

Remote sensing's contribution to evaluating eutrophication in marine and coastal waters

Evaluation of SeaWiFS data from 1997 to 1999
in the Skagerrak, Kattegat and North Sea

Prepared by:

Kai Sørensen, Gunnar Severinsen, Norwegian Institute for Water Research, Norway
Gunnar Ærtebjerg (Task leader), National Environmental Research Institute, Denmark
Vittorio Barale, Christian Schiller, EC Joint Research Centre, Italy

Project Manager:

Anita Künitzer



Cover design: EEA
Layout: Rolf Kuchling, EEA

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European Environment Agency
Kongens Nytorv 6
DK-1050 Copenhagen K
Tel. (45) 33 36 71 00
Fax (45) 33 36 71 99
E-mail: eea@eea.eu.int
Internet: <http://www.eea.eu.int>

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Summary

Monitoring eutrophication in large marine and coastal areas is difficult, and the use of advanced monitoring tools, such as satellite remote sensing, can provide additional qualitative and quantitative information. The satellite data can be an important tool to support the evaluation of the study of the eutrophication in European marine waters. Although the remote sensing technique is limited to the surface layer of the water column, it is considered to give useful additional or complementary information to traditional 'in situ' measurements to assess the state of the marine environment. The biomass of phytoplankton algae in surface waters can be measured as 'chlorophyll-a-like pigments' by remote sensing. Enhanced levels of these pigments, compared to natural background concentrations of chlorophyll-a, are an indication for eutrophication.

The objective of this task was to evaluate estimates of 'chlorophyll-a-like-pigments' by satellite with focus on the SeaWiFS sensor (Sea-viewing Wide-Field-of-View Sensor). Chlorophyll-a maps were controlled against *in situ* data from the Skagerrak, Kattegat and the North Sea for the period September 1997 to the end of 1999. Based on *in situ* data the chlorophyll-a maps were tuned to reflect 'true surface concentrations' of 'chlorophyll-a-like-pigments'. The information and concentrations in the maps were locally compared with *in situ* data and *a priori* general knowledge of the area.

The algorithms to produce the 'chlorophyll-a-like-pigments' from the water using radiance from SeaWiFS observations are presently overestimating the 'true' concentration. In the open sea of the tested areas the overestimation is in the order of 60-70 %. It was not the objective of this study to investigate the scientific rationale behind these findings.

The information in terms of necessary *in situ* data such as the different optical quantities of suspended and dissolved organic material as well as atmospheric data to do such a study was either not available or limited as this kind of data is not collected in ordinary monitoring programmes. We have therefore tuned the satellite images to *in situ* concentrations from empirical statistical analysis only.

The most severe problems retrieving a correct chlorophyll-a concentration from satellite images was in the near coastal areas, and the problems with overestimation of chlorophyll-a were increasing when approaching less saline water as at the Norwegian coast. The water masses in this area have normally high concentrations of dissolved organic material that influences the retrieval algorithms for chlorophyll-a. But knowing the limitation of the data both before and after rescaling to *in situ* concentrations the satellite data gives important information on the environment.

The satellite data gives good information not only on the relative phytoplankton distribution, but also the concentrations when tuning the SeaWiFS-data to the surface concentrations using *in situ* data from the area. Using monthly mean maps in the period May to August gives much information on the phytoplankton biomass in the period when the production most often is nutrient limited. The mean or median value in this period would be the best and most appropriate expression for the level of eutrophication.

Very limited satellite data was available from the winter period November to February in this area. If the goal is to use the satellite data to map eutrophication this is not critical, since this is a period when the phytoplankton is light-limited, and is therefore not related to the nutrient input. The chlorophyll-a maps from the period March to

April/May reflect realistically the magnitude and geographical distribution of the spring bloom, and therefore also the level of eutrophication. Since the spring bloom could reflect the magnitude of the available winter nutrient pool, a chlorophyll-a map showing the maximum concentration in each pixel should be useful for studying the eutrophication level.

In general, the satellite data and information that has been investigated in

this study gives promising possibilities to improve monitoring by a combination of *in situ* data and satellite data. New satellite sensors with improved spatial and spectral resolution, and new insight in solving the problems with the algorithms will improve the accuracy of the satellite data products. From a eutrophication monitoring point of view the number of stations may be reduced in the open sea areas when the quality of the satellite data are controlled on other stations with *in situ* data.

1. Introduction

The application of remote sensing techniques in monitoring marine and coastal waters have shown potential to provide synoptic data/information for a number of physical and bio-geochemical parameters. Remote sensing should have potential to support the evaluation of eutrophication in marine and coastal waters. In this context the possibility to measure the biomass of phytoplankton as 'chlorophyll-a-like pigments' is promising. So far this has been difficult in coastal waters due to the influence by other optical constituents such as yellow substance and particles. New development of algorithms is ongoing and new sensors, such as MERIS (Medium Resolution Imaging Spectrometer) to be launched in 2002, will improve the use of satellite data in coastal areas. Although remote sensing techniques are limited to the uppermost few metres of the water column they are considered to give useful additional or complementary information to traditional *in situ* measurements to assess the state of marine and coastal waters.

In general, *in situ* data are point measurements giving a good vertical resolution of the relevant parameters in the water column. However, it is very often difficult to derive an extra- or interpolation of, *in situ* data to prepare maps showing the status of coastal and marine areas. The satellite derived chlorophyll-a will be a valuable complement to the *in situ* measurements and will, for example, give important information about the representativity of the *in situ* stations.

Chlorophyll-a concentrations in summer periods are indicators of a semi-steady state situation where the production of phytoplankton is equalised by loss mainly

through zooplankton grazing. High summer chlorophyll concentrations indicate high supply rates of nutrients and thus provide an indicator of the state of eutrophication. Satellite maps of chlorophyll in the surface waters will therefore help in assessing the spatial magnitude of phytoplankton biomass and eutrophication.

Chlorophyll maps from satellite data are derived from algorithms based on the radiance signal in the visible part of the electromagnetic spectrum leaving the water. Cloudy conditions will limit the number of available satellite data since optical satellite sensors will not be able to map under such conditions. Therefore the analyses and conclusions of the report are highly dependent on the number of available satellite images. Fortunately, more images are available during the summer period than during winter.

The optical constituents: phytoplankton (measured as chlorophyll-a), inorganic suspended material and coloured dissolved organic material (CDOM) will contribute to the signal leaving the water. The algorithms to derive the chlorophyll-a concentration are developed for oceanic waters. In coastal waters these algorithms have, in the former CZCS (Coastal Zone Colour Scanner) (1979-1985) and in the present SeaWiFS (Sea-viewing Wide Field-of view Sensor), observation problems in discriminating the three optical components with the result that the chlorophyll-a values normally are overestimated. The challenge and subject of this report is to extract meaningful information on chlorophyll-a concentrations in coastal and marine waters from the satellite images.

2. Objective

The objective of this report is to evaluate if estimates of ‘chlorophyll-a-like pigments’ from satellite data can support the evaluation of eutrophication in European marine and coastal waters.

Information derived from selected remote sensing is used:

- to evaluate its meaningfulness for the assessment of the eutrophication status in marine and coastal waters, and, if applicable,
- to compare the information derived from remote sensing techniques with monitoring data collected by Denmark, Norway and Sweden.
- to assess the use of remote sensing as a eutrophication monitoring tool.

The SeaWiFS (Sea-viewing Wide Field-of view Sensor) images were used in combination with *in situ* measurements of chlorophyll-a to evaluate the applicability of satellite images for eutrophication assessment. Data from the launch of SeaWiFS in 1997 to the end of 1999 were used. The region to be considered, and which has sufficient monitoring data to allow this investigation, is the Kattegat, Skagerrak, and eastern North Sea. *In situ* data are here readily available and knowledge of the area from monitoring and research is considerable. Nevertheless, *in situ* data on optical constituents as dissolved organic material (yellow substance, or Gelbstoff) and suspended material is limited, but important in the evaluation.

3. Data and methods

3.1 The investigation area and sampling stations

The investigation area, Skagerrak, Kattegat and eastern North Sea where field sampling was performed during the period 1998–1999 is shown in Figure 1. The sampling frequency of the stations varies considerably. Some stations are frequently monitored and others only occasionally. *In situ* data from Danish, Norwegian and Swedish waters is provided by different institutions and counties as

shown in Table 1. The *in situ* data includes that from routine monitoring programmes run by NERI, NIVA, Institute of Marine Research (IMR) and Swedish Meteorological and Hydrological Institute (SMHI) as well as the different local monitoring projects run by the counties. The content of the *in situ* database is shown in the table, but for this report only data from the uppermost metre of the water column was used.

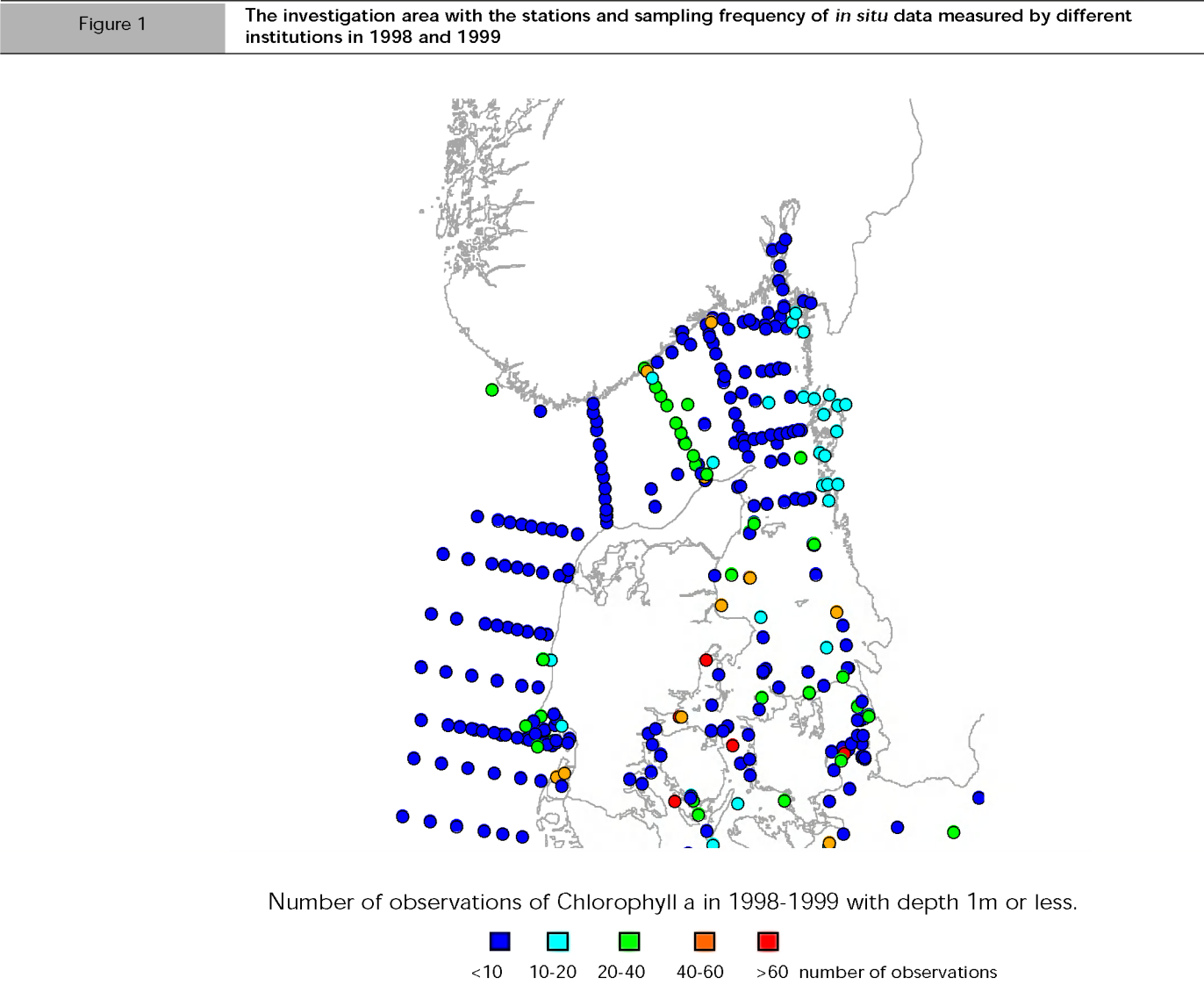


Table 1

The following institutions have contributed with data to this evaluation. The total number of data (all depths) available for the period 1998 and 1999 is indicated in the table

Code	Name of institution	Number of data available in the database
BOR	County of Bornholm, Denmark	65
DMU	National Environmental Research Institute, Denmark (NERI)	1554
HFF	Institute of Marine Research, Research Station Flødevigen, Norway (IMR)	1693
FRB	County of Frederiksborg, Denmark	164
FYN	County of Fyn, Denmark	533
KBH	Copenhagen Municipality, Denmark	415
KBK	County of Copenhagen, Denmark	35
NIVA	Norwegian Institute for Water Research	335
NJY	County of Nordjylland, Denmark	426
RIB	County of Ribe, Denmark	220
RKB	County of Ringkjøbing, Denmark	124
ROS	County of Roskilde, Denmark	32
SJY	County of Sønderjylland, Denmark	250
SMH	Swedish Meteorological and Hydrological Institute (SMHI)	1795
STR	County of Storstrøm, Denmark	265
VEJ	County of Vejle, Denmark	222
VIB	County of Viborg, Denmark	12
VSJ	County of Vestsjælland, Denmark	339
ARH	County of Århus, Denmark	300

3.2 The analytical methods of chlorophyll-a and CDOM

Since the data is collected from different institutions the analytical techniques vary. Chlorophyll-a is determined with both spectrophotometric and fluorometric methods, as well as using different extraction methods. All Danish and most Swedish chlorophyll-a samples are analysed according to the Manual for Marine Monitoring in the COMBINE Programme of HELCOM (www.helcom.fi), which has shown good agreement between NERI and SMHI (HELCOM 1991). The Norwegian chlorophyll-a values are either based on spectrophotometric (NIVA) or fluorometric methods (IMR). Even so, differences in the methods used by different institutions can affect the evaluation. However, these differences might be less than the fact that the SeaWiFS algorithms are based on chlorophyll-a data determined by HPLC

techniques. The HPLC chlorophyll-a method gives lower chlorophyll-a values than the spectrophotometric or fluorometric methods since these are not corrected for interference from other pigments such as chlorophyll-b and -c or degradation products of chlorophyll-a (phaeopigments). Assuming that SeaWiFS chlorophyll-a algorithms give correct chlorophyll-a data, it should in general give lower values compared to the routine *in situ* chlorophyll-a data based on e.g. spectrophotometric methods.

