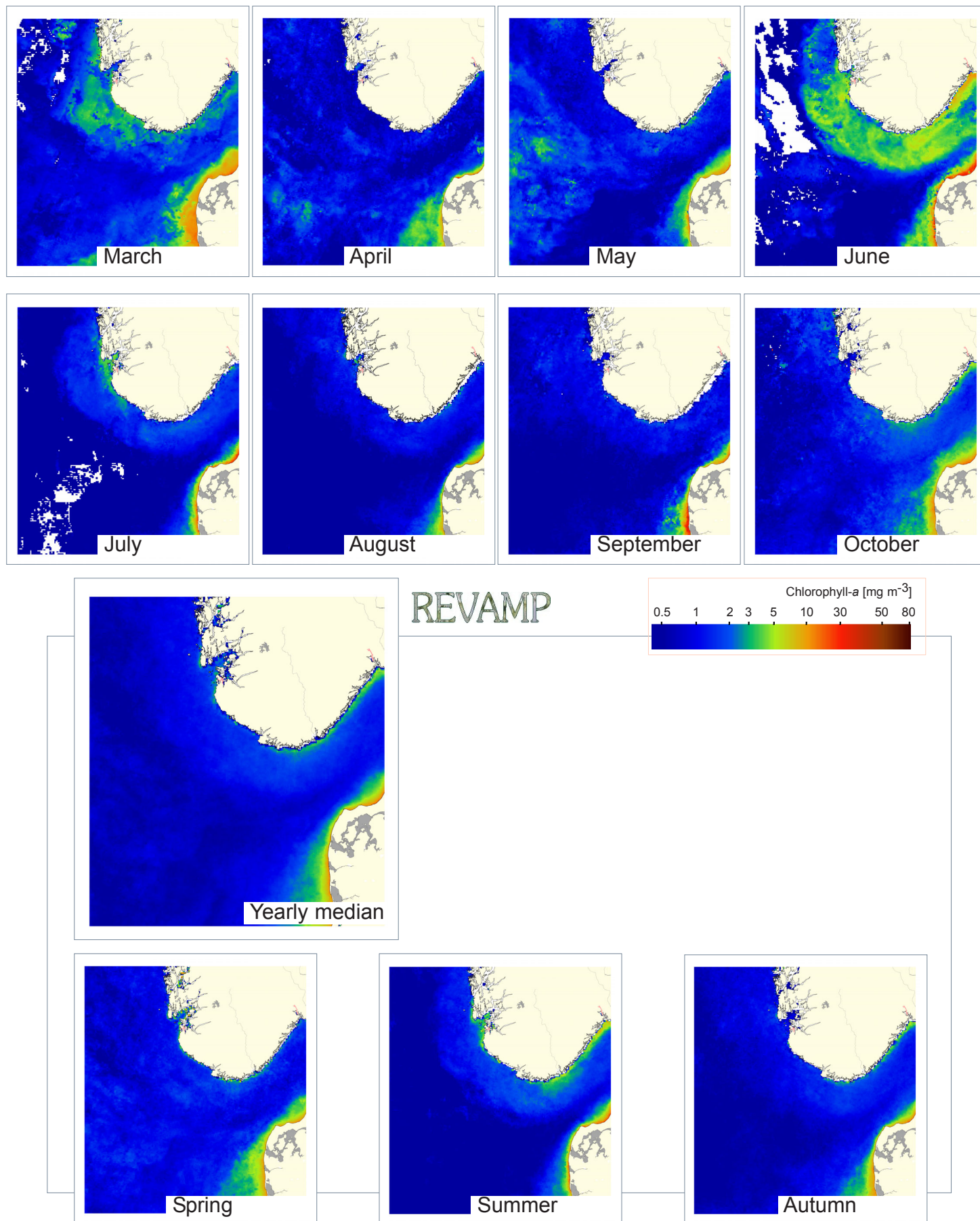
August: At the Southwest and West coast of Norway there is low algal biomass in August. In West outside Bergen the algal community was dominated by small flagellates and the diatom *Cerataulina pelagica*. In the Southwest different species of the diatom Genus *Chaetoceros* was important. At the Danish coast the algal biomass is unchanged since July.

September: Early in September there was a bloom of the diatom *Dactyliosolen fragilissimus* at the West coast of Norway outside Bergen, but South of Bergen there was low algal biomass throughout the whole month. In the second half of September the algal concentration is still low, but the biomass is now dominated by naked dinoflagellates.

October: Late in October the diatoms *Pseudo-nitzschia calliantha* and *Skeletonema costatum* bloomed along the Western coast of Norway. At the Southwest the *Pseudo-nitzschia calliantha* was dominating. At the Danish coast the algal biomass again increases.



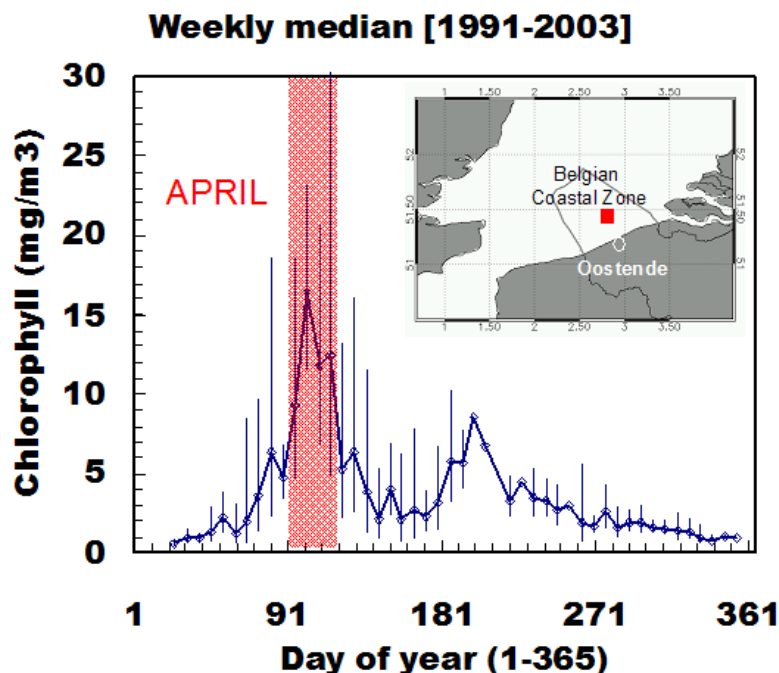
Norwegian South-Western coastal waters: 2003 monthly, seasonal and yearly median Chlorophyll-a concentrations from MERIS



Belgian coastal waters (MUMM)

1) Spring phytoplankton bloom

The April image shows a widespread phytoplankton bloom in the southern North Sea for both coastal and offshore waters. Long term monitoring data in Belgian coastal waters reveals a Chlorophyll-a peak this month with strong seasonal variability. The Figure below shows an example for a station located at 25km off Oostende (indicated by a red square in the Figure). In situ Chlorophyll-a measurements range from approximately 5 to 30 mg m^{-3} in April and decrease to an annual minimum level $\sim 1 \text{ mg m}^{-3}$ in December or January. REVAMP Chlorophyll-a varies from 8 to 24 mg m^{-3} for this station in April 2003, which is consistent with in situ data.



Seasonal variability of in situ Chlorophyll-a at 25km off Oostende.
(Data obtained from Belgian Marine Data Center
originating from MUMM and the Université Libre de Bruxelles).

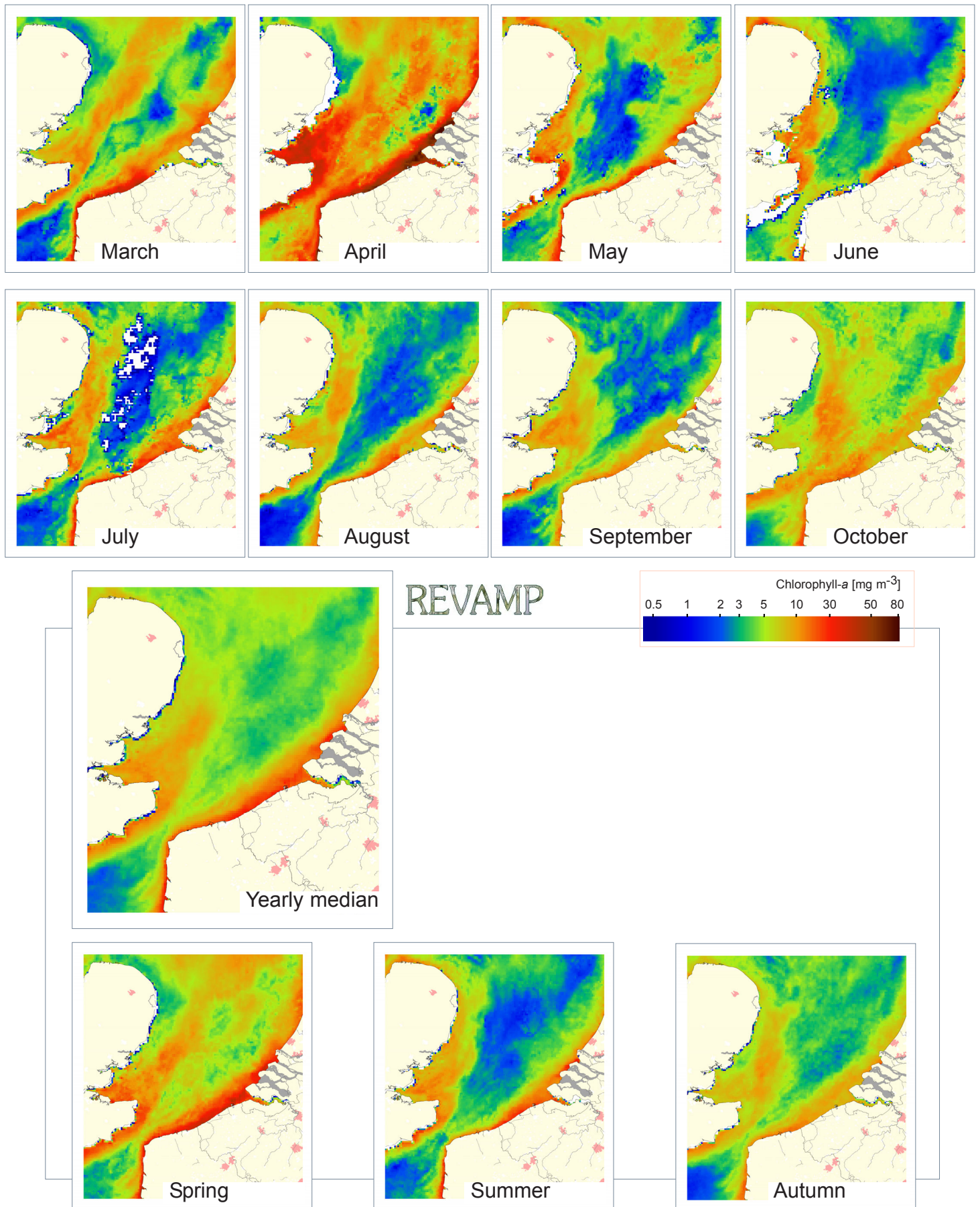
2) Implications for eutrophication assessment

For Belgium, the Netherlands and Germany, one of the criteria used to determine whether an area has a eutrophication problem (in the sense of the 1992 OSPAR convention) is whether the annual Chlorophyll-a maximum exceeds a threshold of 15 mg m^{-3} . This image shows that this threshold is indeed exceeded for the entire Belgian-Dutch-German North Sea coastline. However, there are concerns that some of the high Chlorophyll-a concentrations recorded could be artefacts induced by the very high suspended matter concentrations found close to the Belgian coast.

Further work is required here, though the qualitative difference found between April 2003 and March or May 2003 for both nearshore and offshore waters is considered realistic. Pending improvements in the satellite-derived products it is likely that these products will be used to guide measurement campaigns related to eutrophication assessment but will not be used alone as a sole indicator of eutrophication problems.



Belgian coastal waters and Thames estuary: 2003 monthly, seasonal and yearly median Chlorophyll-a concentrations from MERIS



Dutch coastal zone

All maps show a large spatial variability that has gone unnoticed in routine chlorophyll-a measurements at fixed sampling stations.

Furthermore, the monthly maps depict significant seasonal changes in Chlorophyll-a concentrations.

Perpendicular to the Dutch coast a strong gradient in nutrient concentrations or eutrophication exists: high near-shore and low off-shore values of phosphate and nitrogen.

Near-shore these high nutrient concentrations fuel the development of the spring phytoplankton bloom that reaches a maximum concentration of 30 mg m⁻³ and higher in April.

A prominent species during these spring blooms is the harmful alga *Phaeocystis globosa*. In May the chlorophyll-a concentrations decline, but near-shore they remain relatively high compared to off-shore areas, especially along the south-western coast. In October the Chlorophyll-a concentrations reach values below 10 mg m⁻³ because the strong decline in day length and solar irradiance bring phytoplankton growth to a halt in turbid waters.

The eutrophication-gradient perpendicular to the Dutch coast does not explain why Chlorophyll-a concentrations are relatively high, at 3 to 10 mg m⁻³, in areas approximately 100 km off-shore, on the left hand side of the maps in all months and seasons. Examination of complete North Sea REVAMP maps in this atlas suggest these high Chlorophyll-a blooms originate in the Thames estuary from where they flow Northeastward with the residual current onto the Dutch continental shelf.

