The coastal waters of the North Sea are eutrophic and feature elevated levels of Chlorophyll-a. The complexity of North Sea Water is expressed by the fact that not only Chlorophyll-a but also suspended matter and yellow substance determine the optical characteristics of the water, and by the variation of the specific inherent optical properties (SIOP) with location and time. In the framework of the EU funded research project REVAMP in-situ data were collected in the North Sea in order to characterise the SIOPs of different areas, such as the channel water, the German Bight, the eastern English coast, the central North Sea and the Skagerrak/Kattegat. Five different types of algorithms have been developed which are either tuned to a specific area or implemented using a specific mathematical method. These algorithms include blue-green ratio algorithms, model inversion and neural network techniques. Each algorithm is calibrated with SIOPs. An intercomparison of the different algorithms was performed. The finally developed REVAMP algorithm is a new methodology, which derives the Chlorophyll-a concentration from MERIS spectral surface reflectance spectra based on the standard forward model Hydrolight (using a lookup table approach). With this algorithm a series of monthly, seasonal and yearly maps were generated and compared with in-situ observed values. To obtain these maps, 450 MERIS images were processed. The comparison was done for some transects and for stations of monitoring networks. It was found that REVAMP Chlorophyll-a compares well for most situations, except for situations with probably a very high background concentration of suspended matter. MERIS atmospheric correction was found to be very adequate, except maybe for situations very close to the coast.

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 foodweb 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. Chlorophyll-a is a useful proxy of the phytoplankton biomass. Chlorophyll-a is currently a mandatory monitoring parameter in EC-regulations such as the WFD and OSPAR. Developments over the last decades have shown that Chlorophyll-a can be measured using optical observations from satellite platforms in case 1 waters (O’reilly et al., 1998). There is also evidence that optical measurements can be used to determine Chlorophyll-a in inland waters with relatively low sediment concentrations (e.g. Gons). Still, it is a challenge to determine Chlorophyll-a in coastal waters because there we find a large heterogeneity of plankton species, large differences in background concentrations of other optically active substances such as CDOM and Non-algal particles and a large range in concentrations of Chlorophyll-a itself.
The EC-FP5 funded project REVAMP has been working on this problem during the period 01-02-2002 until 31-1-2005. As a basis existing protocols for the measurement of Inherent Optical properties, Sea surface spectra and concentrations of optical active constituents were revisited (Tilstone et al., 2004). A large data set was collected in most of the coastal waters of the North Sea (completing existing knowledge as published amongst others by Babin et al., 2003 and Bricaud et al., 1995) and analysed for regional and local representative values of optical properties (Tilstone et al, 2005, in prep.). A large number of candidate algorithms were proposed, compared and tested in a standardised software environment providing full access to REVAMP observations of Sea surface reflectance and MERIS image information and flags (Peters et al., 2005). For the selection of the final REVAMP algorithm a set of criteria was developed. All algorithms were used to process approximately 150 observed North Sea spectra into Chlorophyll-a. Comparison with in-situ Chlorophyll-a observations using the predefined set of criteria resulted in the selection of the preferred REVAMP algorithm. This algorithm was subsequently applied to a set of approximately 300 MERIS images of the North Sea in 2003 to produce a basis set of Chlorophyll-a maps that were further aggregated into monthly, seasonal and yearly maps (Peters et al, 2005).

The REVAMP preferred algorithm for Chlorophyll-a estimation in North Sea waters

In the project an operational infrastructure (including an implementation of a state-of-the-art algorithm) was set up to process MERIS RR images of the North Sea into Chlorophyll-a maps in the best possible way. Since the North Sea coastal waters are for a large part case-2, specific algorithms, minimising e.g. the effect of CDOM on the Chlorophyll-a retrieval were sought for, since this is the major flaw occurring when applying case-1 algorithms to case-2 waters (Darecki & Stramski, 2004; Blondeau et al., 2004).

Out of a suite of North Sea algorithms the most appropriate algorithm to retrieve Chlorophyll-a concentrations from MERIS was selected (Pasterkamp et al., 2005). This algorithm has the advantage of being adaptable for other regions. Its applicability 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 algorithm was successful. Because of the optical complexity of turbid coastal waters, frequently used simplified equations were abandoned in favour of the more sophisticated Hydrolight radiative transfer code (Mobley, 1994 and 1998). 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. Instead of the concentrations, absorption and scattering were used as independent variables, which 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 to 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 CHI2 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.

The REVAMP algorithm was calibrated using the median of all SIOP measurements in the database; these results are shown in Figure 1. Figures 2 (and 3), 4, 5 and 6 show subsequently: (2 and 3) the locations where test datasets were collected; (4) reference in-situ Chlorophyll-a concentrations at these locations; (5) input test sea surface reflectance spectra and (6) the results of the Chlorophyll-a calculations from the spectra and the calibrated algorithm as compared to the reference in-situ measurements.
Fig. 1: Algorithm Calibration: For the operational REVAMP processor we used the median of all SIOP values in the REVAMP database.

Fig. 2: Location of SIOP measurements cruises.

Fig. 3: Locations of algorithm selection measurements (A_best dataset).