To be able to do a proper evaluation all available chlorophyll-a data from the area had to be used. Using only HPLC chlorophyll-a is impossible on historical data since this technique is not used in routine monitoring. When using *in situ* chlorophyll data one can regard this as a 'tuning' of the satellite chlorophyll data to 'normal' chlorophyll-a values used in routine monitoring and in general classification systems. The number of *in*

situ chlorophyll-a data used together with the SeaWiFS images is shown in Table 2.

The determination of coloured dissolved organic material (CDOM) is based on standard spectrophotometric methodology at 375 or 380 nm and

expressed as m^{-1} at 375 nm. Data from Danish waters (Stedmond *et al.*, 2000) are measured at 375 nm and data from Norwegian waters at 380 nm. The CDOM data measured at 380 nm is converted to 375 nm by using a factor of 1.105 (Højerslev and Aas, 2001)

Table 2

The number of in situ chlorophyll-a data from the area used in the monthly mean SeaWiFS chlorophyll-a images for the three years

Month	1997	1998	1999
January		49	61
February		125	146
March		57	71
April		155	159
May		114	70
June		61	71
July		65	75
August		147	153
September	101	94	96
October	90	80	95
November	99	96	88
December	65	63	53

3.3 Satellite data and image production

The algorithms used to derive 'chlorophyll-a-like pigments' concentration, from the radiance data collected by the SeaWiFS, are those encoded in the REMBRANDT processing code, developed by the Marine Environment (ME) Unit of the Space Application Institute (SAI), Joint Research Centre (JRC) EC. The software package can be used to process SeaWiFS data from Level-1A (top-of-atmosphere radiance, as provided by the data distributors - NASA's GSFC DAAC) to Level-2 (derived geophysical parameters), and then to Level-3 (daily/monthly composite data products, remapped over specified geographical grids).

The Level-1A data collected by all European satellite data receiving stations, during a given satellite pass, are first merged into a high-resolution image. This step avoids any unnecessary calculations and is particularly well suited to processing all high-resolution data for a given continental zone. The Level-1A data

are calibrated using the pre-launch absolute calibration coefficients provided by NASA, corrected by various calibration coefficients and a factor representing the decay in time of the sensitivity of the sensor. The determination of the various calibration coefficients takes account of the calibration/validation activities conducted in the European Seas by the ME Unit.

The Level-1A to Level-2 processing is based on a combined land-sea algorithm. For marine areas, the REMBRANDT code (Mélin *et al.*, 2000) involves an atmospheric correction scheme and in-water algorithms that provide standard products such as water-leaving radiance (6 channels), aerosol radiance and optical thickness at 865 nm, chlorophyll-a and sediment concentrations, and diffuse attenuation coefficient. The atmospheric correction scheme (Sturm and Zibordi, 2001) accounts for Rayleigh multiple scattering, aerosol single scattering and Rayleigh/aerosol coupling. It calls on ancillary data for atmospheric pressure,

wind velocities and ozone values, provided by National Centre for Environmental Prediction (NCEP) and Total Ozone Mapping Spectrometer (TOMS) data on a daily basis. The calculation of chlorophyll concentration is based on an algorithm, combining surface leaving radiances (O'Reilly *et al.*, 1998; Maritorena and O'Reilly, 2000). The data products for terrestrial applications result from a vegetation index algorithm developed by the Global Vegetation Monitoring Unit of the SAI, JRC EC (Gobron *et al.*, 1999, 2001). The algorithm formulation is optimised so that the index value actually represents the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR).

In the REMBRANDT processing scheme, each pixel of a SeaWiFS image first goes through the vegetation index procedure, where a first classification is made using the top-of-atmosphere signal. The pixels for which the presence of vegetation is detected yield a value of vegetation index / FAPAR. In this way pixels covering land are identified and removed. The pixels that are considered as marine surface are processed through the atmospheric correction algorithm, which retrieves the part of the total radiance due to the surface of the sea. The optical properties of the water surface, then, allow estimates of its constituents. It must be stressed that no *a priori* assumption is made with regard to the nature of the pixel (sea or land). Throughout the processing, a flag value records the performance of the algorithm. Various flags allow for high viewing conditions, cloud-ice tests, cloud edges, bright surface detection (snow, ice, desert), high optical thickness, and so on.

Each individual scene (Level-2) is re-mapped onto geographical grids (2 km resolution), to generate Level-3 data products. Daily, ten-day and monthly composite products are generated for the European region and its marginal Seas (North Sea, Baltic Sea, Mediterranean Sea, Black Sea, Caspian Sea), as well as for zones such as north-eastern Atlantic and Northwest Africa, the Middle East, including Red Sea and Persian Gulf, and

the northern Indian Ocean. The first step for obtaining a daily product is testing if a particular scene has an intersection with the set geographical grid, in other words if the orbital sensor recorded any information for that area. In that case, the scene is re-mapped with a nearest-neighbour technique onto the grid. The various scenes that have been re-mapped, then, are combined to provide a daily product on the map considered. SeaWiFS orbits overlap for high latitudes, so it is possible for the sensor to 'see' twice the same grid point, during the same day, for 2 consecutive orbits. In such a case, the value that is taken for that grid point is chosen from the scene for which that grid point was observed with the lowest viewing angle (satellite zenith angle).

Furthermore, only the pixels smaller than the resolution of the considered map (2 km) are taken into account. This means that the edges of the images are discarded (for viewing angles higher than 43°). These parts of the images are also those for which the accuracy of the atmospheric correction is significantly decreasing. Once daily products have been obtained for a given geographical grid, all daily files are combined to provide ten-day and monthly composites. The marine variables are averaged over the number of days where the information was retrieved, with simple tests to detect unrealistic outliers. The number of samples used for the average is stored. As for the terrestrial outputs, long-term images are obtained by selecting, at each grid point, the vegetation index value of the day, which is considered to be the most representative of a given period. The choice is made so as to select the value of the day that provides the vegetation index closest to the mean index over the period. So each grid point bears a value that is an actual measurement of a particular day, and the conditions of observations for that day are stored with the outputs.

The algorithm for the determination of the chlorophyll concentration has been developed for global (and mostly open ocean) processing and is not specific for the Baltic/North Sea or Skagerrak area nor for the coastal zones in general.

After the processing at JRC-SAI the Level-3 data products were transferred to NIVA to be used with the *in situ* data. The area used covers the range latitude Min / Max: 53.0N / 60.0N and longitude Min / Max: 4.0E / 13.0E. The resolution is 2-km (at centre) and image-size (Pixel / Line): 277 / 391. The activities at NIVA were performed on an imaging processing system (ERDAS IMAGINE).

4. Validation of SeaWiFS chlorophyll-a

4.1 Control of SeaWiFS chlorophyll-a estimates

A few daily processed (Level-2) images from JRC-SAI were compared with *in situ* chlorophyll-a data to control the level of chlorophyll-like-pigments concentration from SeaWiFS data. Satellite data should be chosen as close as possible to the time of the water sampling. Exact timing is not possible, so in practice data within the same day was used. Since not only the time but also the sampling depth and the patchiness in the water will influence such a comparison discrepancy must be expected.

Three daily SeaWiFS images from May 15, August 26, 1998 and April 27, 1999 (Figure 4) were compared with 'simultaneously' (same day) *in situ* chlorophyll-a data. The scenes and the area around the stations were controlled for clouds, and statistics were extracted only from stations without clouds. Advanced Very High Resolution Radiometer (AVHRR) data from the weather satellite data was also used as a quality control for absence of clouds and AVHRR channels 1-5 were investigated. No visible clouds were seen around the *in situ* stations chosen for the comparison. In Figure 3 the AVHRR channel 4 for the three dates are shown. The positions of the *in situ* stations for the three dates are shown in the satellite images (Figure 4).

Chlorophyll-a data from the surface water (upper 0-1 m) has been used in the comparison with the SeaWiFS chlorophyll-a data. $Chla_{SeaWiFS}$ data are taken from an area around each *in situ* station. The area is 0.04° North/South and 0.08° East/West (about 20 km²). This gives statistics (min, max, average, sigma) from 9 to 16 pixels, which was compared with the *in situ* measurements. The correlation is shown in Figure 2. The data is scattered, but assuming that the average value is relatively correct the SeaWiFS data are rescaled according to the equation:

$$Chla_{modified} = 0.6 \cdot Chla_{SeaWiFS} + 0.1$$

adjusted $R^2 = 0.67$ $N=23$

It is nevertheless recognised that the statistical basis (both in space and time) for such a correction is weak.

However, new monthly mean SeaWiFS images were processed from the equation and presented in maps. The values for 'Chlorophyll-a-like pigments' were divided into 8 classes. The classes were divided logarithmically to better resolve differences in the high and low concentrations, which gives a better resolution and discrimination in the chlorophyll-a values near the coast.

Figure 2 Comparison of SeaWiFS (Level-2) chlorophyll-a data and *in situ* surface chlorophyll-a data from same locations at three different dates

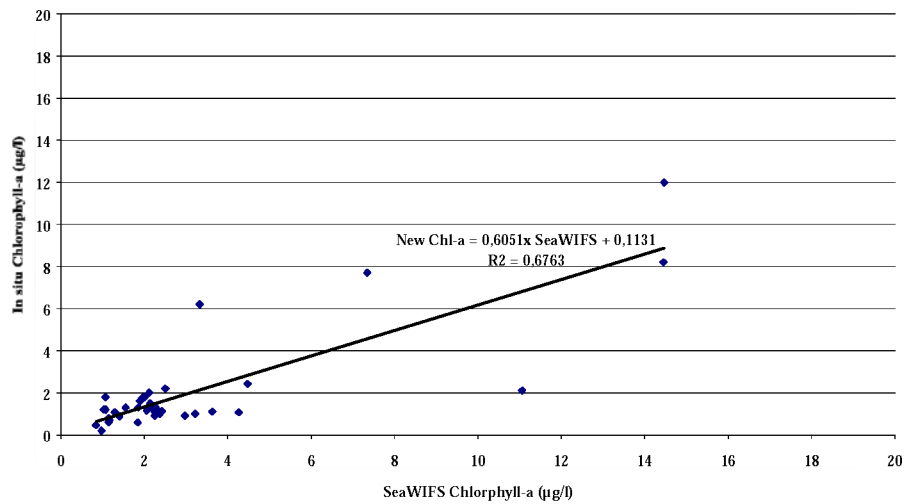
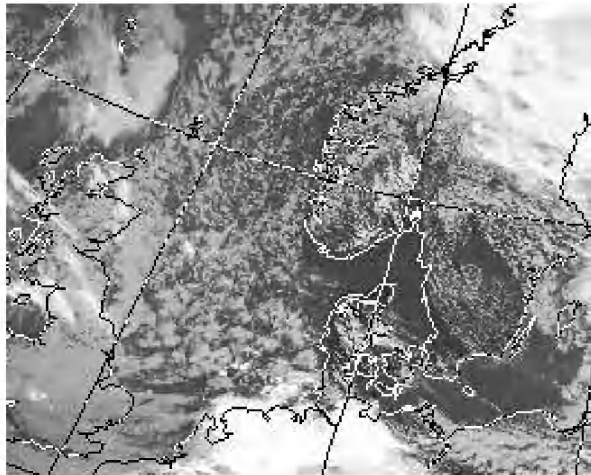
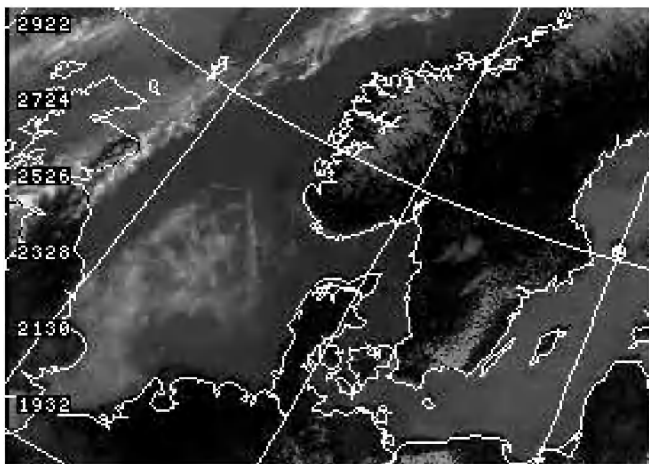


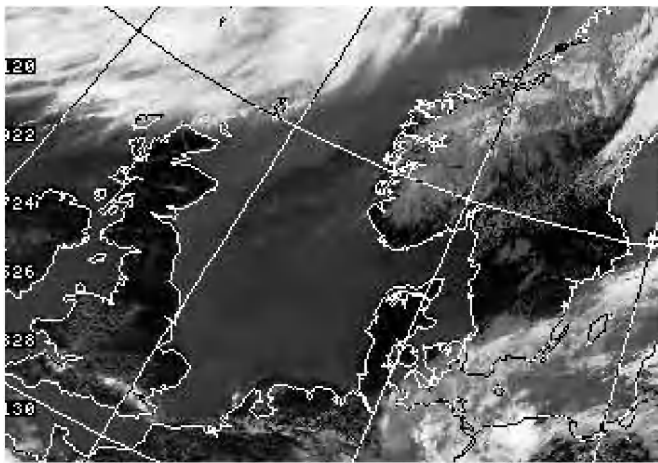
Figure 3 Quick-look images of clouds based on channel 4 of weather satellite NOAA AVHRR data for three different dates. The data is used for control of cloud cover at the *in situ* stations.