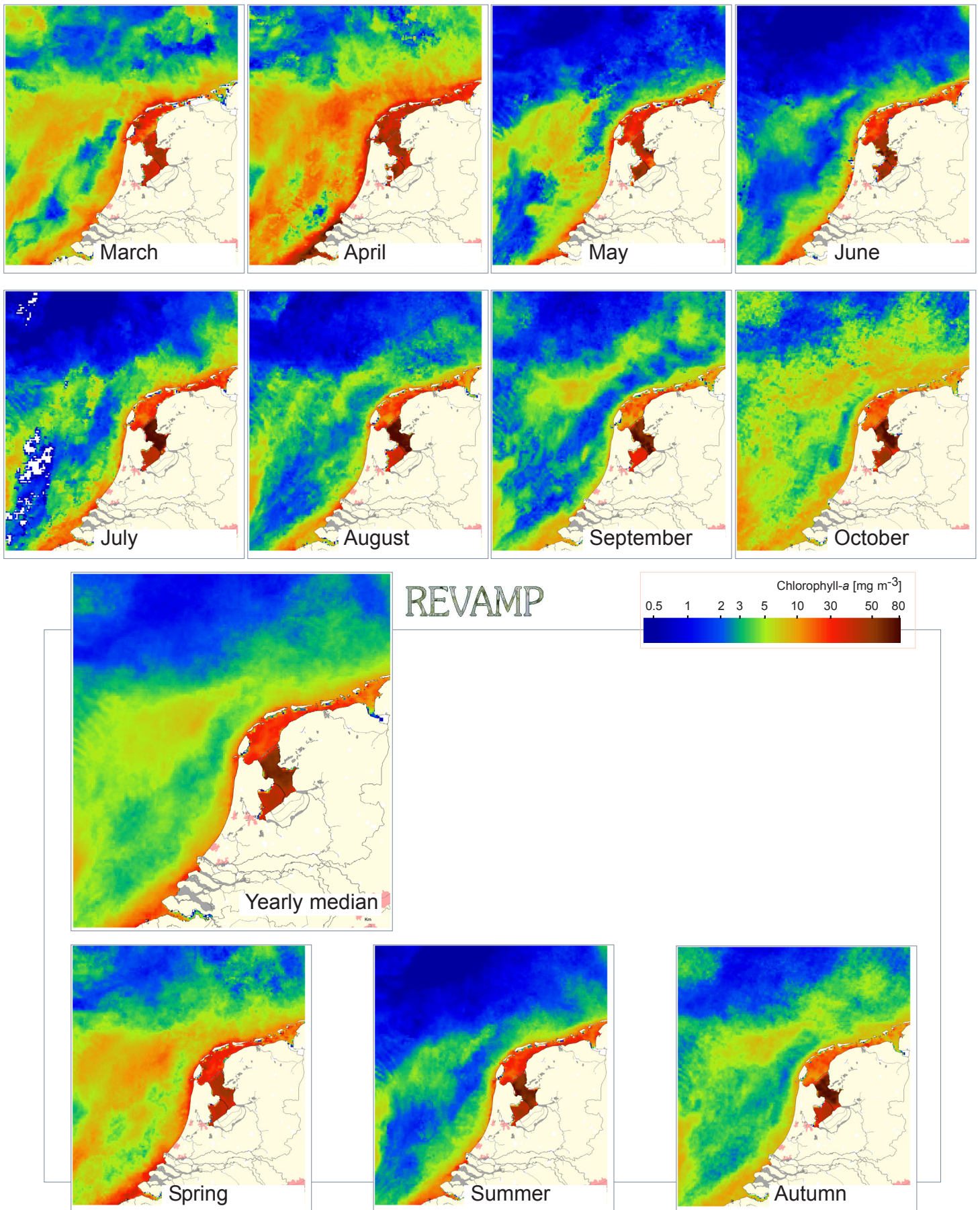
Extremely low Chlorophyll-a concentrations were observed in summer in a part of the Dutch continental shelf, over 50 km north of the Dutch Northern coast. In this area, the Oyster Grounds, water depth is 40 meter, turbulence is relatively low, and increased solar irradiance in spring leads to water column stratification. In May to September this normally leads to a nutrient- and Chlorophyll-a-poor 20 meter surface layer and a higher Chlorophyll-a bottom layer. In some parts of the Oyster Grounds surface chlorophyll-a values were even < 1 mg m⁻³. Because remote sensing techniques only sample the top of the water column, higher bottom-layer Chlorophyll-a concentrations remain unnoticed.

In autumn, a decrease in solar irradiance and an increase in wind-induced turbulence mix the water column and nutrients are delivered back to the surface. This explains the temporally enhanced Chlorophyll-a concentrations in October in this clear water.

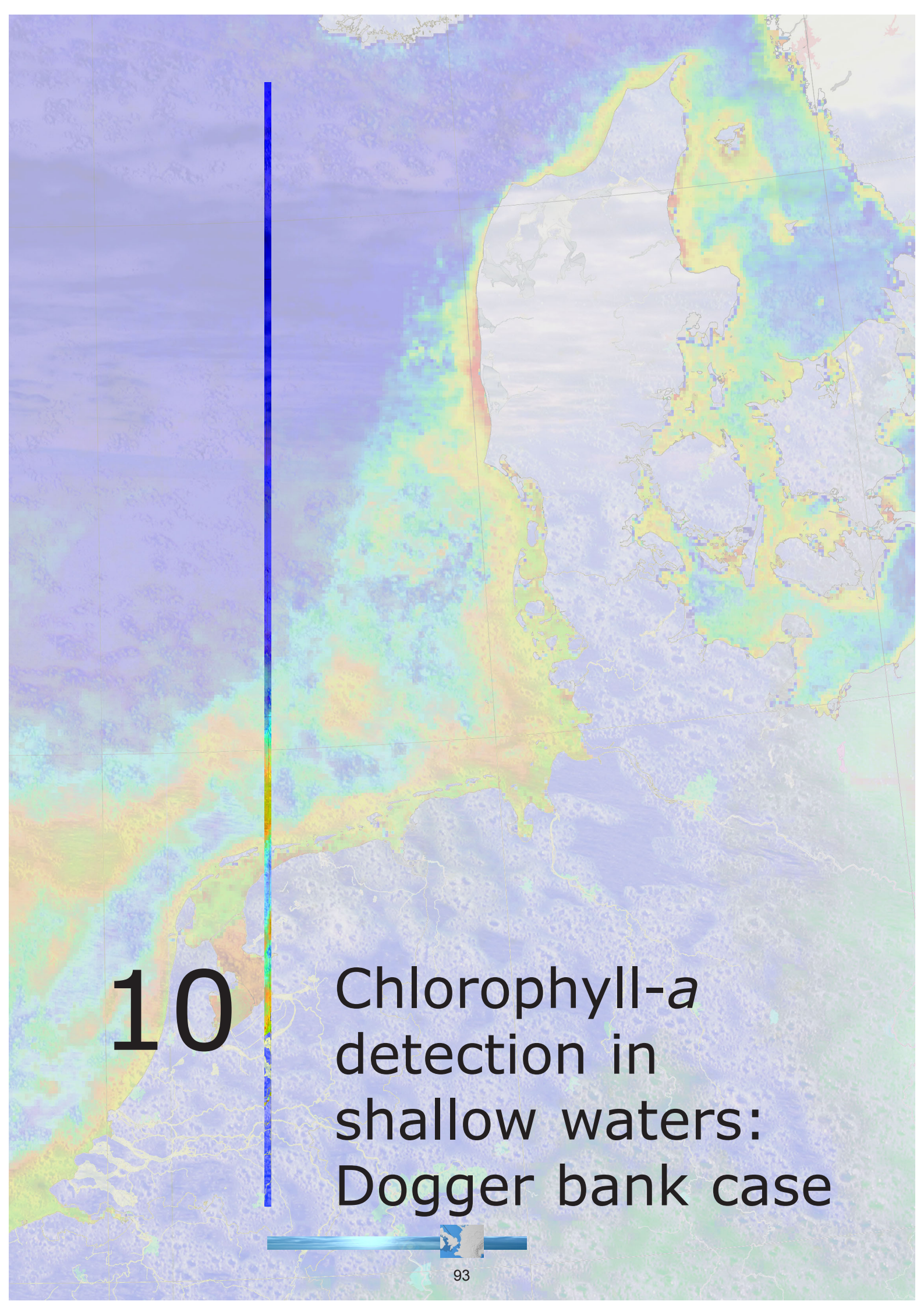
Although the general features of these Chlorophyll-a maps may be explicable, the high spatial variability warrants future examination of the combined use of routine Chlorophyll-a measurements at fixed sampling stations and remote sensing techniques in monitoring eutrophication effects and ecosystem impacts.



Dutch coastal waters: 2003 monthly, seasonal and yearly median
Chlorophyll-a concentrations from MERIS







10

Chlorophyll-*a*
detection in
shallow waters:
Dogger bank case

The Dogger Bank

Located in the southern North Sea, the Dogger Bank is a relatively shallow transition area of approximately 18 to 40 meters depth and is located between deep (> 50 meter) water to the North and shallow water (< 40 meter) to the South.

The Dogger Bank has an economically important fishery and distinct macrofauna communities that are supported by high seasonal primary production, which is typical in this area.

Due to its shallowness, the water warms up relatively quickly in spring and according to satellite imagery, blooms can occur as early as 14th February 2003. This particular spring bloom peaked in mid March, and exhibited concentrations of more than 10 [mg m^{-3}] of Chlorophyll-a (Fig. 1).

The summer of 2003 (Fig 2) was characterized by low Chlorophyll-a concentrations, but in autumn (Fig. 3) a significant bloom could be detected which started in mid August and continued until the end of September.

Some small-scale, patchy, filaments can be seen in the images of 14 & 15 February, which are typical features of algal blooms in this area. The presence of two major blooms in spring and autumn and the absence of blooms in summer can also be seen in the monthly and seasonal maps in this atlas.

The spatial and temporal dynamics of the Chlorophyll-a concentration are important for ecological, primary production or fisheries research in this region and the phytoplankton production provides food for higher trophic levels. Water column turbidity in this region alters the light availability in the water column which in turn affects both pelagic and benthic production.

Optical remote sensing in this area, has the potential to advance our understanding of the spatial and temporal dynamics of phytoplankton in this area.

Do satellites 'see' the Dogger Bank?

Because the Dogger Bank is such a shallow area at specific points (minimum depth ~18 meter), some of the incident sunlight may reach the sea floor. The sea floor, can reflect a portion of the sunlight back towards the sea surface.

This bottom-reflectance can influence the reflectance spectrum as seen by the satellite, and hence the chlorophyll-a concentration that is derived by the REVAMP algorithm.

The amount of light penetration in the water column ultimate effect on the remotely sensed chlorophyll-a concentration and consequently benthic and pelagic primary production.

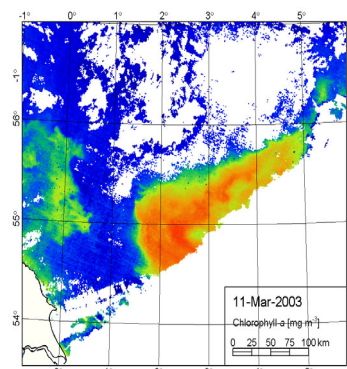
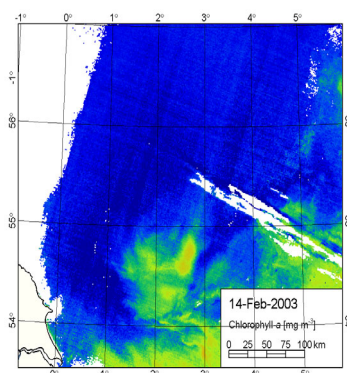


Fig 1: Early spring bloom

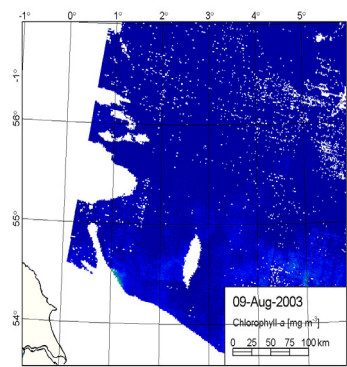
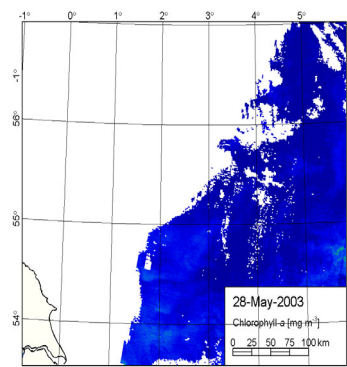


Fig 2: Low activity during summer



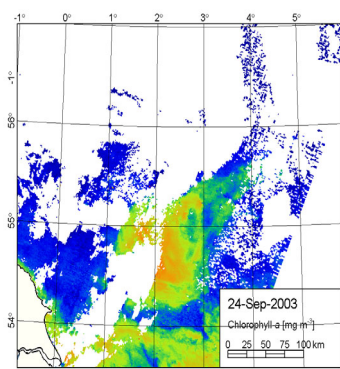
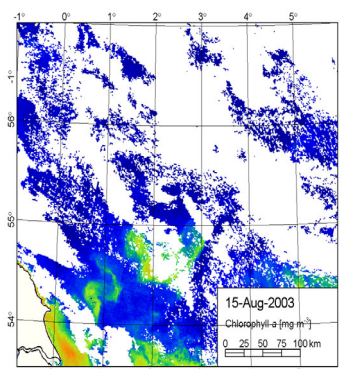


Fig 3: Autumn bloom, beginning end of August, peak end of September.