Fig. 4: Chlorophyll-a values of algorithm selection dataset (A_best dataset).
Aggregation and map production strategies:

A presentation of daily 450 images of Chlorophyll-a in an atlas is of little interest to end-users. Therefore the REVAMP Quality Assurance Committee and selected end-users were asked in which form the maps should be presented to them. They recommended presentation of the maps as monthly, seasonal and yearly aggregated products. Other relevant user recommendations with respect to Value Added Products were collected and discussed by (Van der Woerd et al., 2002 and Eleveld et al., 2004).

The whole procedure going from MERIS reflectance image to aggregated REVAMP Chlorophyll-a maps takes four major steps, namely:

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 for every image pixel.

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.

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.

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

The "L3-processor" included in the BEAM3.1 software was used to aggregate the individual Chlorophyll-a scenes to monthly and seasonal composites. Finally, a total number of 450 individual MERIS scenes (of the year 2003) were used for the aggregation. They were 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).
Results of the REVAMP 2003 MERIS processing

The resulting binned maps were printed in Peters et al., 2005. Some results will be presented and discussed in this paper.

It came forward during discussions and evaluations that the maximum composites are of great value to researchers and managers that need an overall picture of which blooms occurred. When looking at the monthly composites in the atlas (Peters et al., 2005) also the approximate timing of the blooms can be seen. In Fig 7 a number of blooms can be observed. E.g. the spring bloom of *Phaeocystis* along the Southern part of the Dutch coast is clearly visible. One can also observe the extend of a large *Coccolithophores* bloom along the Norwegian coast; Spring blooms in the German Bight; blooms over the Dogger Bank (which happened in March and October) and a number of patchy blooms of various identified species in the English Channel.

The yearly median composite provides an overview of the general Chlorophyll-s distribution in the North Sea and can be used as supportive information in the delineation of eutrophication affected areas. Fig 8 shows the general accepted picture that general Chlorophyll-a concentrations are highest near the coasts and estuaries where nutrients enter the North Sea system. Comparison with the maximum image in Fig. 7 indicates that quite severe blooms of short duration have occurred at places with overall low Chlorophyll-a concentrations. Of course these blooms are also visible in the monthly median composites.

It is interesting to compare the yearly median maps with the OSPAR maps of eutrophication threatened areas as displayed in Fig 9. It seems that the boundaries of eutrophication threatened areas are quite schematic and rather based on the extend of the National Monitoring networks.
Remote sensing images provide a synoptic overview of the chlorophyll-a concentrations in the North Sea on a day-to-day basis. The resulting maps have been used to investigate the seasonal and spatial variations, which can teach us more about the underlying processes that drive the 'North Sea' system. For long-term trend detection, however, we need to establish the relationship between actual and historical in-situ data measured routinely by national monitoring agencies. In this way we can 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. 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.

**Comparison of yearly median Chlorophyll-a at Dutch monitoring network points**

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 (Fig 10) 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).

**Comparison of time series of Chlorophyll-a at individual monitoring network points**

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 two stations are presented, located
in the central North Sea (TERSLG175, Fig 11) and the turbid Dutch coast (GOERE6, Fig 12). 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.

Fig. 10: Yearly median in-situ Chlorophyll-a at monitoring net-work points compared to yearly median remote sensing estimates (based on MERIS)

Fig 11: Time series for chlorophyll-a in 2003 at station TERSLG175 (low Chl situation; central North Sea)
Fig 12: Time series for chlorophyll-a in 2003 at station GOERE6 (High Chl situation near the Dutch coast)
Comparison with transect observations by the Ferry-box project

Figures 13 and 14 show two transects of Chlorophyll-a observations between Oslo and Hirtshals as made by the Ferry-box project (blue squares). The REVAMP Chlorophyll-a estimates from concurrent MERIS images are superposed and it immediately becomes clear that the MERIS observations follow the in-situ observed values quite close, except near to the coast. Figure 13 shows an additional benefit of remote sensing: the location of a number of local peaks can be exactly determined while the in-situ transect misses most of this information.

Conclusions

The REVAMP Atlas (to be found at www.brockmann-consult.de/revamp/) 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. 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.

Comparison with yearly median values at 16 monitoring network points shows that the Chlorophyll-a results from MERIS images processed with the REVAMP algorithm are quite acceptable with a variance that is in the same order or smaller than the variance in the in-situ monitoring data. Time series of REVAMP Chlorophyll-a compares quite well with the in-situ data time series on two monitoring network points. Both high Chl and low Chl events are well reproduced. Comparison along transects on a single day (using data from the Ferry-box project) shows that variations along long transects

Although it could not be confirmed that the REVAMP algorithm performs well at all locations in the North Sea, it has at least been made visible that the algorithm performs quite well at various locations of different nature. Further validation is recommended.

The REVAMP database containing spectral observations of water leaving radiance, IOPs and concentrations of Chlorophyll-a, TSM and CDOM will be maintained initially for use by REVAMP partners and will be opened for public access in February 2007. Information can be found at: http://www.mumm.ac.be/datacentre/Databases/REVAMP/

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Literature