AVHRR 1998-05-15 1223 UTCCCh4

AVHRR 1998-08-26 1329UTC Ch4

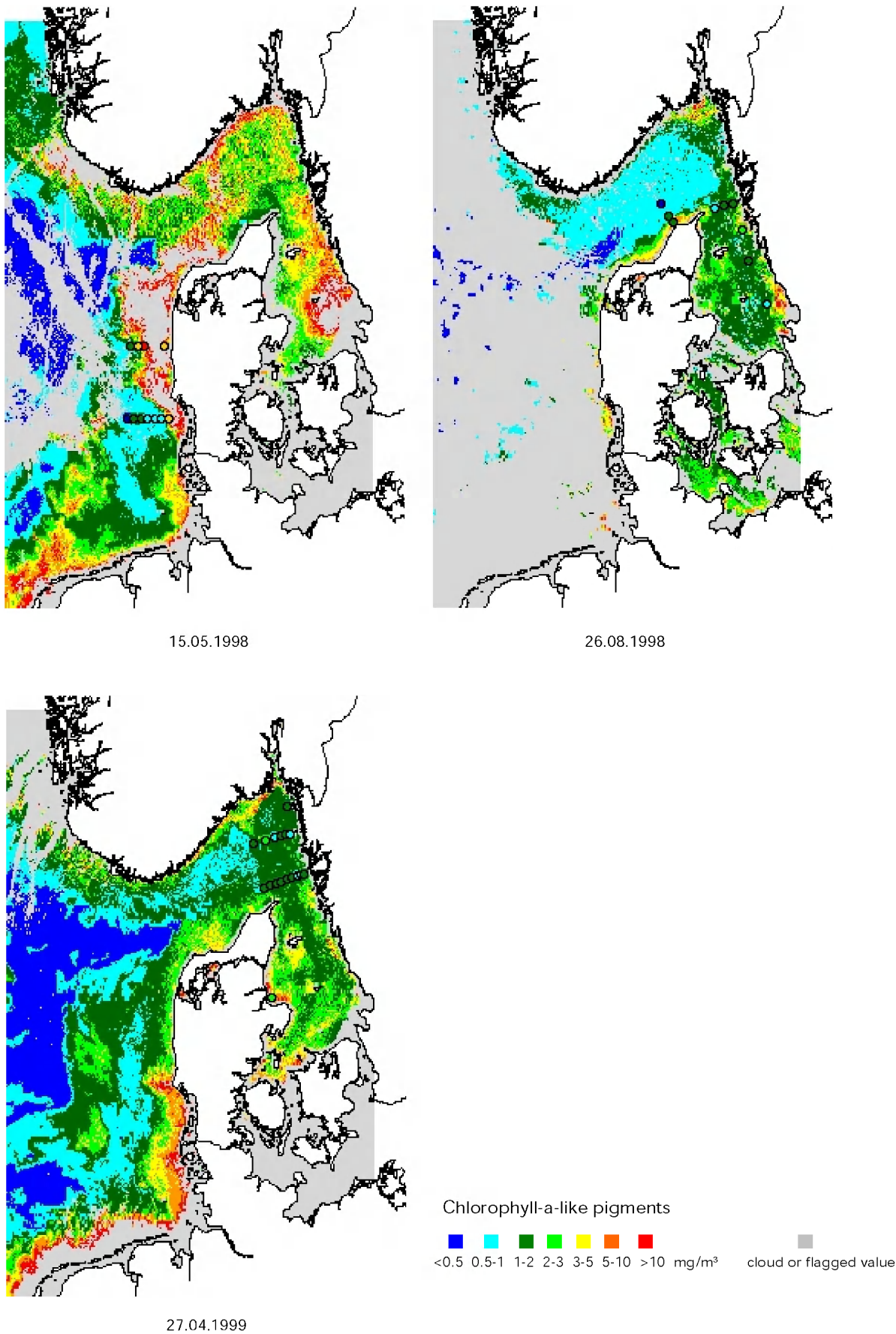


AVHRR 1999-04-27 1423 UTC Ch4



SeaWiFS image from three dates used in control of the original SeaWiFS Chl-a data against *in situ* data of the same dates.

Figure 4



4.2 Effects of subsurface chlorophyll-a maximum

Optical quantities in the surface water (upper 0-5-(10) m) contributes to the water-leaving radiance from which the SeaWiFS chlorophyll-a data is calculated. Since this comparison between SeaWiFS and *in situ* data is based on the surface

chlorophyll-a data it was relevant to investigate if any subsurface chlorophyll-a maximum could significantly contribute to the signal. In order to get an estimate of the magnitude of this effect a comparison of chlorophyll-a in the surface and at 5 m depth was performed (Figure 5 and Figure 6).

Figure 5 Correlation of *in situ* chlorophyll-a data from surface (0-1 m) and 5 m depth. Based on all data from the area.

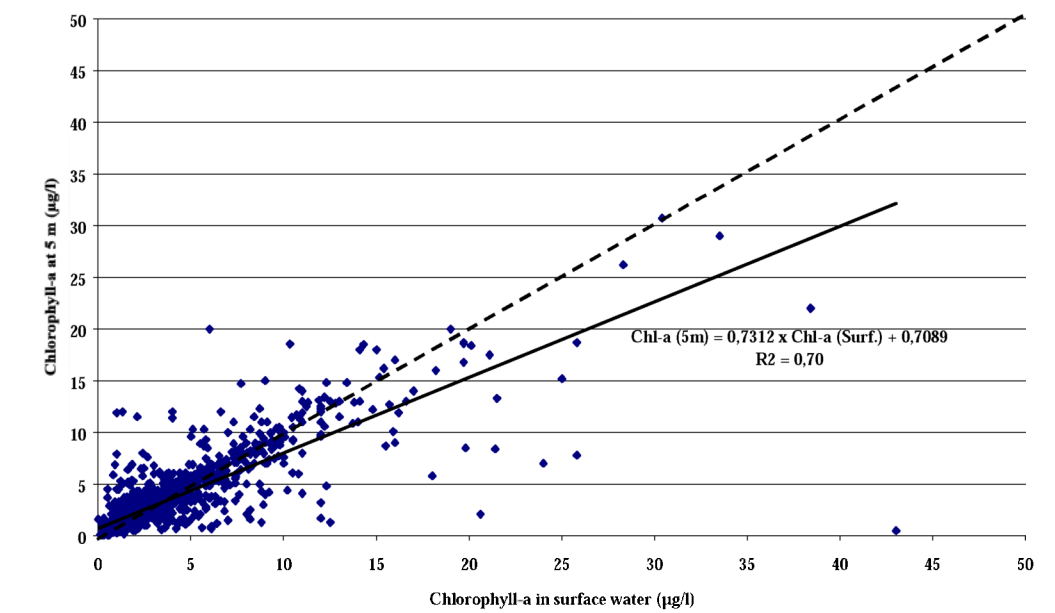
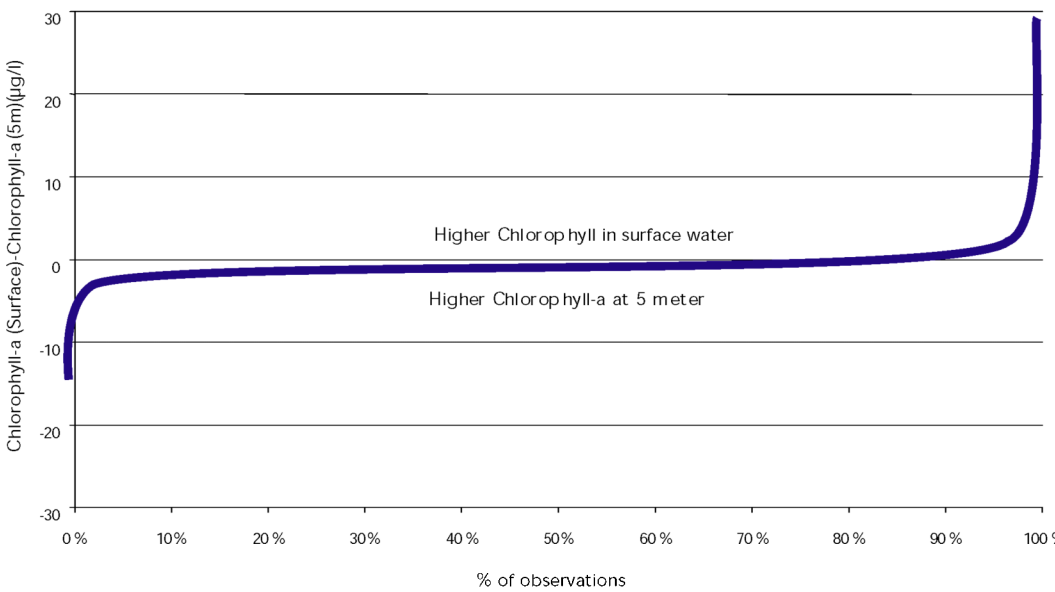


Figure 6 Difference between surface and 5 m chlorophyll-a concentration. Based on all data from the area.



In 10-15 % of the observations the values are higher at 5 m than in the surface, but only approximately 5 % of the observations had concentrations that could significantly contribute to the water-leaving radiance. In 10-20 % of the observations, the surface chlorophyll-a value was highest. It seems that using only the surface value should not introduce any significant error in the rescaling of the SeaWiFS data to the *in situ* chlorophyll-a values at the surface.

4.3 Effects of coloured dissolved organic material, CDOM

The main optical quantities that will influence the satellite retrieving algorithms are the coloured dissolved organic material, CDOM (yellow substance). This variable is normally not a routine measurement in coastal monitoring programmes and is not well documented. The variability and

concentration is, however, measured at the Norwegian coast, and this and some other data of CDOM is investigated.

The CDOM values measured at 375 nm relative to the salinity are shown for the eastern North Sea off the Danish west coast and in the Kattegat (Figure 7). The North Sea data is high in salinity, but has relatively high CDOM values with the main input from the rivers to the German Bight. In the open sea area of Kattegat the CDOM show a weak relationship with the salinity. At the Norwegian Coast (Figure 8) the CDOM is slightly higher and, in the area of river influence, (Outer Oslofjord) up to 5-8 times higher. In this area one could expect strong effect in the SeaWiFS algorithm for chlorophyll-a retrieval, resulting in a higher overestimation of the chlorophyll-a values. The source for the high CDOM concentration in the Outer Oslofjord is the River Glomma, but the concentration is in the same range as the Elbe River (Aas and Højerslev, 2001).

Coloured dissolved organic material (CDOM) versus salinity in the Kattegat and the Jutland Coastal Current 1999. (Data from Stedmon et al., 2000)

Figure 7

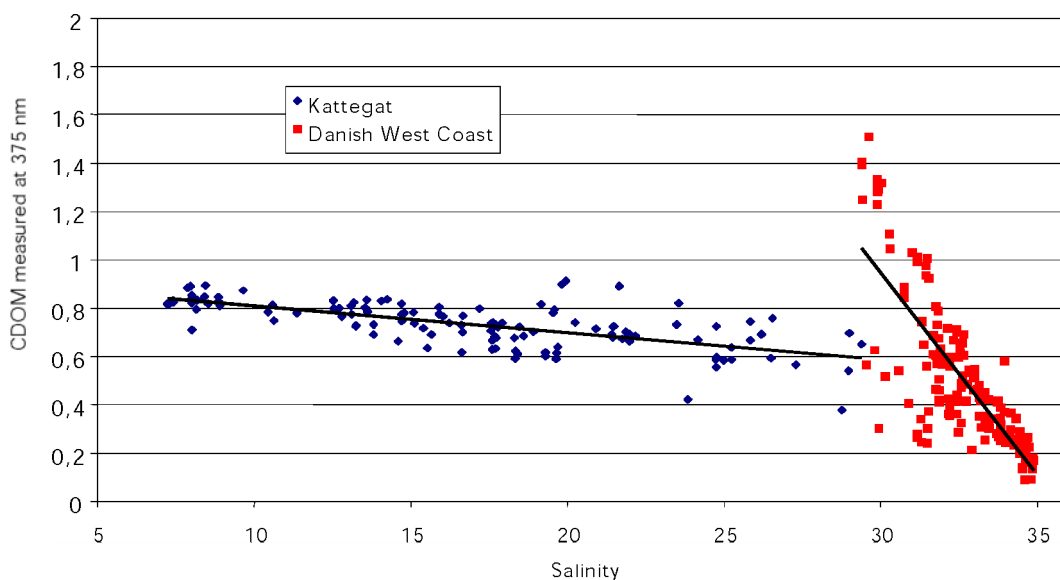
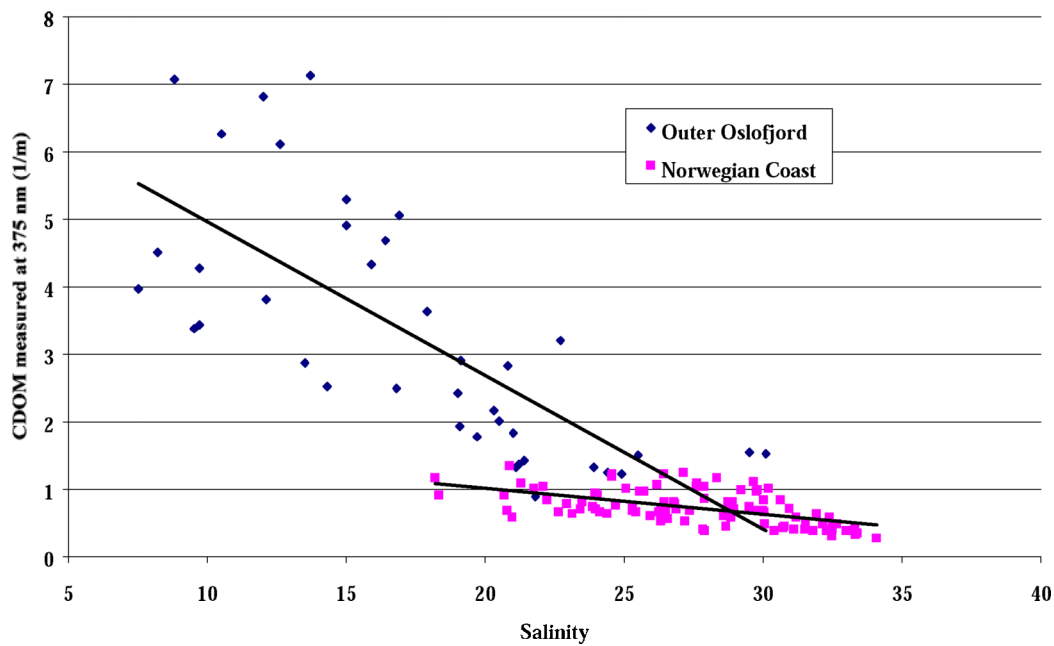