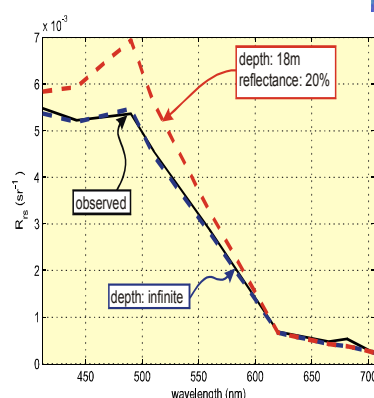


Fig 4: clear water - May 28th

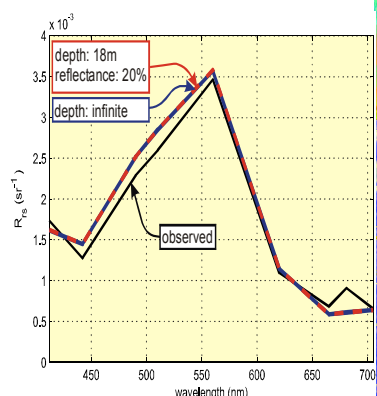


Fig 5: turbid water - March 11th

We present two contrasting cases, for very clear and turbid waters in this area.

For the clear water example MERIS imagery from 28th May was used (Fig 4), when very low concentrations of Chlorophyll-a ($<1 \text{ mg m}^{-3}$) were measured over the Dogger Bank.

The turbid water example was derived from a MERIS image of 11th March (Fig. 5), when the spring algal bloom was at its peak ($\sim 10 \text{ mg m}^{-3}$).

The influence of bottom reflectance on the associated reflectance spectrum was simulated using a radiative transfer model (Hydrolight) by running the model with and without (infinite depth) the bottom depth.

The black line in Fig 4 and 5 are the observed reflectance spectrum from the MERIS satellite, and the dashed blue line is the default model fit when bottom reflectance is ignored. The red line was calculated using Hydrolight for a bottom depth of 18 meters depth and a (spectrally flat) reflectance of 20%.

The influence on the reflectance spectrum for the turbid water case (Fig 5) is negligible (blue and red line on top of each other), however, the influence on the clear water spectrum is large.

The calculation also showed that the light available at the bottom is 10-20% relative to just below the surface, depending on wavelength. So, for clear water, satellites do 'see' the bottom of the Dogger Bank, but how does this affect the retrieved chlorophyll-a concentration?

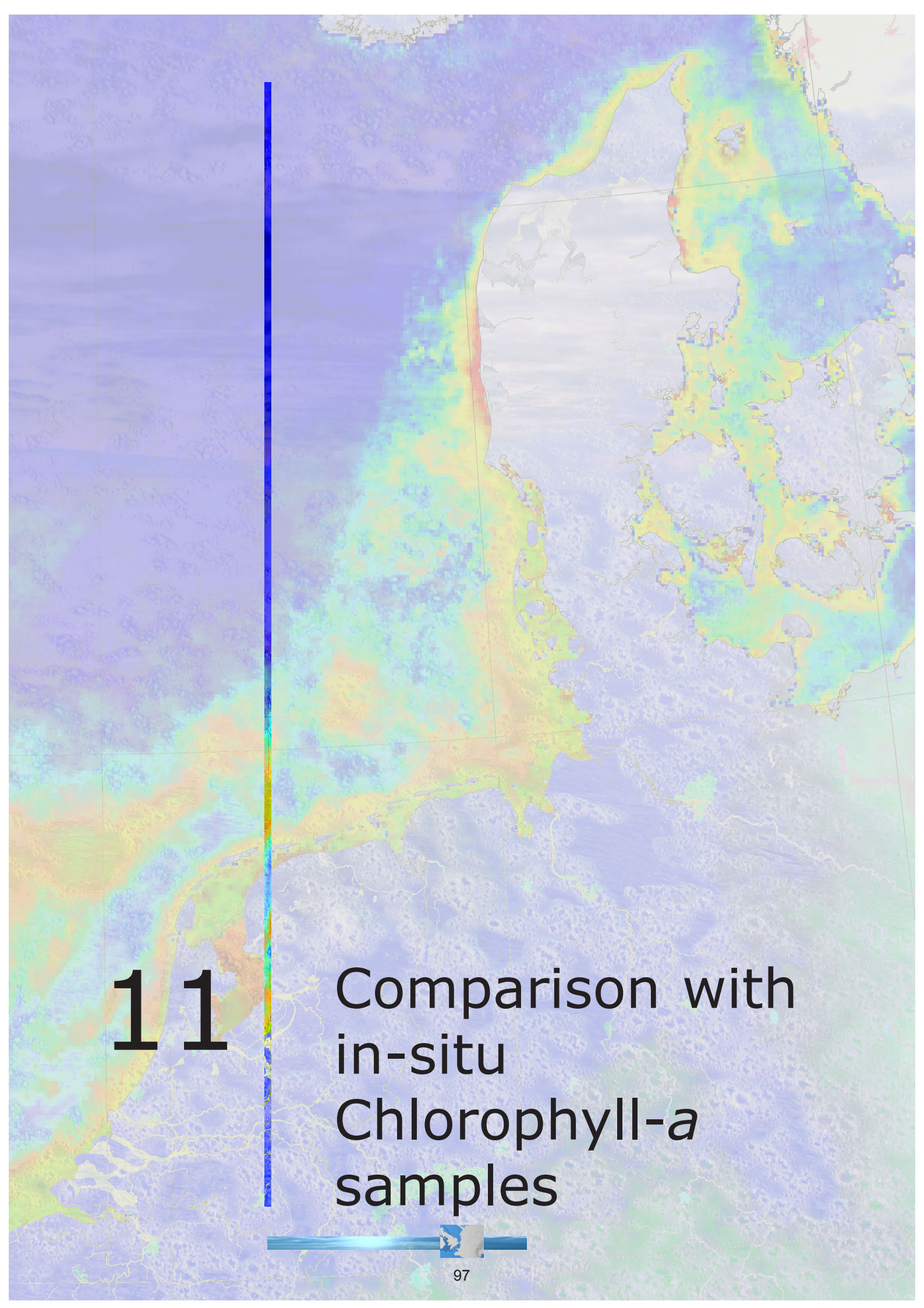
When the Chlorophyll-a concentration was retrieved from the red reflectance spectrum (with bottom reflectance), the value hardly changed (from 0.63 ± 0.41 to $0.62 \pm 0.33 \text{ mg m}^{-3}$) and remained within the error bounds.

So the tentative conclusion is that the influence of bottom reflectance on the retrieved Chlorophyll-a concentrations over the Dogger Bank is negligible for turbid water pixels and small for clear water pixels.

However, the error in the clear water case (Fig 4) may increase when the bottom reflects more than 20% of the light or when there are components in the water column that could be confused with the Chlorophyll-a absorption spectrum.

We therefore have to remain cautious when interpreting Chlorophyll-a patterns in shallow areas with clear water.





11

Comparison with
in-situ
Chlorophyll-*a*
samples

Part 1: Laboratory intercomparisons of in vitro Chlorophyll-a (to show the inherent inter-laboratory variability)

The REVAMP partners who perform Chlorophyll-a analysis by High Performance Liquid Chromatography participated in three intercomparisons of the in vitro Chlorophyll-a method, two of which were arranged by the MERIS and AATSR validation team (MAVT) in 2002 and a further intercomparison was arranged by REVAMP partners, the results of which are documented in the REVAMP intercomparison document available at http://envisat.esa.int/workshops/mavt_2003/.

A total of eleven MAVT teams, represented by 19 laboratories, participated in the MAVT intercomparison and 5 of these were partners in the REVAMP project (Table 1).

Institute or laboratory	Principal investigator	AO-project	HPLC methods	Spectrophotometric method	Fluorometric method
SOC (Southampton Oceanographic Centre)	Weeks	290	Chl1, Chl2		
CEAB (Centre d'Etudes Avancés de Blanes)	Weeks	290		Chl2	
LPCM (Laboratoire d'Océanographie de Villefranche sur mer)	Antoine	322	Chl1, Chl2		
SU (Stockholm University)	Kratzer	371		Chl2	
IOW (Baltic Sea Research Institute Warnemünde)	Siegel	468	Chl2		
NIVA (Norwegian Institute for Water Research)	Sørensen	609	Chl2	Chl2	
UIB (University of Bergen)	Sørensen	609		Chl2	
IMR (Institute of Marine Research, Norway)	Sørensen	609			Chlorophyll-a
GKSS (GKSS Research Centre)	Doerffer	647	Chl1, Chl2		
MUMM (Management Unit for the North Sea Mathematical Models)	Roose	698	Chl2		
PML (Plymouth Marine Laboratories)	Aiken	9001	Chl2		
JRC (JRC IES/IMW)	Zibordi	9020	Chl1, Chl2		
IVM (Institute for Environmental Studies, Netherlands)	Peters	9096	Chl2		
AquaSense (Netherlands)	Peters	9096		Chl2	
Steins lab (Denmark)	Fell	9106		Chl2	
ILAT (Institute für Lebensmittel, Arzneimittel und Tierseuchen)	Fell	9106		Chl2	
NTNU (Norwegian University of Science and Technology)	Fell	9106	Chl2	Chl2	
IOLR (Israel Oceanographic and Limnological Research Institute)	Fell	9106			Chlorophyll-a
IGB (Leibniz-Institute of Freshwater Ecology and Inland Fisheries)	Fell	9106	Chl2		

Table 1. Participants in the NIVACal 1 and NIVACal 2 chlorophyll-a intercomparisons in 2002 (Sørensen et. al., 2003).

These results were used to improve the methods and routines to both for HPLC and spectrophotometric Chlorophyll-a method. The two intercomparisons were performed by NIVA (NIVACal 1 and 2) and included both the algal pigment indices Chl1 and Chl2 using HPLC, and Chl2 was also determined by spectrophotometric methods. In the intercomparisons, samples from algal cultures and natural samples collected off the coast of Norway were used. The results are found in the ESA publication SP 531 and in the publication from the MAVT working meeting in Frascati November 2003 (Sørensen et.al., 2003).

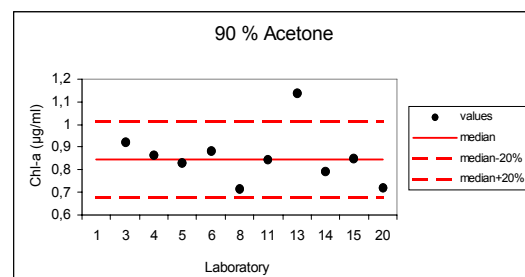
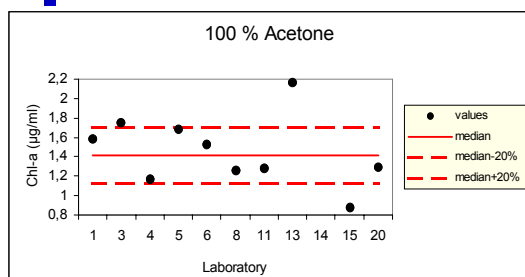
Both natural samples (NIVACal 2) and samples from algal cultures (NIVACal 1) were prepared at the NIVA laboratory and sent to the other laboratories on dry ice. The samples were prepared from cultures with different cell concentrations of the diatom *Skeletonema costatum* and from natural water samples from Norwegian fjords situated in southern Norway. Samples of extracted pigments were also prepared from algal cultures. This was used to discriminate the errors in the extraction step and determination step.

The results from the laboratory algal samples were treated according to the method of Youden where each participant analyse samples in pairs, and the result for each pair is presented as a point in a Youden plot. Each laboratory's location in the diagram gives information regarding the kind and magnitude of error. The use of pair of samples of the same or slightly different concentrations and the way of presenting the results allow us to determine whether the results have a random or a systematic error. In case of only random errors, the points will be evenly distributed between the quadrants, whereas a grouping along the 45° line expressing the deviation from the "true" values indicates mainly systematic errors.



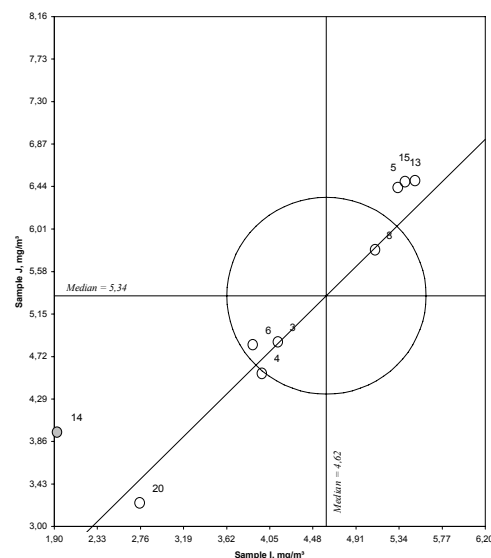
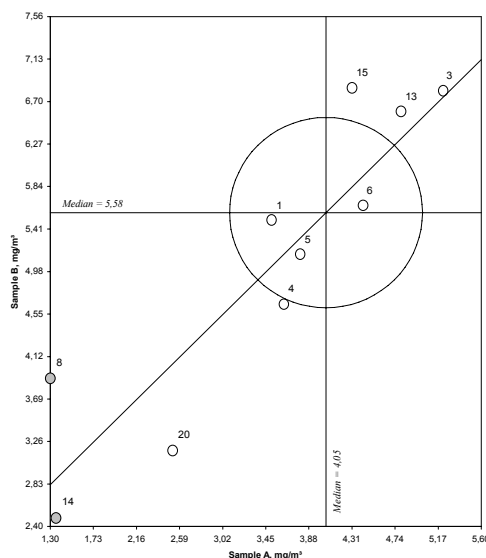
The results from the determination of the Chlorophyll-a extract by the laboratories showed that for the 100% acetone extracts, two out of the ten laboratories deviated by more than 20% from the median. The overall variation (CV) between laboratories is 26%, but 15% when disregarding the two deviating laboratories. The overall CV between the laboratories for the 90% acetone extract is 14 %. Apart from one of the results (laboratory 13), the CV between the laboratories is acceptable (8 %). The REVAMP partners are here represented by laboratory number 3, 4, 6, 8 and 15 and overall has < 10 % deviation.