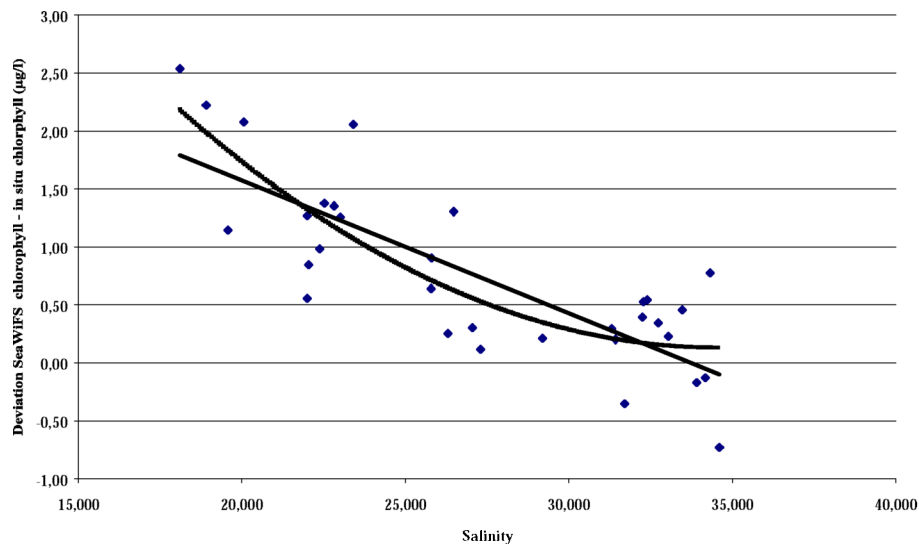
Figure 8 Coloured dissolved organic material (CDOM) versus salinity at the Norwegian coast and in the Outer Oslofjord (with strong influence from River Water).



The deviation between SeaWiFS chlorophyll-a and *in situ* chlorophyll was controlled against salinity. CDOM was not measured at these samples. In general one can assume that lower saline water has higher CDOM values. The deviation between SeaWiFS and *in situ* data varies with the salinity (Figure 9) giving higher difference with lower saline water as expected. Since low saline water often is

associated with higher concentration of suspended material the effects could also be due to higher scattering from particles. One should also be aware that low salinity is often found at short distance from land, which means that errors in the pixel data could be caused by land or atmospheric effects on the radiance signal. These effects need further investigation.

Figure 9 Deviation between SeaWiFS and *in situ* chlorophyll-a versus salinity. Trend lines are indicated.



5. Monthly mean SeaWIFS chlorophyll images

In this evaluation, monthly mean data was processed and recalculated as described in chapter 4. However, due to temporal and spatial variation of chlorophyll-a concentrations evaluation is difficult when the satellite data and *in situ* data are not simultaneously collected. Most of the *in situ* data is from situations where cloud free satellite data is not available. Also, different numbers of daily satellite images have been included in the calculated monthly mean image both between months, but also between different areas within the same month due to patchiness of cloud cover. This gives different numbers of data behind the mean values, and some areas have therefore a 'better mean value' than others. This had to be taken into account when using and interpreting the data. The comparison must be based on all the available *in situ* data whenever this is collected and all the recalculated month mean SeaWIFS images. Doing such a comparison, the *in situ* and SeaWIFS chlorophyll-a data should, on average, give realistically the same level of magnitude if the SeaWIFS data is correct. In the following figures all available *in situ* data is superimposed on the monthly mean SeaWIFS image from the same month to make the comparison easy.

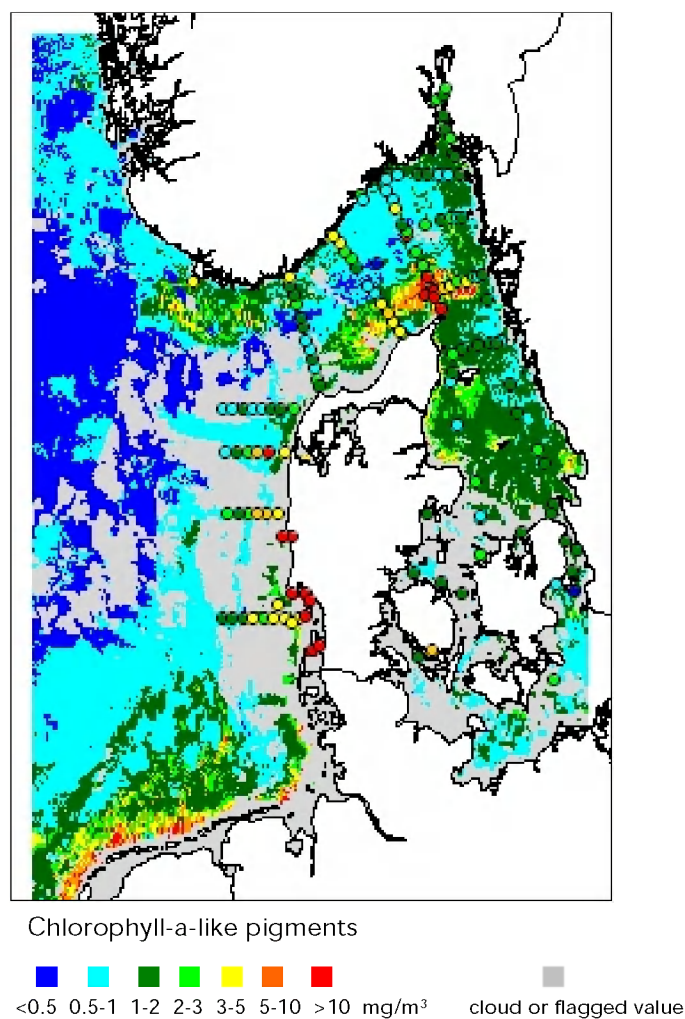
The monthly mean chlorophyll-a images from September 1997 to December 1999 are presented in Appendix A. For the 3 months after the launch of SeaWIFS in 1997 both September and October are partly cloud covered and in November only a small area of the North Sea is cloud

free. No SeaWIFS data are available from December 1997. For winter and spring 1998, the cloud cover varies from about 100 % in January and is also highly cloud covered in February, but both March and to some extent April are good. The summer months mean images in May to August are more or less cloud free giving a lot of information. In September and October the area west of Denmark is mostly cloud covered and only the Skagerrak and Kattegat have some cloud free areas. The winter months November and December are of no use.

The winter period in 1999 is the same as in 1998 with no data in January and partly clouded in February. However, February 1999 is better than the 1998 situation, and March and April are nearly cloud free. The summer months May to September 1999 are as good as in 1998, but October is partly covered and November and December are of no use.

In the following, some of the monthly mean SeaWIFS images will be discussed in further detail. The extensive *Chatonella* bloom in April and May 1998 is obvious in both Skagerrak and the North Sea. In April (Figure 10) high chlorophyll-a values outside Skagen are well documented in the SeaWIFS data with concentrations of 5-10 mg/m³ and even > 10 mg/m³ are also seen in the *in situ* data. Off the west coast of Denmark the SeaWIFS values were flagged as erroneous due to atmospheric effects (clouds), high concentrations of phytoplankton or suspended material.

Figure 10

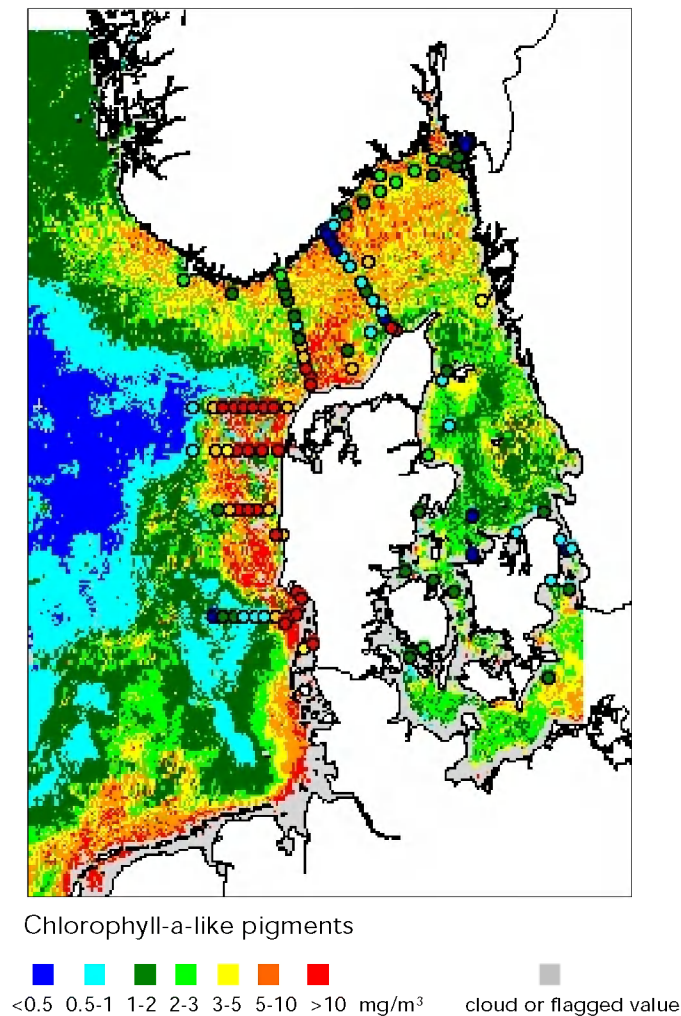
Month mean SeaWiFS chlorophyll-a image and *in situ* data from April 1998.

In May (Figure 11) the *Chatonella* bloom is dominating near the Norwegian Coast with chlorophyll-a values >10 mg/m³ measured by SeaWiFS. The *in situ* measurements in the central Skagerrak and at the Norwegian Coast have not detected the high concentrations that are indicated by the satellite, but high

concentrations are well documented off the west coast of Denmark. The explanation of this discrepancy is that the *in situ* data is only based on one cruise which is very different in time from the daily satellite data that is dominating in the monthly mean SeaWiFS image.

Monthly mean SeaWIFS chlorophyll-a image and *in situ* data from May 1998.

Figure 11



The satellite images give correct geographic distribution of chlorophyll and therefore, indirectly, also the level of eutrophication. But one cannot assess whether an area is eutrophicated from only the chlorophyll-a concentration without knowing the background concentrations of chlorophyll-a.

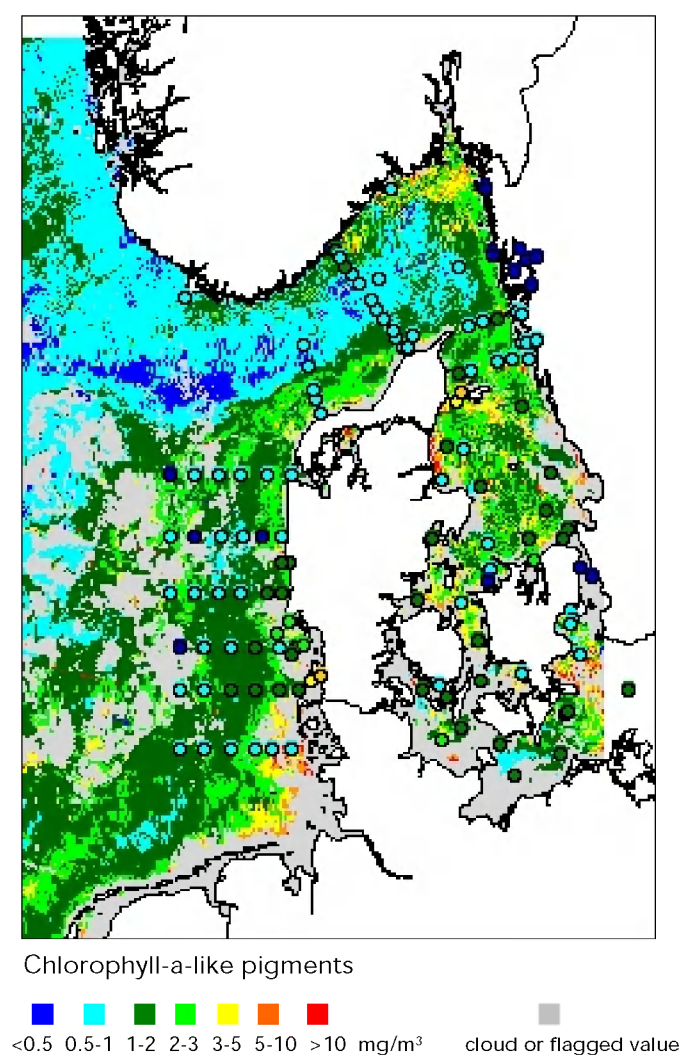
The Jutland Coastal Current from the German Bight and along the west coast of Denmark is shown well in many of the monthly mean images e.g. Figure 13 This current normally has high concentrations of particulate material and yellow substance, which would tend to overestimate the SeaWIFS chlorophyll-a values, but the chlorophyll-a level retrieved from SeaWIFS is in good agreement with the *in situ* measurements.

This is true especially for higher concentrations when the concentration interval is large, but partly also for lower concentrations (Figure 11).

In February 1999 (Figure 12) the estimation of chlorophyll-a from SeaWIFS is higher than the *in situ* data and this may be caused by the suspended material, which at that time is normally high off the west coast of Denmark.

In general there are very high concentrations of suspended material in the Wadden Sea in the German Bight and in the Jutland Coastal Current off the west coast of Denmark, highest at the coast and decreasing toward west. In winter the surface water in the North Sea can also be very turbid due to re-suspended fine sand.

Figure 12

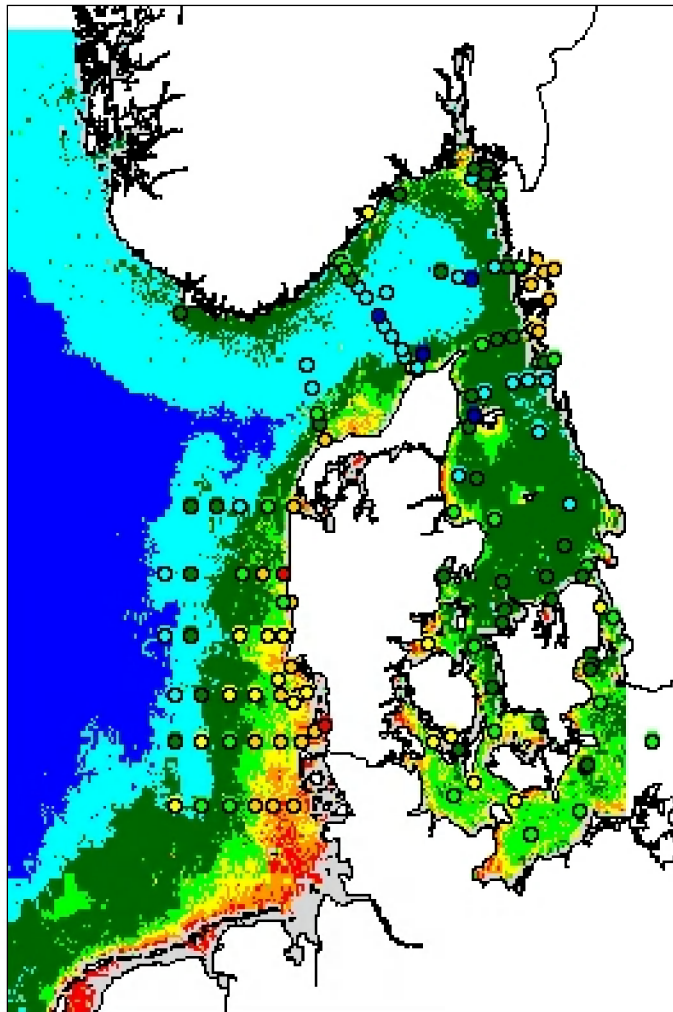
Monthly mean chlorophyll-a image and *in situ* data from February 1999.

In the German Bight and along the west coast of Denmark, in the image of August 1999 (Figure 13), the concentration of chlorophyll corresponding to values $> 3 \text{ mg/m}^3$ is generally in areas of high concentrations of suspended material during summer. But, as in May 1998, there is a reasonable agreement between

SeaWiFS and *in situ* chlorophyll-a data. No other Danish areas in Kattegat or Belt Sea have input of high levels of suspended material. There is no big river outlet except the Göta River in Sweden, which affects the coast and the archipelago areas north of Gothenburg and the eastern Skagerrak.

Monthly mean chlorophyll-a image and *in situ* data from August 1999.

Figure 13



In the north-east Skagerrak the Glomma River gives inputs of suspended material, which normally is highest in April to June. The concentrations could rise to 5 mg/l in

the open area outside the archipelago. The SeaWIFS chlorophyll values are too high close to the coast in this area (Figure 13).

6. Summer mean chlorophyll images

The summer mean values based on monthly mean values from May to September 1998 and 1999 are shown in Figure 14. The *in situ* data used and presented in the summer mean images is based on mean values of 5 or more dates of observations in the period. In the Kattegat region the satellite data is in good agreement with the field data. In the small part of the western Baltic Sea the concentrations are higher but also in agreement with the *in situ* data. Off the west coast of Denmark, the satellite derived chlorophyll-a tend to be generally higher than the *in situ* data. This might be because the *in situ* data are few and the satellite data represents a mean value of several data sets. But it could also be due to the generally higher concentrations of CDOM and suspended matter along the Danish west coast. Anyhow, the *in situ* and satellite data supplement each other and are in relatively good agreement even in some of the near-coast areas.

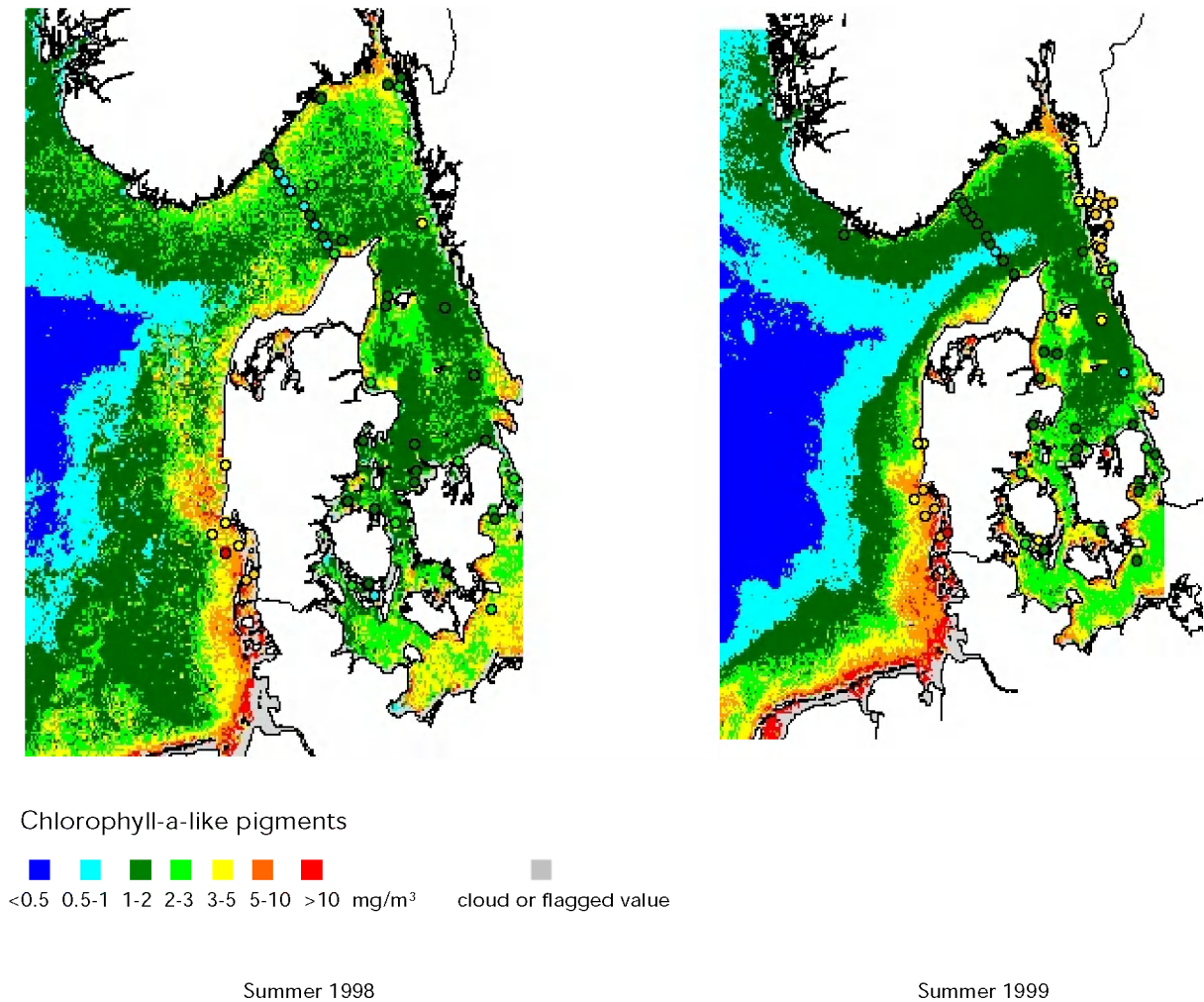
The *Chatonella* bloom (May 1998) affects the summer mean image from 1998, while the summer mean of 1999 indicates a more 'normal' distribution with highest concentration along the coasts and in the shallow areas. At Horns Rev off the Danish west coast this is very evident, as well as the shallow areas in the western Kattegat and in the areas around the Kattegat islands Læsø and Anholt. That the chlorophyll-a concentrations are lower in the open areas of eastern Kattegat is in agreement with results from the Danish monitoring programme (Hansen *et al.* 2000).

The low level of chlorophyll-a in the central North Sea, which also is seen as a 'tongue' into central Skagerrak, is well documented in the images. This tongue is in good agreement with the main currents in the area (Figure 15). The *in situ* data from the Arendal—Hirtshals transect between Norway and Denmark is very well reflected in the satellite image and the station in the 'tongue' of Atlantic water that comes into the central Skagerrak. But the Skagerrak front that during summer extends from Skagen towards the northeast is not seen in the summer mean images, only in some of the monthly mean images e.g. in the September images. This is probably due to the fact that the chlorophyll during summer is mainly concentrated in the subsurface halocline at the stratified side of the front (Heilmann *et al.*, 1994)

Six stations, four close to the coast and two offshore, (Figure 16) in the area were selected for a closer evaluation of the SeaWiFS derived chlorophyll-a concentrations compared to *in situ* chlorophyll measurements. Due to the high level of coloured dissolved organic material at the Norwegian coast, three stations in a gradient from the Glomma River towards west were chosen. At these stations all the SeaWiFS chlorophyll-a statistics were picked out from the monthly mean images during the summer period May-September and presented cumulatively with the *in situ* data from the same period. The data are presented in Figure 17 and Figure 18.

Maps of summer mean values of SeaWiFS chlorophyll-a from 1998 and 1999. Mean value of all SeaWiFS data from May to September. The in situ data presented represents mean value of more than 5 observations in the same period.

Figure 14



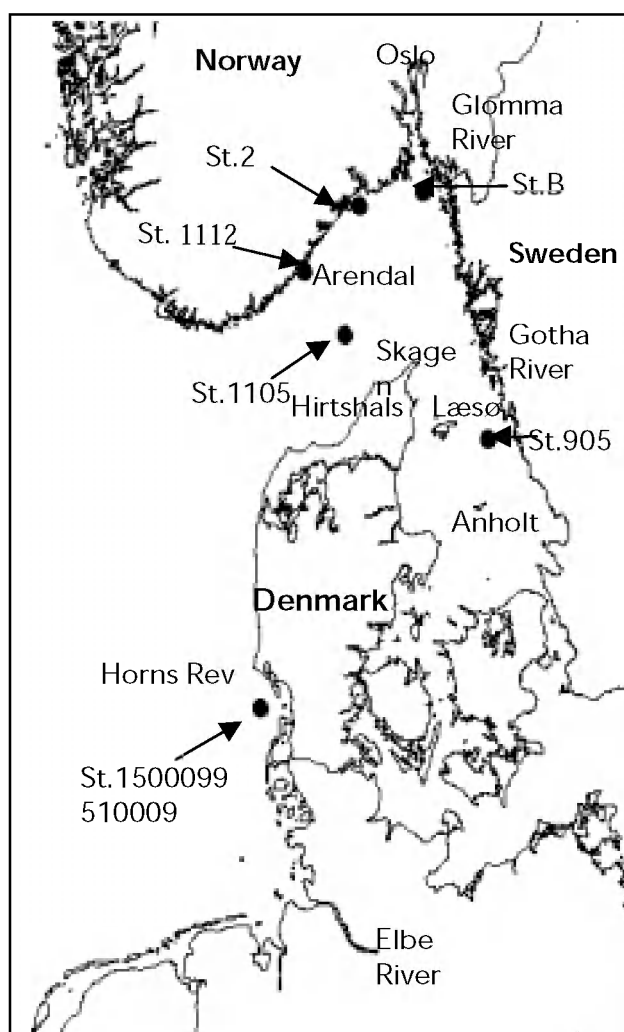
Map showing the main currents in the area. From OSPAR COMMISSION (2000).

Figure 15



Figure 16

Map of stations where all summer (May-September) *in situ* chlorophyll-a data and SeaWiFS chlorophyll-a data have been compared.



Off the west coast of Denmark (Station 1510009) the SeaWiFS data is in good agreement with the *in situ* data (Figure 17), even though this area normally has high concentrations of particles. This could be explained by the fact that the CDOM have the most severe influence on the chlorophyll-a retrieval from the algorithms. Also in the central Skagerrak (Station 1105) where Atlantic water is dominating, there is good agreement between the two data sets, which is to be expected since this area, on average, has the lowest values of CDOM and particles. The Kattegat station (905) is the only area in this comparison where the SeaWiFS chlorophyll-a are lower than the *in situ* chlorophyll-a data, which means that in this area the satellite data would underestimate the eutrophic situation. The present data cannot explain this difference.

Looking at the near coastal stations off the Norwegian coast (Figure 18) the situation is opposite compared to the Kattegat station with SeaWiFS giving higher chlorophyll-a concentrations than the *in situ* measurements. The station off Arendal (Station 1112) shows slightly higher SeaWiFS chlorophyll values. The deviation between *in situ* and satellite data is increasing when moving eastwards, and at the river influenced station B in the outer Oslofjord the SeaWiFS gives higher values by approximately a factor of 2. In general this area has higher coloured dissolved organic material (CDOM) than the coastal areas of Denmark and Sweden indicating that CDOM seems to have larger effects than particles in the chlorophyll-a algorithms.

Comparison of cumulative *in situ* values of chlorophyll-a and the satellite chlorophyll-a off the west coast of Denmark (Station 1510009), in central Skagerrak (Station 1105) and in the Kattegat (Station 905).