Results of the HPLC analyses of the chlorophyll-a extracts in 100% (left) and 90 % (right) acetone during the NIVACal 2 (Sørensen et.al., 2003).



An example of the result from the NIVACal 1 illustrates the variation that was found between the laboratories in the MAVT intercomparison for the MERIS validation period in 2002-2003. The points in the Youden plot show the result from a pair of samples (AB or IJ). The circle shows the deviation of 20 % from the median value of the sample pair.

Youden plots of two pairs of results from the NIVACal 1 for HPLC analysis of chlorophyll-a. The left graph presents the sample pairs AB, the right the graph sample pairs IJ. "Outliers" are marked grey.



In the last MAVT-intercomparisons (NIVACal 2) the CV between participants were from 14-38% when excluding "outliers". However, a result from a pair of sample with high concentration vary much among the participants, and excluding this pair, the CV among participants were between 14% and 19%. The main results for the HPLC results concerning the step of determination (Chlorophyll-a extracts) was overall good (<10%), but some laboratories was recommended to check there analytical procedures.

In the overall analyses the algal sample showed higher error as expected than the step of determination, indicating that some laboratories have incomplete extraction or other systematic error. The overall error for 7 of the 11 labs was within 20%, and except for a few sample pairs, the REVAMP partners showed acceptable agreement, and from the REVAMP intercomparison, methodological improvements were also suggested.

Part 2: Comparison with in-situ data in Dutch coastal waters

Remote sensing images provide a synoptic overview of the chlorophyll-*a* concentrations in the North Sea, on a day-to-day basis and can be used to investigate the seasonal and spatial variations at high resolution, which can teach us more about the underlying processes that drive the 'North Sea' system.

To be useful for long-term trend detection, however, we need to establish the relationship between actual and historical in-situ data that are measured routinely by national monitoring agencies. to verify whether remote sensing and in-situ measurements of Chlorophyll-*a* give the same value.

There are a number of things that need to be considered when evaluating in situ and remotely sensed Chlorophyll-*a* data.

First of all, the measurement scales are of different orders of magnitude; while in-situ measurements typically sample about 1 to 2 liters of water, a remote sensing measurement covers tens of hectares, averaged over a specific surface layer.

Secondly, in-situ measurements typically extract the algal pigments from the cell, whereas remote sensing 'sees' intact algal cells with an array of pigments as they interact with the underwater light field.

Thirdly, because of the rapidly changing conditions on the North Sea, remote sensing and in-situ measurements are only directly comparable when sampled within a small time window (~1 hour), and it is often very difficult to fulfill this criteria.

Finally, the measurement protocols that are used by national monitoring agencies can differ from those used by other research laboratories.

These differences can have a significant effect on the measured Chlorophyll-*a* concentration (as pointed out by the laboratory intercomparisons from Part1 of this chapter).

The advantage of remote sensing is that it can provide a uniform measurement method for the whole North Sea but taking into consideration the above points, the remote sensing data still needs to be validated.

A time series of in situ Chlorophyll-*a* measurements in 2003 was used for a number of fixed monitoring stations on the Dutch (Rijkswaterstaat) and Southern UK (PML) coasts (16 data points in total). By using a time series, random differences introduced by scale dissimilarity and a-synchronous sampling are averaged out and the systematic offsets can then be investigated.

In the scatterplot on the right hand side, the green squares represent the yearly mean chlorophyll-*a* for each measurement station. The horizontal and vertical error bars represent the standard deviation over all measurements at each station, for in-situ and remote sensing measurements, respectively.

The relative root-mean square difference between remote sensing and in-situ is 33%, with a correlation coefficient of 0.93.

Part of this difference can be attributed to the statistical uncertainty in the median value (calculated as the geometric mean).

This exercise shows a lack of systematic offset between both datasets.



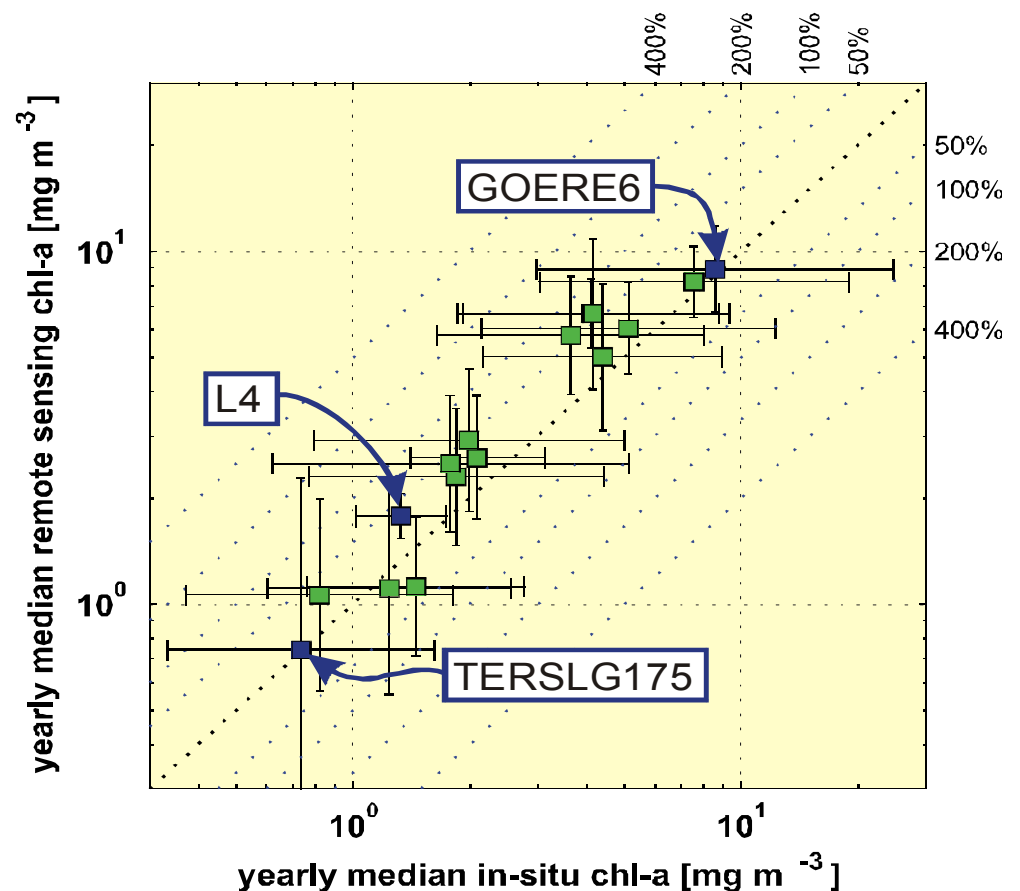
It is also possible to look at the seasonal patterns in Chlorophyll-*a* concentration at the above stations. Again, sufficient data points are necessary to make meaningful comparison.

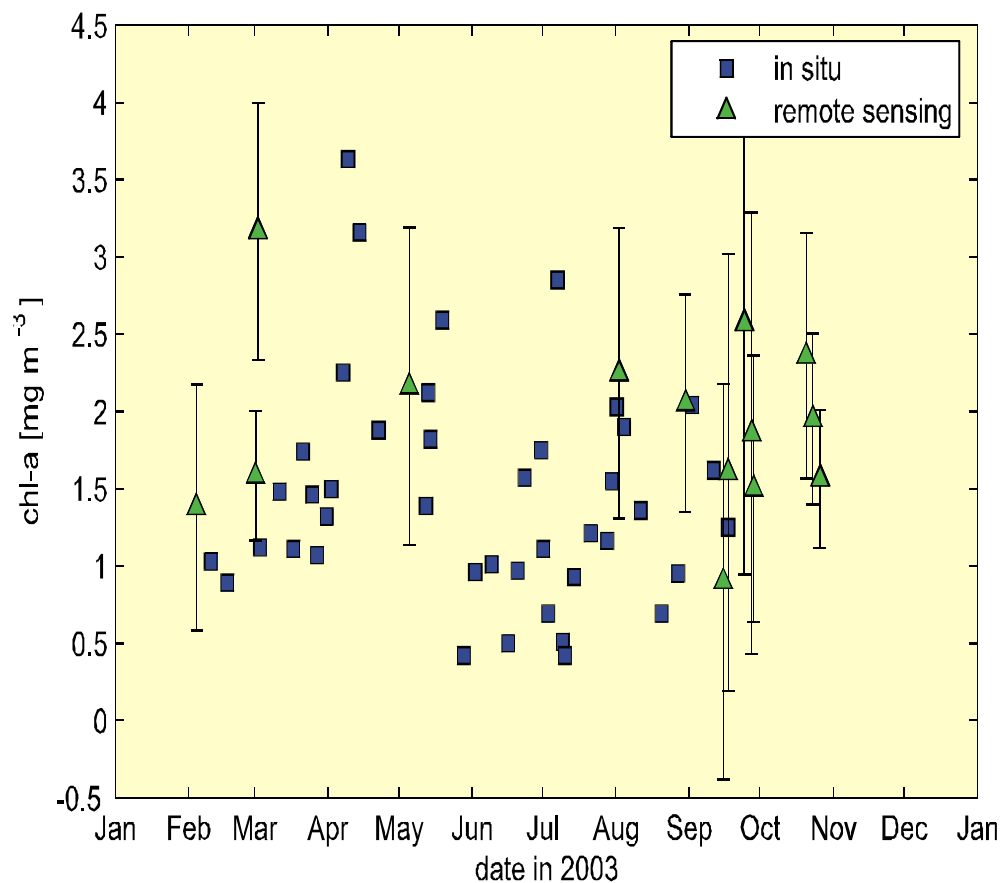
Below, the time series for three stations are presented, located in the Channel (station L4), central North Sea (TERSLG175) and the turbid Dutch coast (GOERE6). These stations cover different regimes with low and high suspended matter and dissolved organic matter which can be higher than the range in chlorophyll-*a* concentration.

The vertical error bars on the remote sensing data points indicate the standard error or confidence product. The error in the in-situ measurements is unknown.

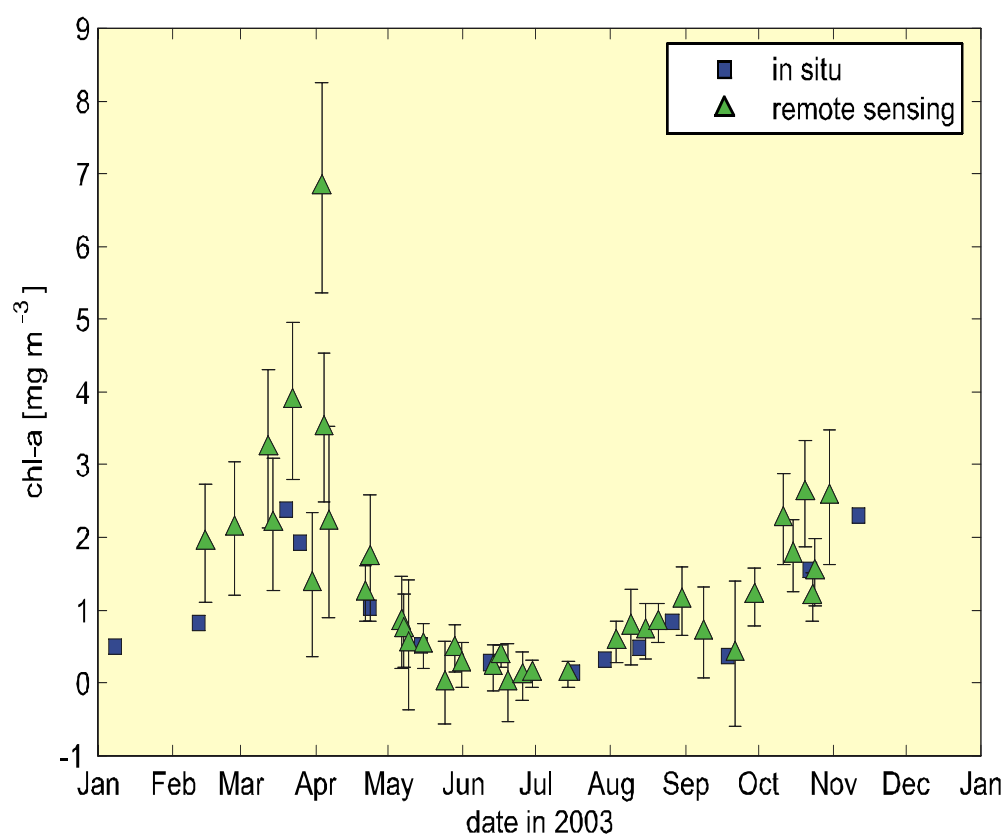
The timing and magnitude of the algal blooms as seen in remote sensing and in-situ data series show a good agreement. Also the error bars on the remote sensing data seem to provide a good estimate of the true error in these measurements.

The estimated error was calculated individually for each remote sensing pixel, which is rarely available in remote sensing imagery but is one of the novel products from the REVAMP project.