Figure 17

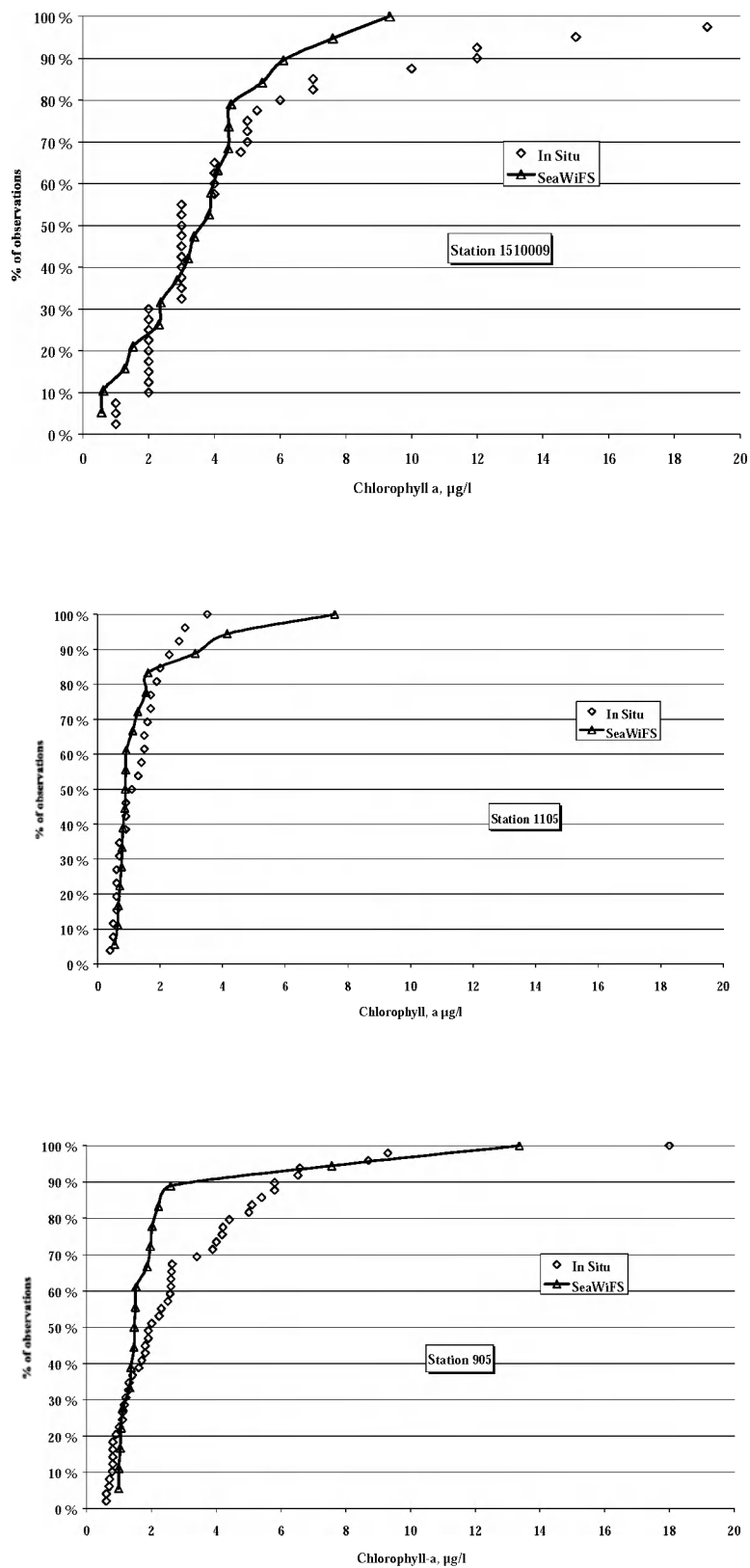
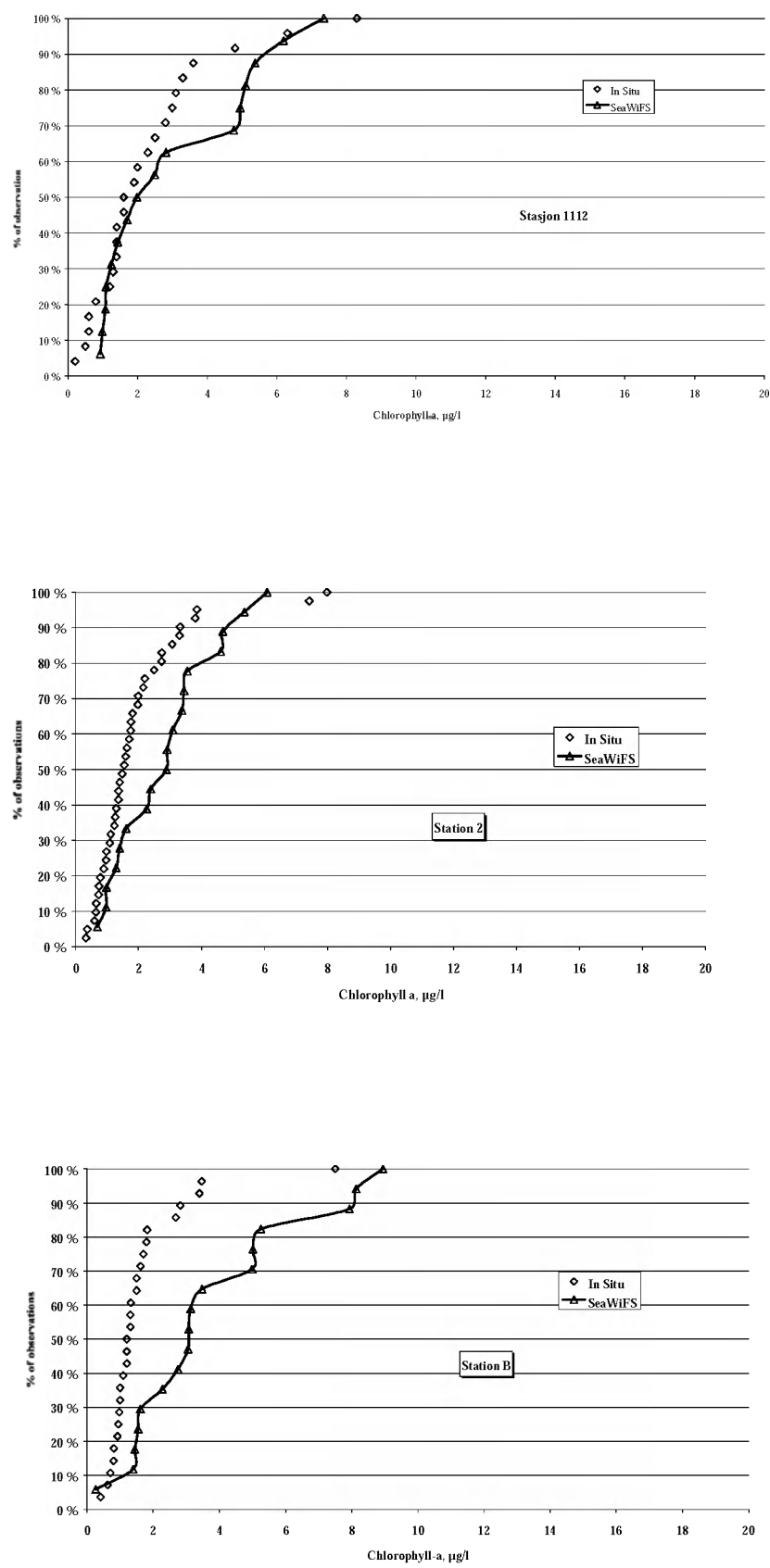


Figure 18 Comparison of cumulative *in situ* values of Chlorophyll-a and the satellite Chlorophyll-a at the Norwegian Coast (Station 1112, Station 2) and in the outer Oslofjord (Station B) close to the river outlet.



7. Conclusions

The analysis of chlorophyll-a maps, obtained from SeaWiFS satellite images processed with the REMBRANDT (version 01) code, has shown significant overestimate with respect to *in situ* observations of chlorophyll-a. The overestimate is mostly attributed to the use of a 'global' bio-optical algorithm for chlorophyll-a computation not specific for the Skagerrak, Baltic or North Sea waters characterised by high absorption values of coloured dissolved organic material. Even in the open areas of Skagerrak the present algorithms overestimate the chlorophyll-a. The use of a 'rescaling' function for chlorophyll-a values, defined with *in situ* data taken at the same time as the satellite images, has significantly decreased the uncertainties in the chlorophyll-a maps even though some coastal areas still highlight chlorophyll-a overestimates.

Clearly algal bloom monitoring can significantly benefit from satellite data and cannot be simply monitored by a fixed net of stations, dedicated cruises or ships-of-opportunity. Eutrophication mapping through satellite colour data (i.e. SeaWiFS or MERIS) should mostly address the creation of 'time composite' products for those periods of the year when blooms may occur. In the months of November through February, phytoplankton production is mostly light limited and is not related to the input of nutrients. Because of this the satellite data, which at that period of the year are highly affected by cloud cover, are not considered essential.

In the months of March through April (and in some cases in February too), chlorophyll-a maps could be of some interest to identify and characterise spring blooms, which may reflect the magnitude of the winter nutrient pool even though frequent and strong winds may limit their development.

In the months of May through September, the chlorophyll-a maps could ensure the definition of the level of eutrophication,

even though frequent and strong winds could again mix the deep water nutrients into the euphotic zone increasing biomass in the stratified areas. In contrast, under calm conditions, the phytoplankton stratifies in subsurface maxima at depths making their detection impossible through space sensors. On the other hand, Cyanobacteria, which dominate in the Baltic Sea during summer, accumulate at the surface during calm periods. These conditions make questionable the comparability of satellite data collected over different years.

Thus, in the operational use of satellite colour data for the detection of eutrophication levels in the Nordic Sea areas, the most relevant information seems to be the capability of detecting and mapping the maximum spring concentrations and the mean summer concentrations of chlorophyll-a.

Whether satellite data makes it possible to exclude any routine monitoring station is not easy to elaborate from the present investigation and the images so far. Further investigation is needed where the variability at the station must be compared with the monitoring frequency and also other objectives of the station (e.g. investigation of deep water oxygen deficiency). In the North Sea it is maybe from a eutrophication point of view possible to exclude stations west of the 34.5 isohaline where winter nutrient concentrations are close to background values. In this central area of the North Sea the surface water is normally not much affected by land-based nutrient loads, but this is also the area where oxygen deficiency problems sometimes arise in the bottom water.

Information from the central North Sea can also be used to improve the present algorithms or be used in later work with new sensors such as MERIS on ENVISAT. The MERIS-sensor will have improved spectral capability to handle difficulties in the coastal areas (Doerffer et.al., 1999).

Ongoing research on algorithm development and improvements in this area will be performed within the framework of validation activities on MERIS where projects such as e.g. VAMP

— Validation of MERIS data products (NIVA, UIO, IMR and GKSS) and the EU-project REVAMP — Regional Validation of MERIS Chlorophyll-a Products in North Sea Coastal Waters.

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We would like to thank Mr. Didrik Danielsen at the Institute of Marine Research, Norway for supporting this project with important data. We are also grateful to the other contributors from the Swedish Meteorological and Hydrological Institute and persons involved in sampling and analysis in the different countries and institutions.

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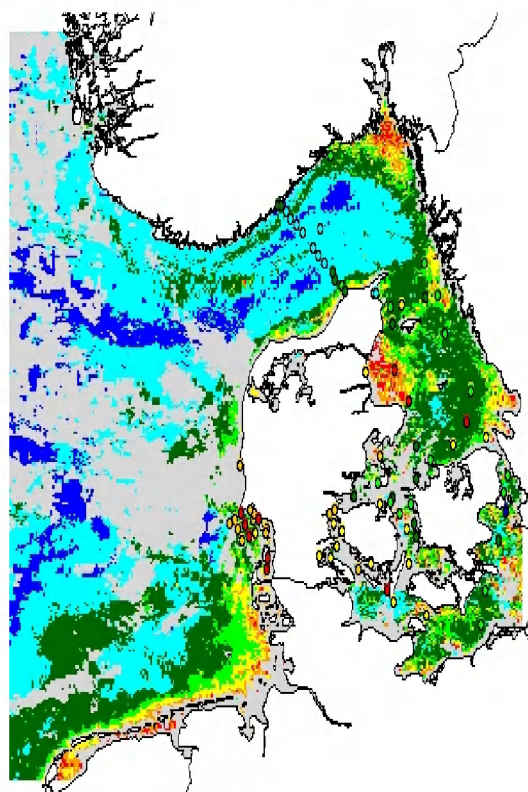
List of acronyms

EC:European Commission	NIVA:Norwegian Institute for Water Research, Norway
HRPT:High Rate Picture Transmission	NCEP:National Centre for Environmental Prediction
FAPAR:Fraction of Absorbed Photosynthetically Active Radiation	REMBRANDT: REtrieval of Marine Biological Resources through ANalysis of ocean colour DaTa
GVM:Global Vegetation Monitoring	SAI:Space Application Institute.
IMR:Institute of Marine Research, Norway	SeaWiFS:Sea-viewing Wide-Field-of-View Sensor
JRC:Joint Research Centre	SMHI:Swedish Meteorological and Hydrological Institute, Sweden
LAC:Local Area Coverage	TOMS:Total Ozone Mapping Spectrometer.
ME:Marine Environment	GSFC:Goddard Space Flight Centre.
NASA:National Aeronautics and Space Administration	DAAC:Data Active Archive Centre.
NERI:National Environmental Research Institute, Denmark	

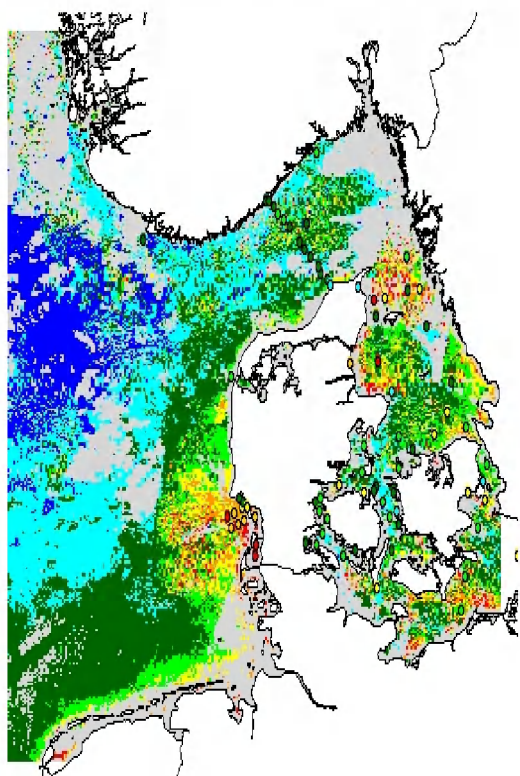
Appendix A

Monthly mean SeaWiFS chlorophyll-a images from September 1997 to December 1999, rescaled to in situ chlorophyll-a measurements, and compared to monthly mean in situ chlorophyll-a measurements at monitoring stations.

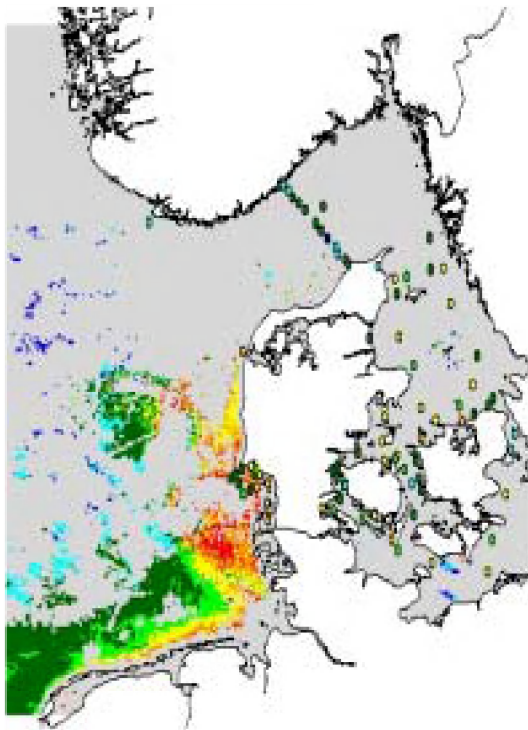
Monthly mean SeaWiFS Chlorophyll-a Images from September to November 1997.



September 1997



October 1997

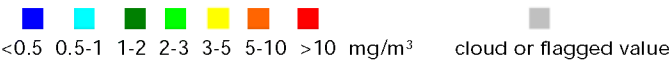


November 1997

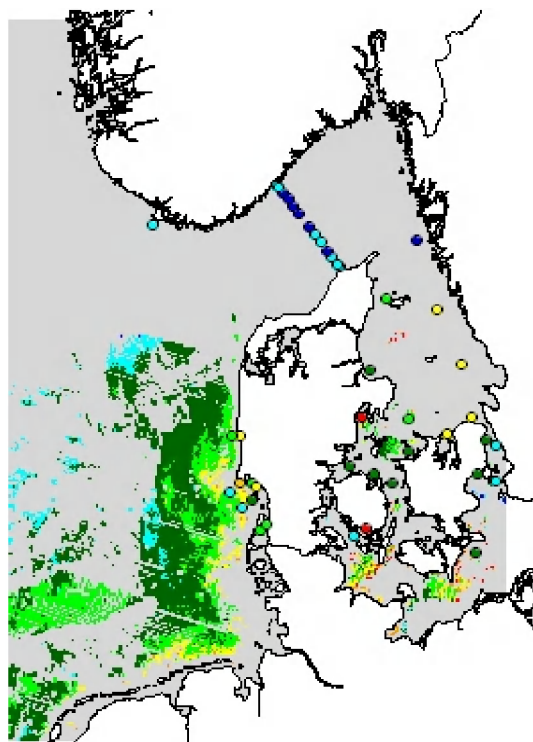
No
SeaWiFS
Data

December 1997

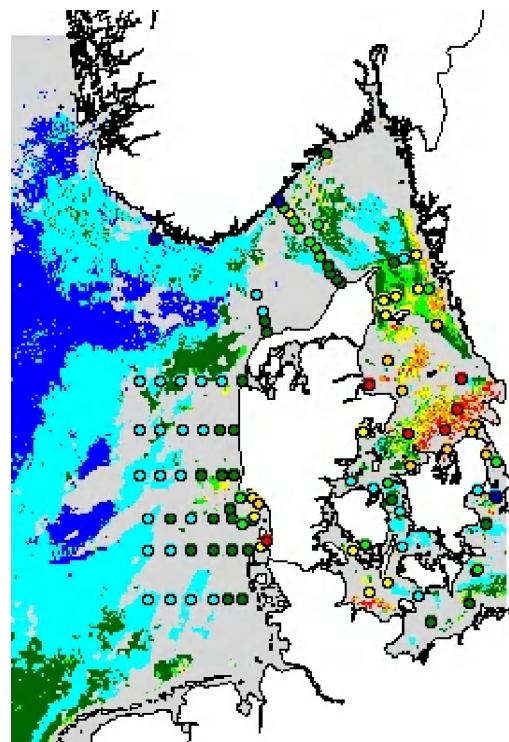
Chlorophyll-a-like pigments



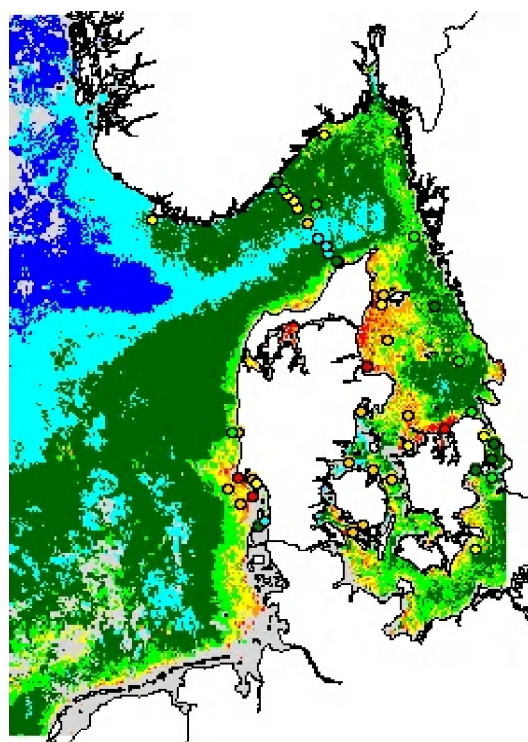
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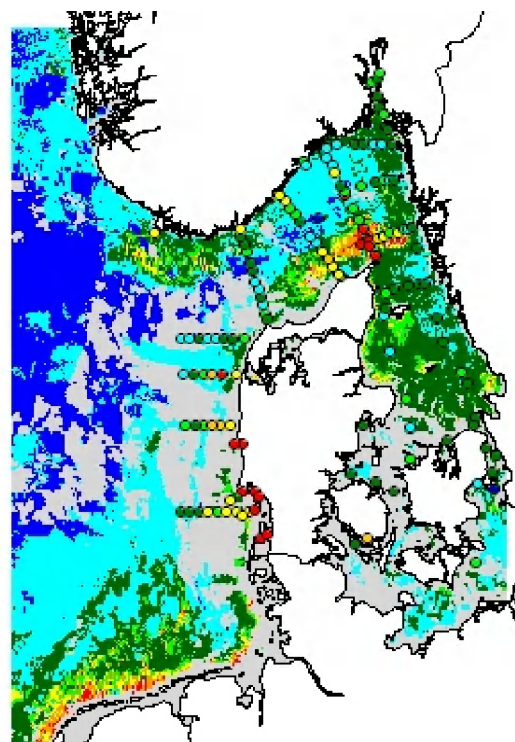
January 1998



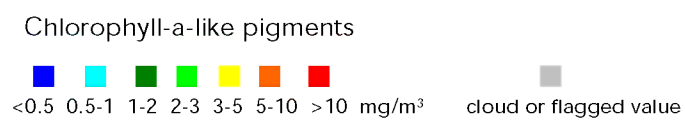
February 1998



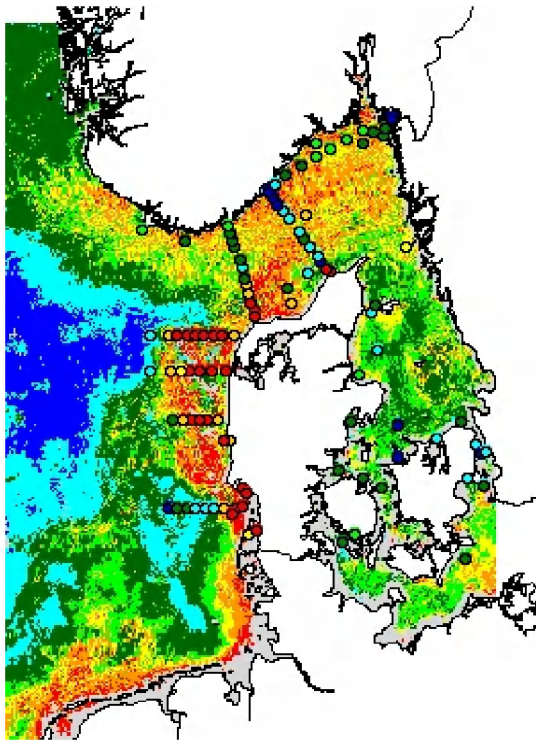
March 1998



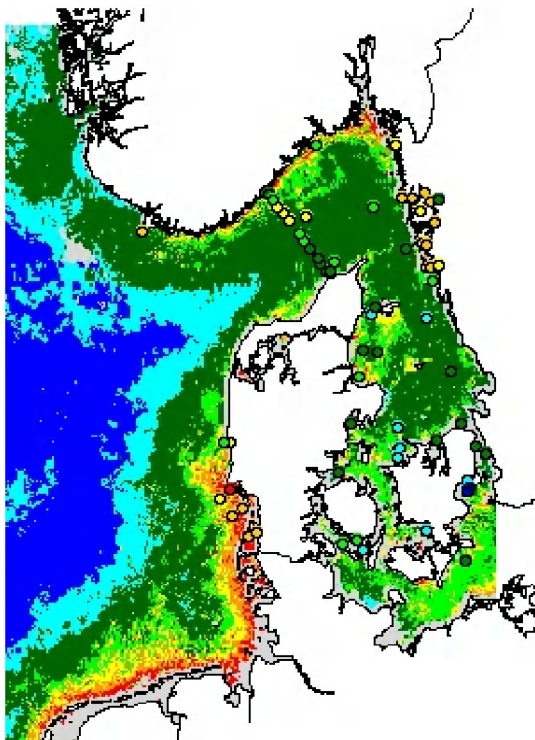
April 1998



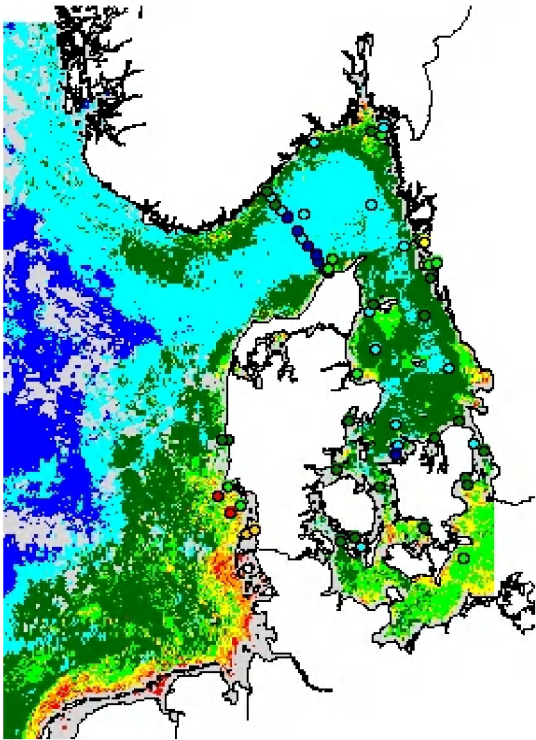
Monthly mean SeaWiFS chlorophyll-a images from April to August 1998.