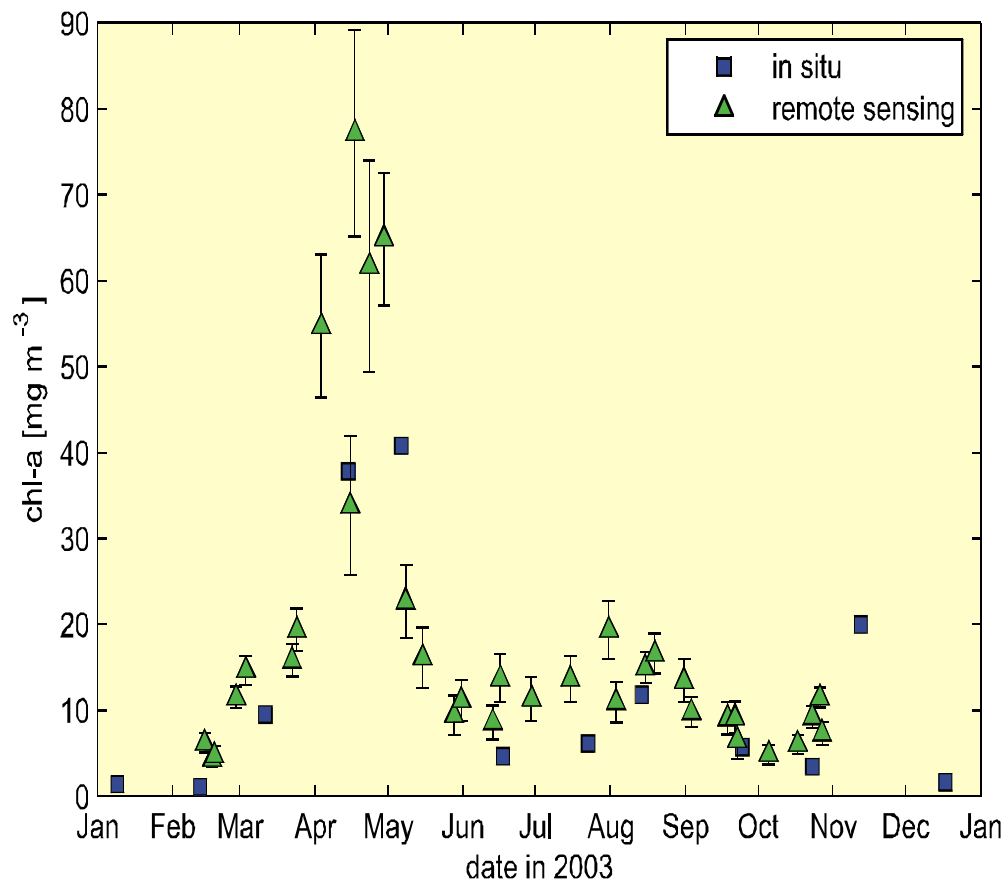


Time series for chlorophyll-a in 2003 at station L4



Time series for chlorophyll-a in 2003 at station TERSLG175





Time series for chlorophyll-a in 2003 at station GOERE6

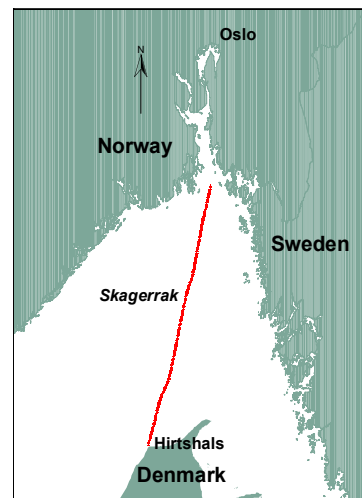
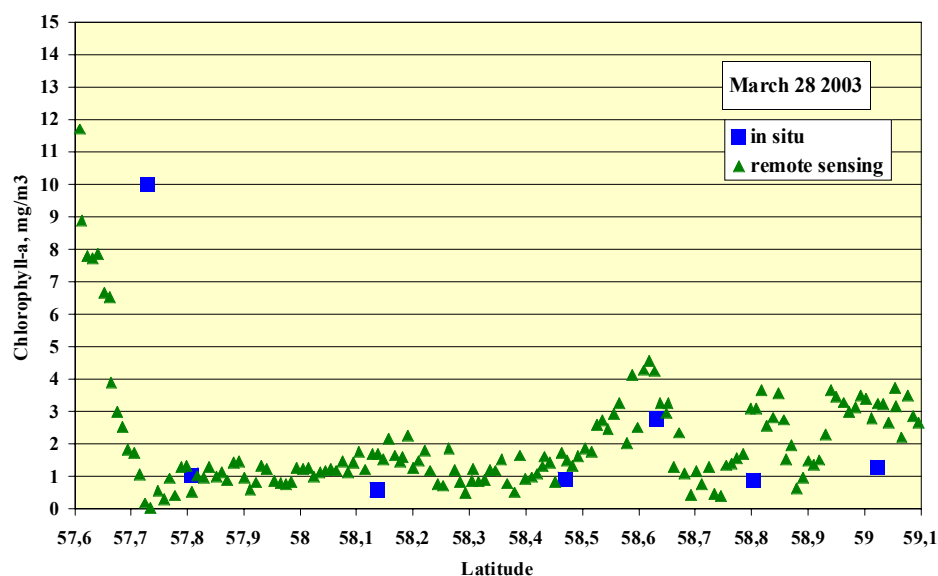
Part 3: Comparison from the Skagerrak area 2003

Data from the ferrybox system onboard the Color Festival between Hirtshals at the northern coast of Denmark to Oslo (Oslo Fjord) was also used for validation of the remote sensing chlorophyll-a images. The ferrybox system is operated by NIVA through the EU-project FerryBox. The location of the ship track is shown in the map to the right.

The in situ stations used in the validation are located along the ship track between the coast of Denmark at latitude 57.7 and the outer Oslo Fjord in the north eastern part of Skagerrak at latitude 59.1. The satellite passes when the ferry is around latitude 58.0-58.1, and the time difference for station close to the Danish coast is - 2-3 hours and the outer Oslo Fjord + 2-3 hours relative to the MERIS over pass time.

The in situ samples were collected at about 3 meters depth. At bothends of the transect there is a greater disagreement between coincident satellite and in situ measurements which can be due to the problems of sampling in these dynamic areas and the time difference relative to the satellite pass.

The data from 28th March shows good agreement with the in situ data .although at both ends of the transect there is still a large deviation between the satellite and in situ data.

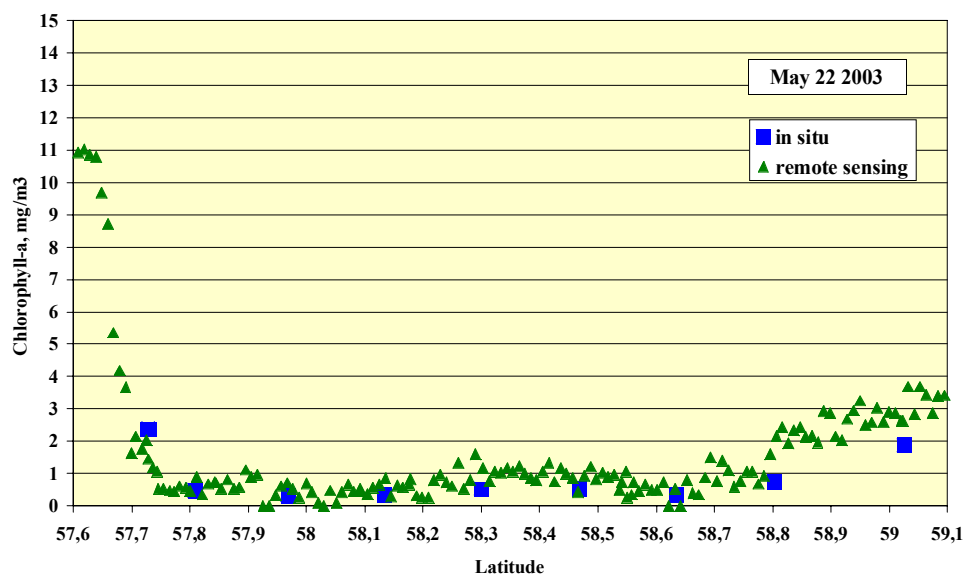


The ship of opportunity track in the Skagerrak used for validation of the satellite Chlorophyll-a.

Comparison between in situ and remote sensing Chlorophyll-a for March 28 2003.

Comparison between in situ and remote sensing Chlorophyll-a for May 22 2003.

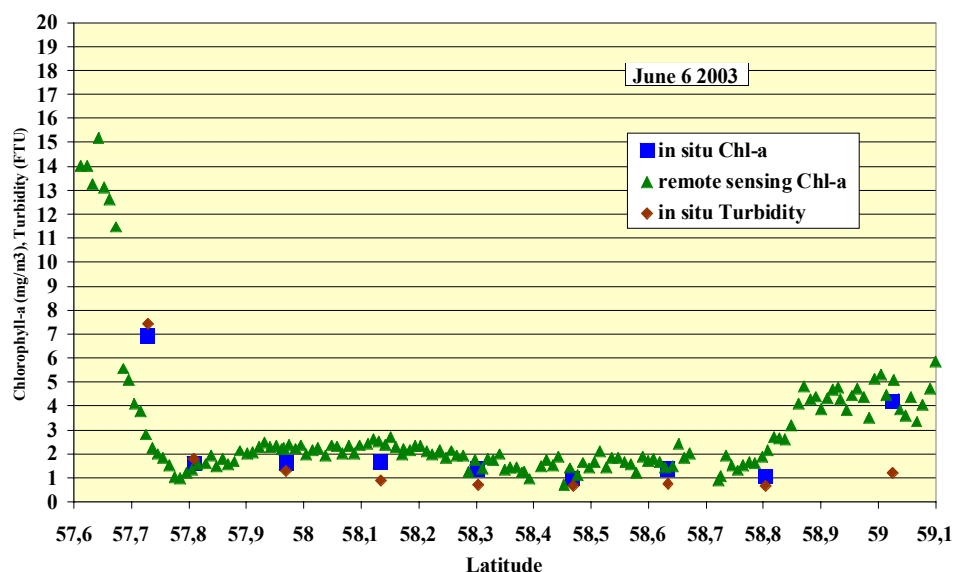
Data were also compared on 22nd May and also showed good agreement, although values on the Danish coast could not be validated due to missing in situ data near the coast.



In early June when diatoms still dominated the phytoplankton, the agreement was also very good. High Chlorophyll-a values were also found along the Danish coast on 22nd May, but the remote sensing Chlorophyll-a was overestimated possible due to land adjacency affects.

Comparison between in situ and remote sensing Chlorophyll-a for June 6 2003.

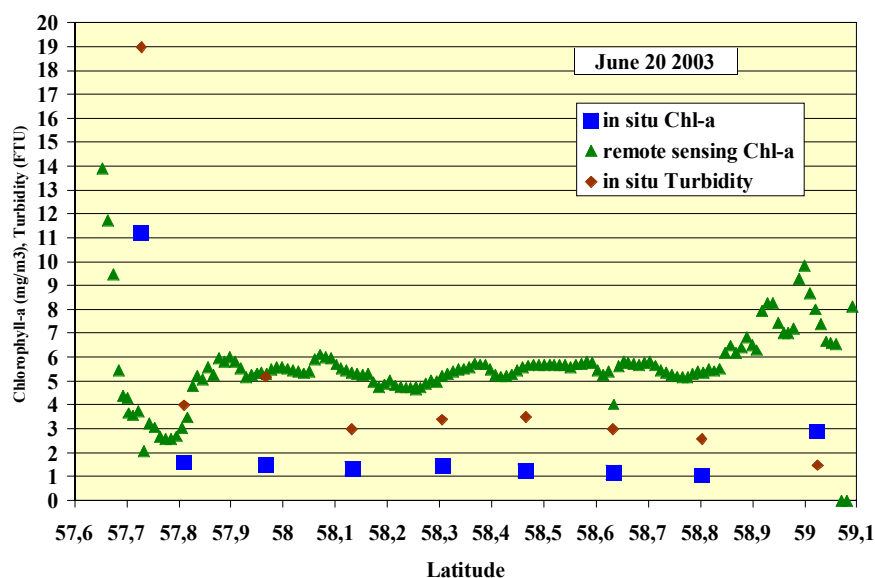
Included also the measured in situ turbidity illustrating the particle scattering.



Later in June the bloom of the coccolithophoride *Emiliania huxleyi* dominated the whole areas except close to the coast when the remote sensing Chlorophyll-a was overestimated by a factor 4 to 5. The turbidity measurements in late June illustrate the high scattering in the water masses.

There was a dip in the remote sensing Chlorophyll-a data close to the Danish coast where there seems to be a better agreement between remote sensing and in situ Chlorophyll-a probably due to the lower abundance of coccolithophorids and less scattering which can contaminate the Chlorophyll-a signal.

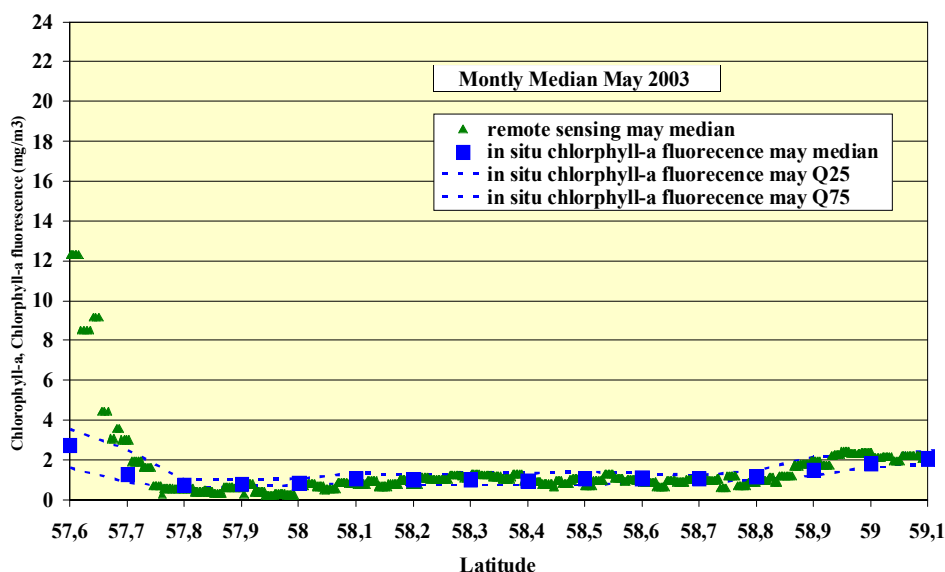




Comparison between in situ and remote sensing Chlorophyll-a on June 20 2003. Included also the measured in situ turbidity illustrating the particle scattering.

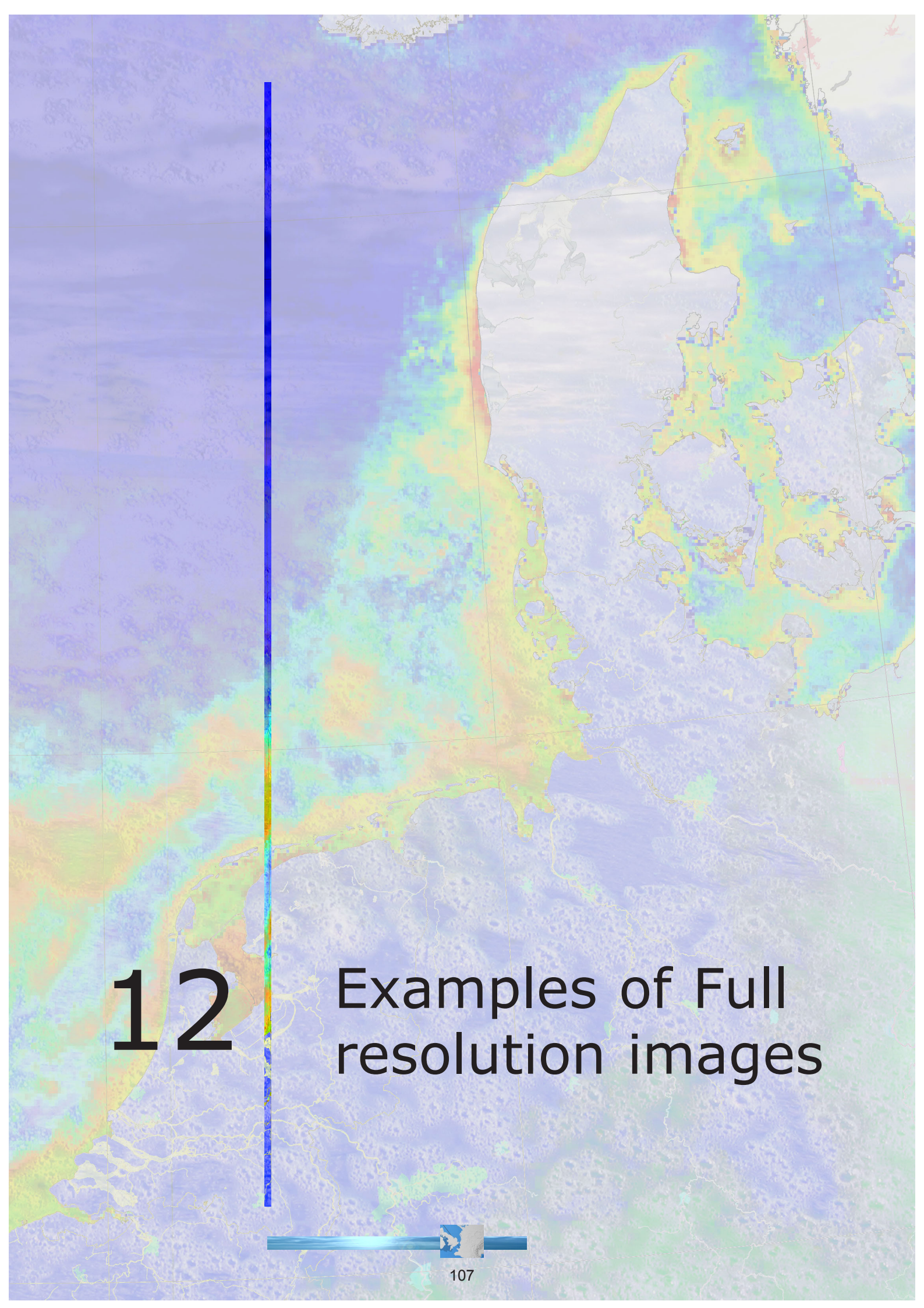
Comparison of monthly median chlorophyll-a images with monthly median values from the chlorophyll-a fluorescence measured by the ferrybox system was performed in May 2003. The interpretation of chlorophyll-a fluorescence is difficult due to the diurnal variation of the fluorescence relative to the chlorophyll-a, however night time fluorescence gives a better agreement with chlorophyll-a concentration, which could also be seen in some of the in situ chlorophyll-a measurements. For the monthly comparison we used the night fluorescence and compared with the monthly average of the remote sensing chlorophyll-a.

In May the remote sensing Chlorophyll-a agreed well with the in situ data. The median remote sensing Chlorophyll-a values are close to the in situ median and mostly within the upper (Q75) and lower quartile (Q25) and 50 % of the ferrybox data fall within these quartiles. The largest deviation was seen at the Danish Coast at 57.6 North where the Chlorophyll-a was overestimated by a factor 2 to 3 compared to the Chlorophyll-a fluorescence. The Chlorophyll-a fluorescence and the Chlorophyll-a samples are measured at about 3 meters depth whereas the surface chlorophyll-a could be higher in these stratified waters. Using ship of opportunity data for satellite validation is under investigation in the FerryBox project but should be interpreted taking into consideration the points highlighted above.



Comparison between in situ Chlorophyll-a fluorescence from the ferrybox system and remote sensing chlorophyll-a for the May 2003 monthly median. The upper and lower quartile for the ferrybox data is shown.





12

Examples of Full
resolution images

On the next pages we will show five examples of MERIS Full Resolution images. These images have a pixel size of approximately 300 x 300 m and are specifically suitable to illustrate the intricate patterns of phytoplankton (through its by satellite observable main pigment Chlorophyll-*a*) near the coast.

A special feature of MERIS is that this full resolution mode has about the same spectral and radiometric resolution as the reduced resolution (which was used to build the monthly and seasonal composites in this Atlas).

This also means that the results from the REVAMP Chlorophyll-*a* algorithm are compatible in the two different resolution modes.

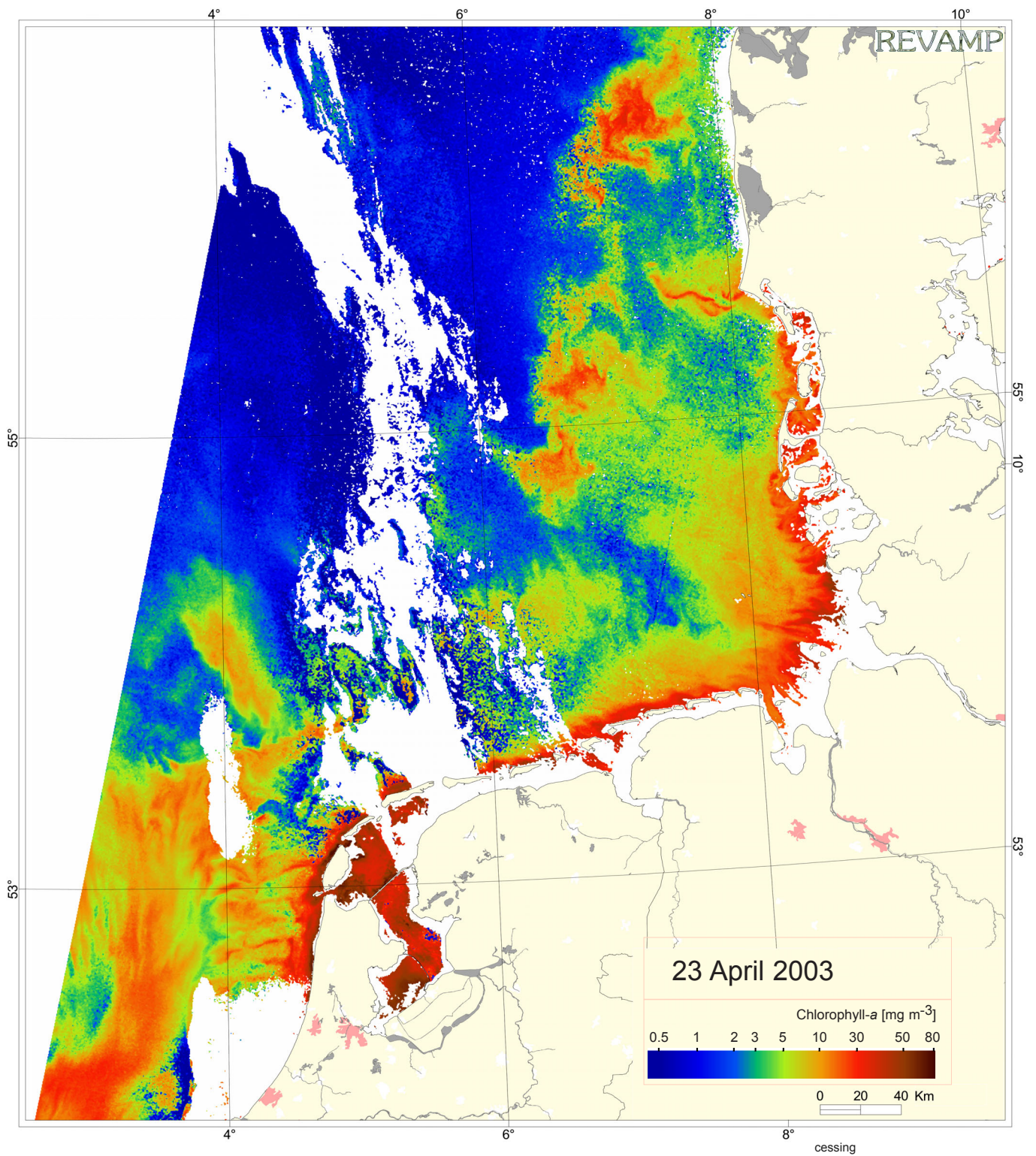
One has to take into consideration that momentary scenes will suffer from cloudiness therefore the featured full resolution images were selected for minimum cloud cover.

The five featured scenes are:

- 1) 23 April: German Bight. The image shows very detailed patterns of *Phaeocystis* blooms
- 2) 22 May: Skagerrak / Kattegat + Oslo Fjord: Some bloom along the Norwegian coastline. High concentrations of Chlorophyll-*a* along the Northern part of Denmark extending into the Kattegat.
- 3) 13 June: Dutch and Belgian coast; German Bight: Patchy blooms along the Dutch, Belgian and Danish coast. Elevated Chlorophyll-*a* levels in front of the Westerscheldt estuary.
- 4) 14 July: English Channel: Patchy blooms with elevated concentrations in the Seine estuary and in the Wash.
- 5) 3 August: Dutch and Belgian coast: Patch blooms with high Chlorophyll-*a* levels along the Southern part of the Dutch coast. Note the elongated patterns of Chlorophyll-*a* in the Flemish Banks. Further research should verify the reality of these patterns since there may be deviations in high sediment areas.

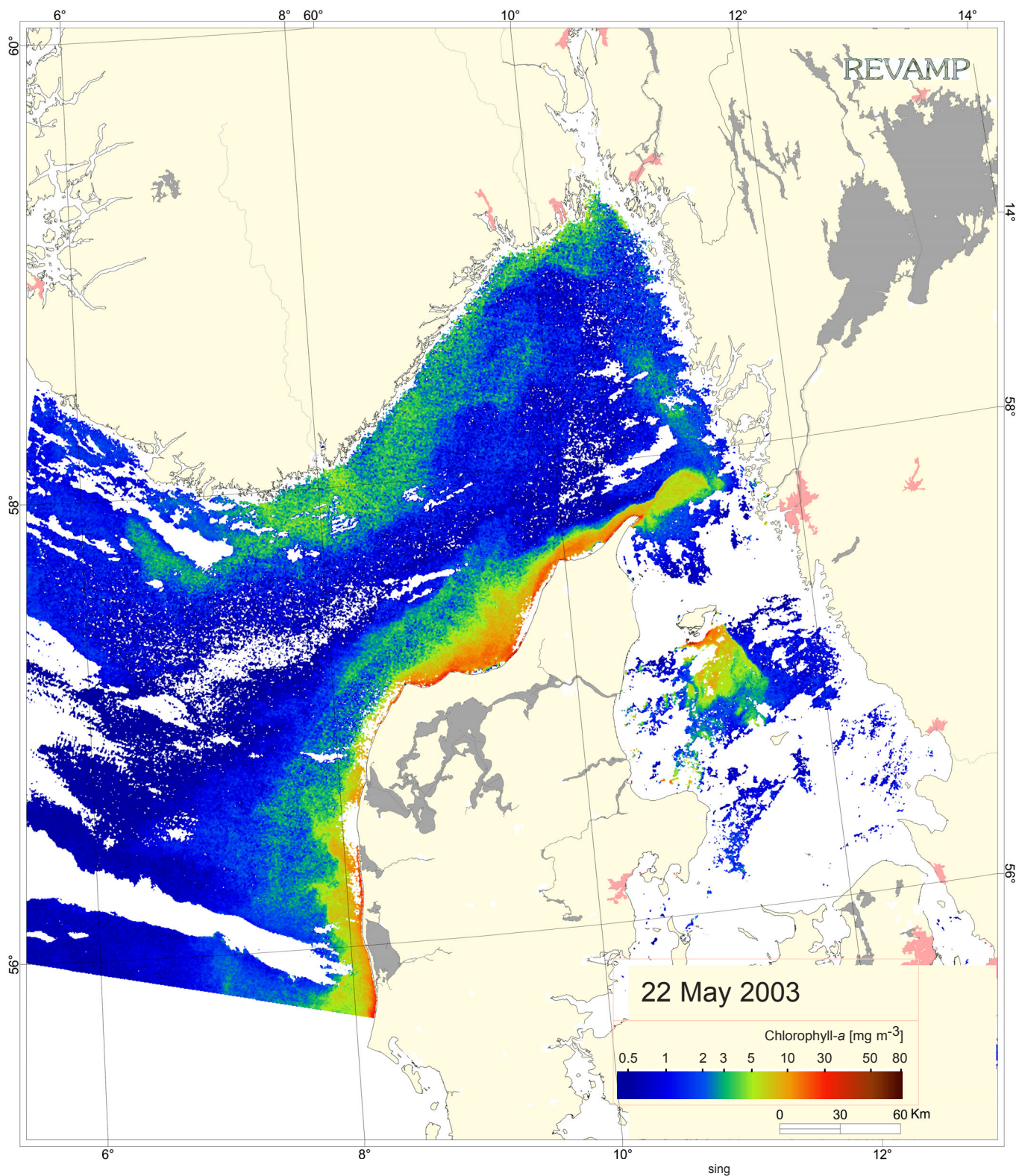
All MERIS Full Resolution scenes were specifically for REVAMP processed to surface reflectances by the ACRI-ST processing - Coastwatch GMES services.





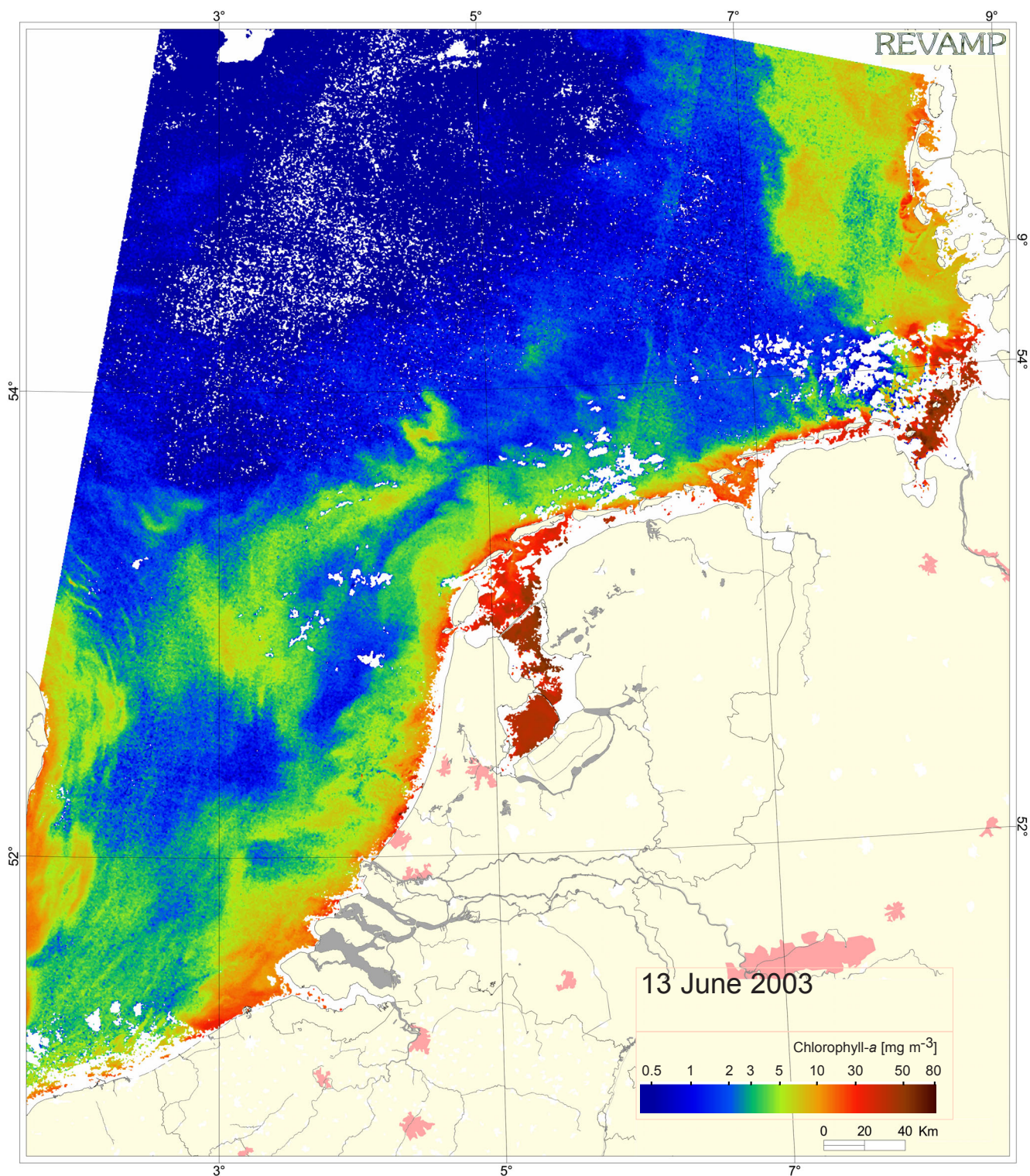
Surface Reflectances ACRI-ST processing - Coastwatch GMES service
 Chlorophyll-a REVAMP processing





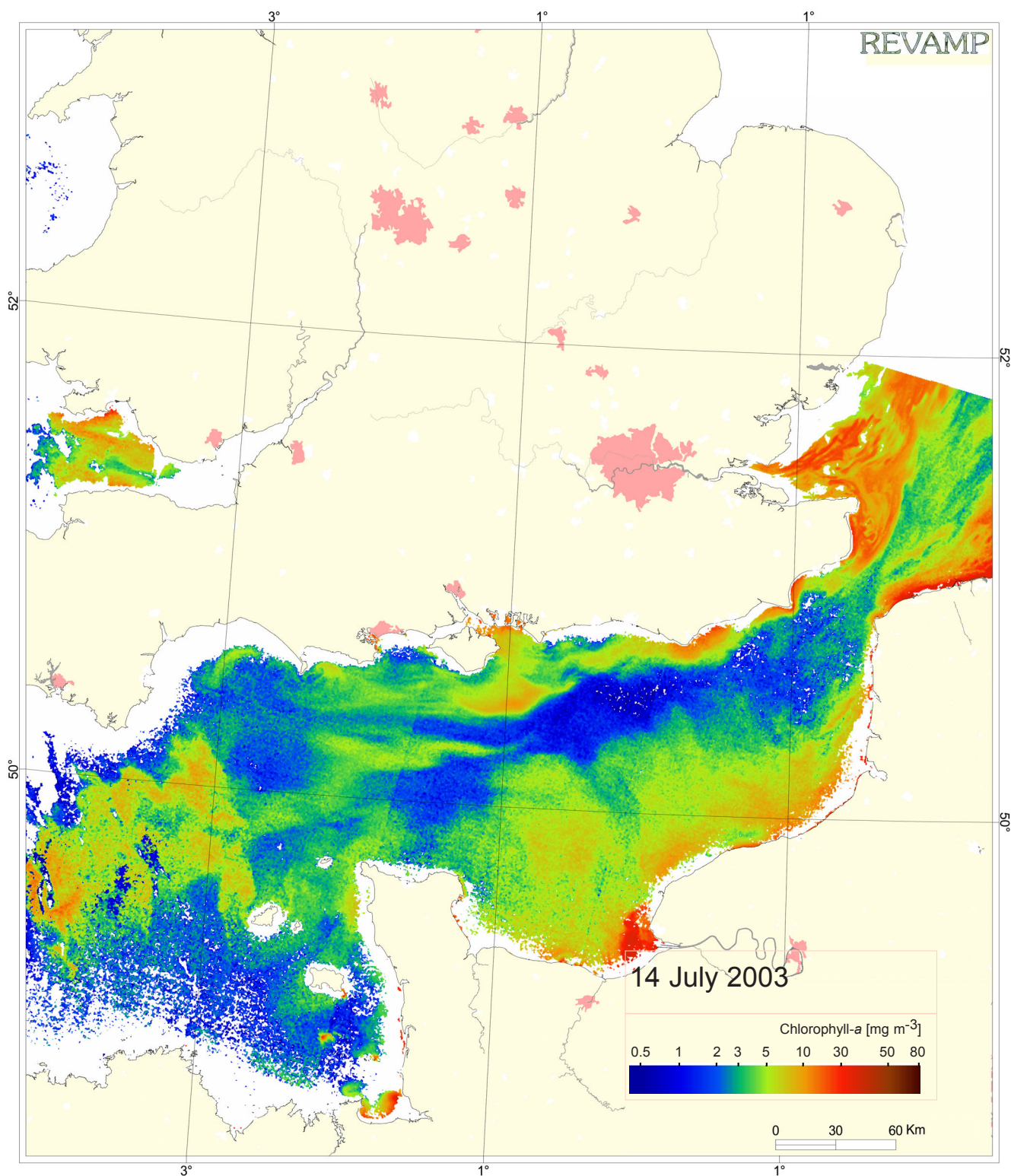
Surface Reflectances ACRI-ST processing - Coastwatch GMES service
Chlorophyll-a REVAMP processing





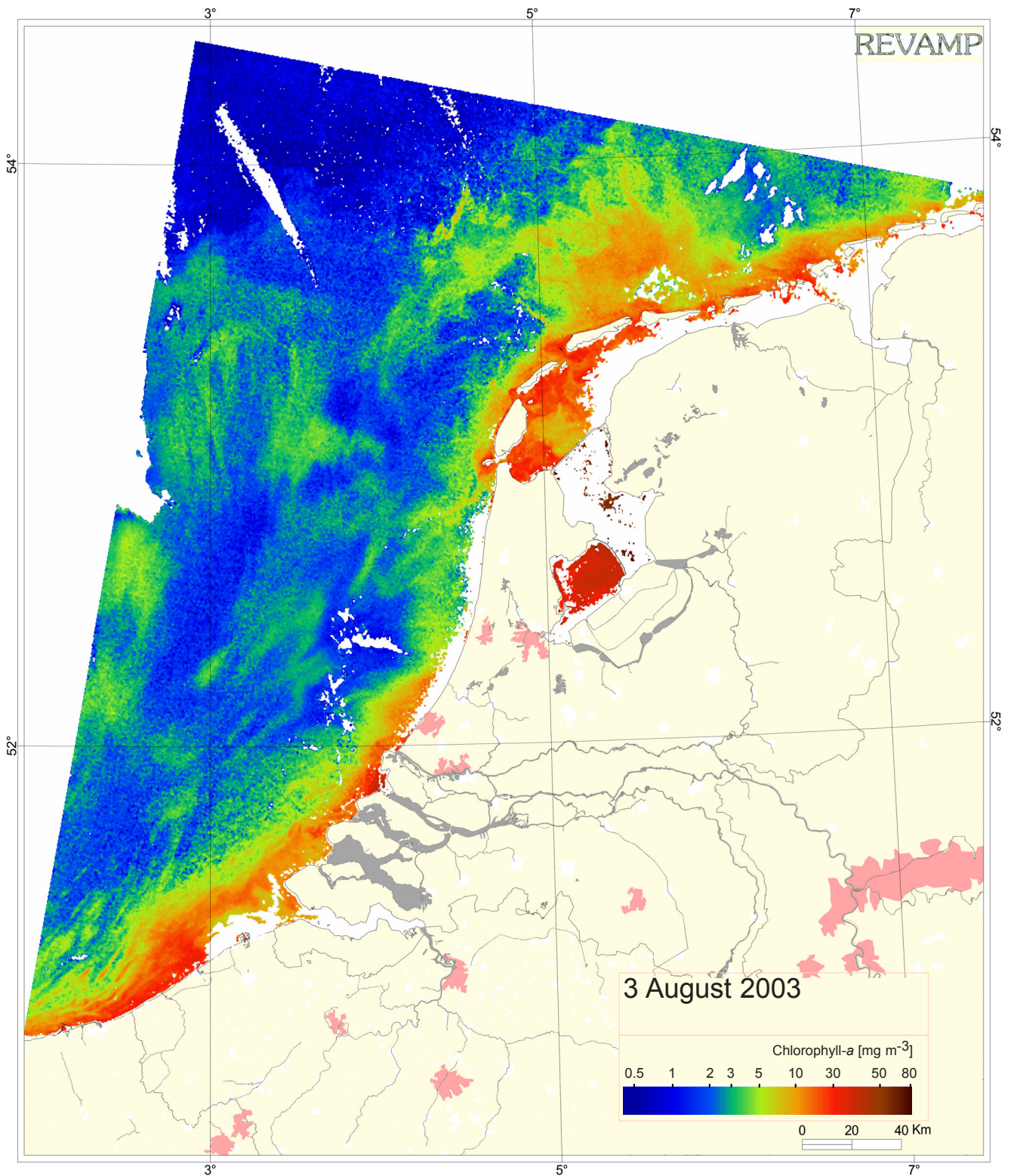
Surface Reflectances ACRI-ST processing - Coastwatch GMES service
Chlorophyll-a REVAMP processing





Surface Reflectances ACRI-ST processing - Coastwatch GMES service
Chlorophyll-a REVAMP processing





Surface Reflectances ACRI-ST processing - Coastwatch GMES service
Chlorophyll-a REVAMP processing





13

Conclusions and Recommendations



CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This Atlas and the accompanying digital data products and visualization software represent the fruit of 3 years' work by the REVAMP consortium, a multidisciplinary team of scientists from 8 European institutions with expertise in optical remote sensing, oceanography, optical measurements, computer science and marine environmental management.

The motivation for this Atlas is the need for marine environment managers and scientists to have reliable information on phytoplankton distributions and dynamics for the assessment of eutrophication and related human impacts (especially in the framework of the OSPAR convention), for an understanding of the marine foodweb and trophic interactions and for an evaluation of the marine carbon cycle (primary production and global change).

The REVAMP Atlas presents Chlorophyll-a concentration maps for the year 2003 as derived from the MERIS instrument onboard Envisat and processed by the REVAMP processor using standard MERIS water-leaving reflectance products as input. Monthly, seasonal and annual medians and maxima are shown for the North Sea from the Western Channel (4° West, 48-51°N) to the Shetlands (60° North, 4° West - 5° East) and the Kattegat (10-13° East, 56° North). The quality of products has been assessed a priori, using the quality detection algorithm associated with the REVAMP Chlorophyll-a algorithm, and a posteriori, by expert analysis and in comparison with in situ data. In addition to the standard North Sea maps each REVAMP region is treated in detail with zoomed imagery and a description of special events detected such as algae blooms.

As examples, algae blooms corresponding with seaborne measurements of various species have been analysed in detail for the German Bight, Danish waters, the Skagerrak, the English Channel, the Scottish East coast, the Southwestern Norwegian waters and Belgian waters.

Complementary to the hardcopy Atlas a CDROM can be obtained via the REVAMP website containing the digital data presented in the atlas, maps and freely-available image processing software for easy visualization and extraction of data. The aim is that any marine manager or scientist with no prior experience in remote sensing and with a standard desktop or portable PC can access and use the data for his/her own purposes. This was demonstrated to be entirely feasible at the REVAMP users workshop, where, in a two-hour tutorial session, thirty such users succeeded in installing, understanding and using the software to access the REVAMP products.

But REVAMP is not just an Atlas. While production of this Atlas has been the focus for all REVAMP activities and represents the culmination of our efforts, the REVAMP project leaves many other results that may be of use to the research community. As examples, considerable efforts have been put into:

- Assessment of user requirements relating to satellite-derived Chlorophyll-a products.
- Seaborne measurements to improve the calibration of satellite Chlorophyll-a retrieval algorithms and the validation of satellite-derived reflectance and Chlorophyll-a products. Much of this work can be found in conference papers presented at the MERIS validation workshops held in 2002 and 2003 and published in the corresponding workshop proceedings.
- Laboratory and seaborne measurement protocol intercomparison exercises. These have been combined with experience from other projects (such as NASA-SeaWiFS based initiatives and the COLORS and Coastlooc EC projects) to yield the REVAMP measurement protocols.



- Collection and archiving of optical data acquired during and prior to the REVAMP project. This REVAMP database will be maintained initially for use by REVAMP partners and will be opened for public access in February 2007.
- Scientific publications describing, for example, algorithm development and performance, measurement methods and analysis of results have been drafted for publication in peer-reviewed journals and conference proceedings.

Some of these publications are already available at the time of writing for consultation. Others will emerge in the coming years when the various peer-review procedures are concluded.

These results can be found on the REVAMP web site:

www.brockmann-consult.de/revamp/



The REVAMP project has reached its contractual conclusion, but this is not the end of the story for satellite mapping of Chlorophyll-*a* concentration. In fact, this is just the beginning. This atlas represents the best that could be achieved by the consortium at the time of its production, but the field of optical remote sensing is evolving very rapidly thanks to technological advances in available satellite sensors and to accompanying scientific progress in processing methods. Over the last ten years the launch of SeaWiFS, MODIS and MERIS have dramatically increased the interest in satellite-derived Chlorophyll-*a* maps and have spurred major improvements in algorithms for Chlorophyll-*a* retrieval. Improvements in seaborne and laboratory instruments have led to important improvements in the optical measurements required for their calibration and validation. Over the next ten years such improvements in hardware are expected to continue and to stimulate further advances in research and, hence, products. The following directions for future research have been identified during the course of the REVAMP project:

1. General or region-specific algorithms?

Algorithms for retrieval of Chlorophyll-*a* in "Case 2" coastal waters have not yet converged towards an agreed "best approach" in contrast to open ocean "Case 1" waters where most algorithms are closely related. For specific regions there is as yet no consensus on whether a general purpose spectral-fitting type algorithm will perform as well as or better than algorithms designed specifically for that region and possibly using only a subset of the available bandset combined with expert knowledge of the region and careful calibration. However, it is emerging that the multiband spectral-fitting type algorithms are most suitable for seamless processing of imagery over a range of optically different regions.

2. Algorithm treatment of reflectance input errors

For multiband or full-spectrum fitting algorithms questions remain regarding the possible exclusion or weighting of bands where significant input reflectance errors can be expected. In the case of MERIS key wavelengths in this respect are 412.5 nm, which is important for distinguishing between yellow substance absorption and Chlorophyll-*a* absorption but is most prone to atmospheric correction errors, and 708.75 nm, which is important for evaluating red Chlorophyll-*a* absorption in turbid waters (in combination with 665nm).

3. Algorithms for product quality

Within the lifetime of the REVAMP project there has been a noticeable shift of research effort from the design of algorithms for chlorophyll retrieval to the design of algorithms for the assessment of the *quality* of retrieved chlorophyll-*a* products. The approach adopted within REVAMP is described in Chapter 6 and the results for the quality of products are presented in Chapter 8. However, questions remain regarding how to design an algorithm that will give a reliable assessment of product quality in both turbid waters with high sediment content (for example, along the Belgian-Dutch-German North Sea coast) and in the much clearer waters of the Northern North Sea and Norwegian coastal zone. Further research into product quality algorithms is needed to settle such questions more satisfactorily.

4. Regional calibration of specific inherent optical properties

A key question at the beginning of the REVAMP project was how algorithms should be designed or calibrated regionally to improve with respect to global products generated from a single algorithm and calibration dataset. Measurements were made, particularly of inherent optical properties, in order to determine systematic variations of the specific inherent optical properties (for example, the absorption of phytoplankton normalized by Chlorophyll-*a* concentration) as function of region, season or species.



It was hoped that any such systematic variations could be exploited for algorithm improvement. No conclusive answer could be found, however, to this question and research will continue on this subject, particularly via long time series of high quality optical measurements with associated information on phytoplankton species and condition.

5. Validation measurements

Despite the considerable efforts deployed within the REVAMP project, high quality, in situ data for validation of the satellite products, both water-leaving reflectance and Chlorophyll-a concentration, remains sparse. Constraints on near-simultaneity (e.g. within one hour) between satellite and seaborne measurements reduce acceptable "match-up" validation data to a very small number of points, particularly after exclusion of satellite pixels flagged as less reliable because of atmospheric correction or other processing difficulties. Relaxation of such time constraints to allow the use of non-simultaneous or even weekly/monthly "climatological" in situ data for validation yields many more data points but adds validation uncertainty owing to time variation. Moreover, all validation methods are affected by the different spatial averaging between satellite pixels (radiometrically averaged over 250m or 1km square pixels) and seaborne water samples (subsamped from typically a 10 litre bottle of water). Validation will improve during the lifetime of MERIS merely from the addition of data points every year to the existing sparse dataset.

6. Atmospheric correction

Although not within the scope of the REVAMP project, it must be noted that imperfect atmospheric correction of data from satellite sensors such as MERIS is still a significant source of error for water-leaving reflectances and derived products such as Chlorophyll-a concentration. This is particularly critical in coastal waters where turbid water effects (non-zero near infrared water-leaving reflectance) and possibly absorbing aerosols and adjacency effects (scattering of light from land into the field of view of the sensor) are typically strongest. Significant improvements in the MERIS water-leaving reflectance products, used as input by REVAMP, were found towards the end of the project. Further improvements may be expected for MERIS and other sensors in the years to come, in particular through the possible use of aerosol climatologies, which constrain atmospheric correction algorithms to models typical of aerosols usually present in the region considered.

7. Use of auxiliary data or climatologies

In addition to the aerosol climatologies mentioned above, and the meteorological data (wind speed, atmospheric pressure, ozone content) typically used in processing of optical remote sensing data, the REVAMP project considered the use of additional auxiliary data or "climatologies" in combination with the satellite input data to help improve retrieval of Chlorophyll-a. For example, a digital bathymetry may provide clues about optical water type (sediment concentrations are often correlated with depth) as may a salinity "climatology", giving typical salinity over a spatial and temporal (e.g. monthly) grid. A similarly gridded Chlorophyll-a climatology may give an indication of concentrations likely to be encountered enabling abnormally high retrieved concentrations to be flagged as either suspect or extreme. The use of such climatologies was finally not adopted for the production version of the REVAMP processor, though this represents a promising direction for future research as does, more generally, the use of non-satellite data from measurements or models as input to constrain a Chlorophyll-a retrieval algorithm.

8. Open software

Computer software development is not generally considered as research. However, the adoption of "open" programming environments and the willingness of scientists and their funding agencies to promote the public distribution of software tools, as is the case for the BEAM software used by REVAMP and for NASA's SeaDAS software, are major factors that would accelerate research in the field of optical remote sensing.

9. MERIS follow-on

Finally, the enthusiasm generated by MERIS raises the question of what happens when Envisat ceases functioning. There are some ideas within the European Space Agency to follow-up the Envisat-MERIS mission with another ocean colour sensor. However, it is clear that such a follow-up will not be ready in time. This gap might be alleviated by use of non-European ocean colour sensors such as MODIS. However, such a change could significantly impact product quality (MODIS lacks, for example a band at 709nm) and doubts over continuity could discourage investment by users in integrating ocean colour products with their existing infrastructure.

Many of these issues are discussed in more details in the reports of the International Ocean Colour Coordinating Group (IOCCG, reports downloadable from <http://www.ioccg.org>) and in references cited therein.

Recommendations for future work - users

This research has not been merely a scientific exercise but is directed towards usage of the products by communities such as water quality managers. Both during the project and after its completion, feedback from users was and is essential to tailor products according to needs.

Users also reinforce validation of products and are well placed to identify anomalies, whether extreme events not detected by conventional monitoring or erroneous data that escapes detection by the quality algorithm.

Publication of data in this atlas and the associated digital data and visualization software facilitates the uptake and analysis of the REVAMP Chlorophyll-*a* products by these user communities.

Although REVAMP is formally completed this researcher-user interaction will continue in the coming years through other national and international initiatives.

In particular the satellite products presented in this atlas have not yet been integrated with complementary information sources such as conventional monitoring measurements or ecosystem models. Such integration will demonstrate the great advantage of the remote sensing technique: the spatial coverage that is unimaginable using seaborne measurements.

On the other hand, the limitations of the remote sensing technique - temporal breaks owing to cloud coverage, lack of information on subsurface Chlorophyll-*a*, and possible concerns about product quality - will thus be mitigated by the high frequency of data that is possible from autonomous moored instruments, by the high quality of data that is generally achieved by measurements on individual water samples, and by the possibility offered by ecosystem models to interpolate and extrapolate Chlorophyll-*a* fields vertically and in time.

While we hope and believe that this atlas will contribute to an improved understanding and management of the North Sea environment, we are also firmly convinced that this is not the final word. Research into and usage of such products will develop significantly over the coming years taking advantage of the basis provided by the REVAMP project.



Acknowledgements

We would like to thank:

- The EC for co-funding this interesting and challenging project.
- Mike Rast (ESA-ESTEC), Hartmut Heinrich (BSH) and Eon O'Mongain (UCD) for actively supporting the project team as the REVAMP Quality Assurance Committee.
- The EC scientific officer Bernard Denore for his kind suggestions and interest in the progress of the project.
- ESA for allowing us to use the complete suite of 2003 North Sea MERIS Images.
- Especially Jean-Paul Huot (ESA-ESTEC) for joining our meetings to provide us with the latest insights on MERIS atmospheric correction and sensor and image quality.
- Brockmann Consult for distributing the MERIS data.
- The ACRI-ST processing - Coastwatch GMES service for providing MERIS FR Surface Reflectances.
- Captains and crews of numerous ships of opportunity.
- The projects Colors, CoastLooc, MULTICOLOR, FerryBox, MERIMON2000 and VAMP for providing data and protocols.
- RIKZ and Hans Roberti for allowing the use of MWTL Chlorophyll-a data for the comparison chapter.
- David Johns at the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) for identifying phytoplankton species for the UK east coast.
- Louis Peperzak at RIKZ, Middelburg for providing the text on the phytoplankton species and processes in the Dutch coastal waters.
- The Coastwatch User federation and the EEA Copenhagen for their evaluation of the prototype results of REVAMP.
- VU reprografie department for very-high-quality and rapid printing of the prototype and final Atlas.