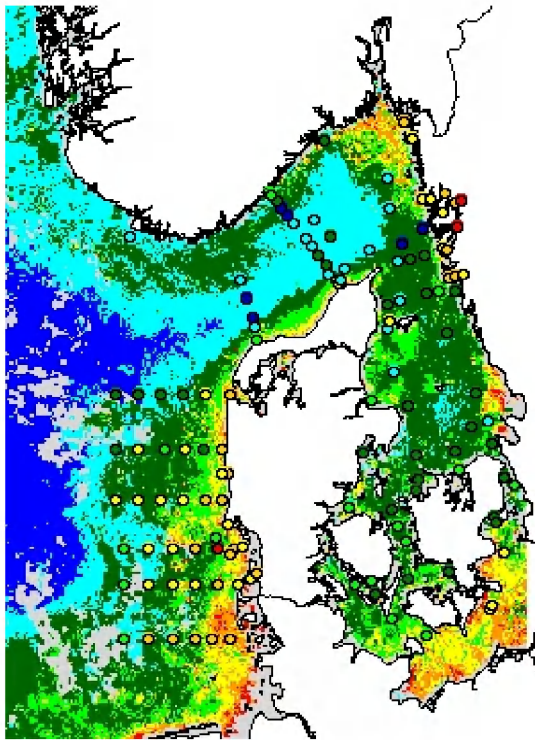
May 1998



June 1998



July 1998

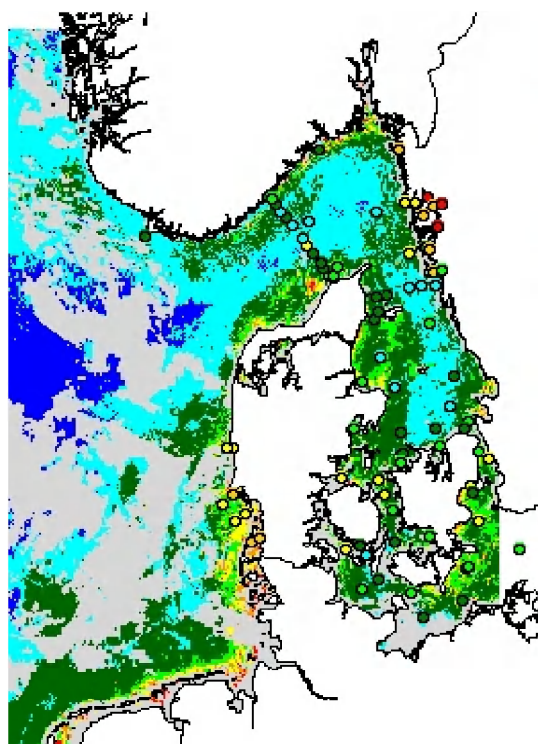


August 1998

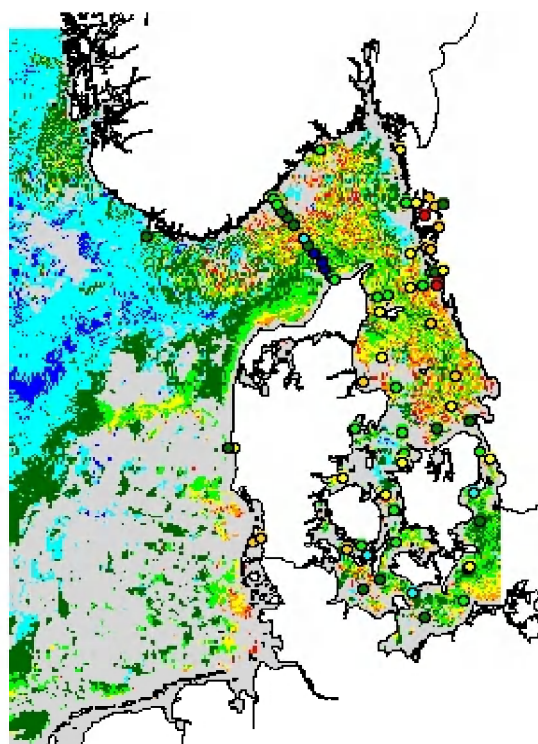
Chlorophyll-a-like pigments



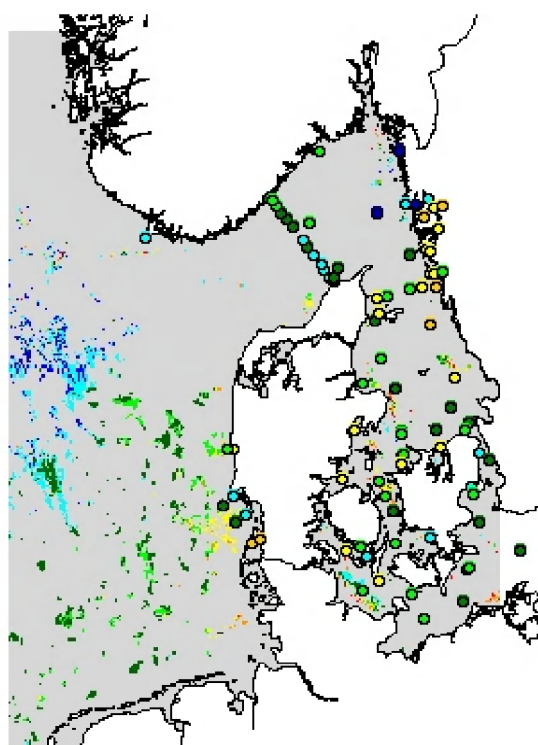
Monthly mean SeaWiFS chlorophyll-a images from September to December 1998



September 1998



October 1998

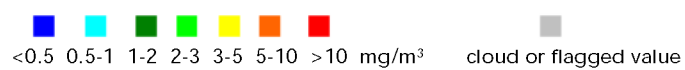


November 1998

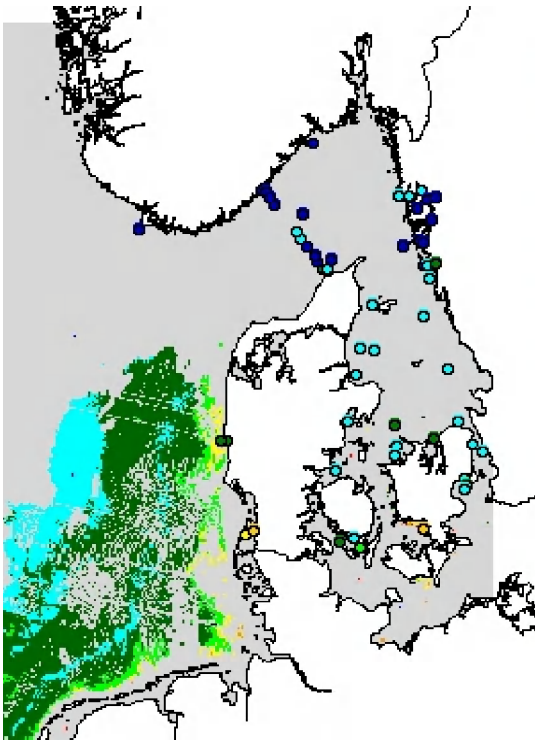
No
SeaWiFS
Data

December 1998

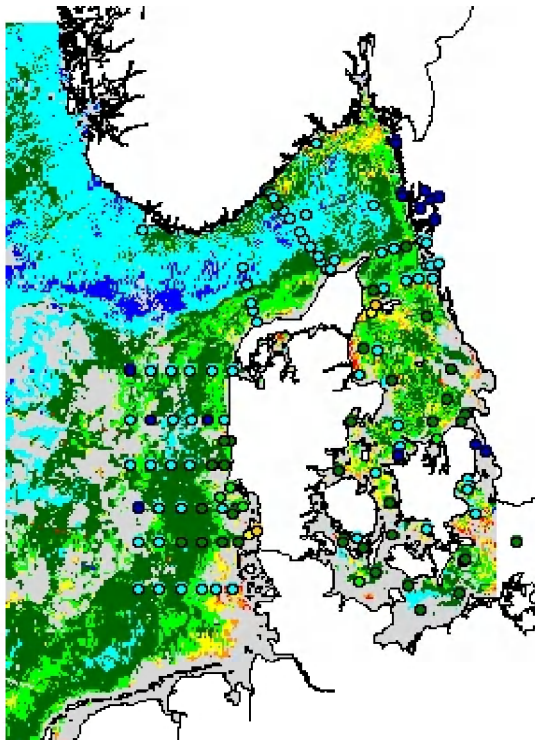
Chlorophyll-a-like pigments



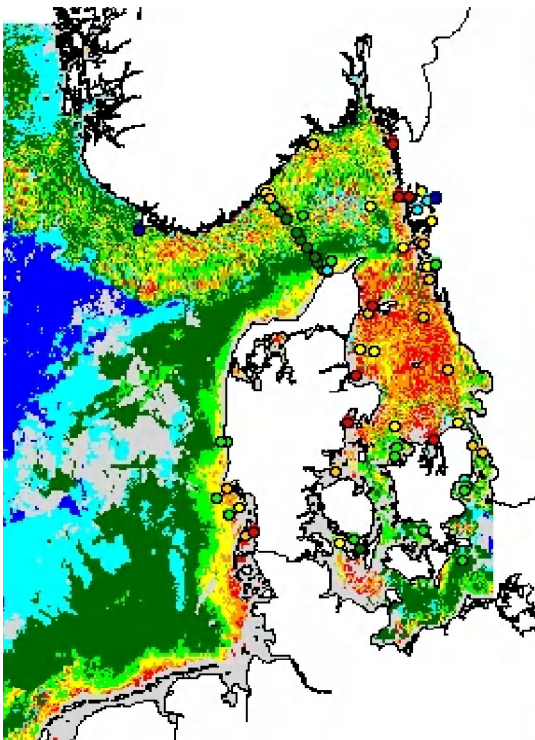
Monthly mean SeaWiFS chlorophyll-a images from January to April 1999.



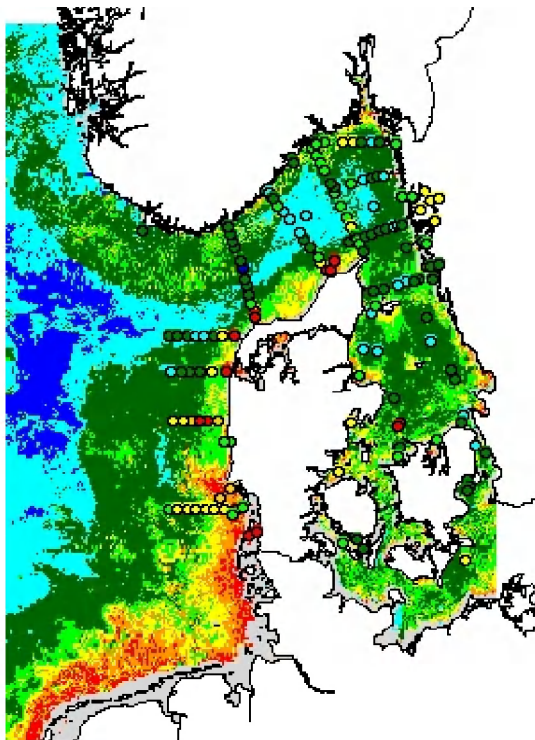
January 1999



February 1999

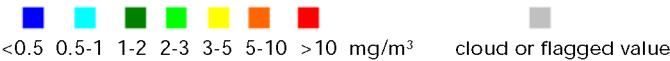


March 1999

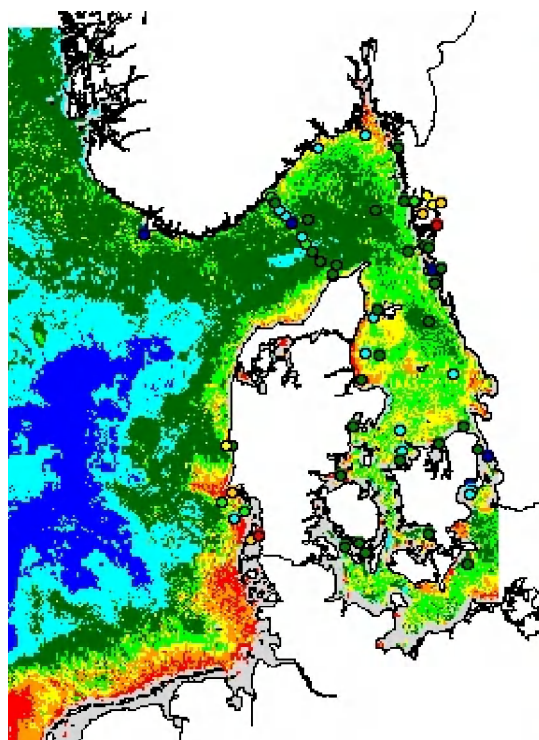


April 1999

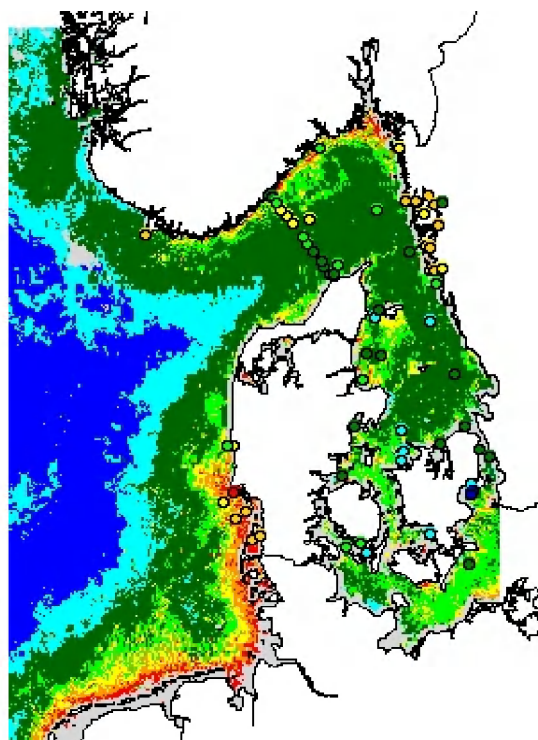
Chlorophyll-a-like pigments



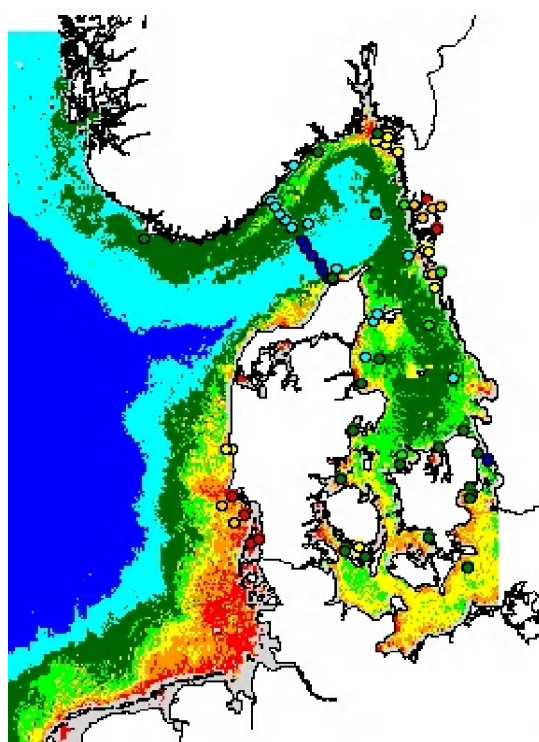
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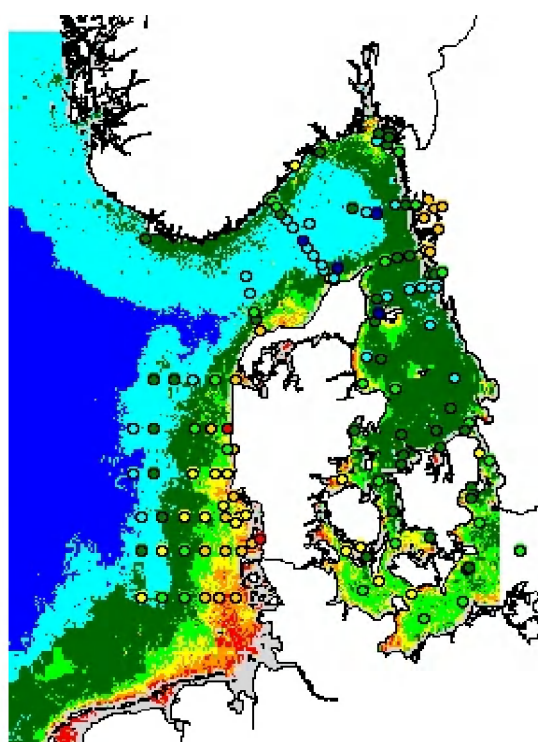
May 1999



June 1999

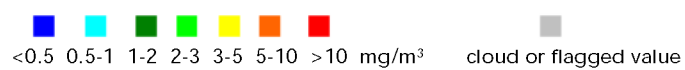


July 1999



August 1999

Chlorophyll-a-like pigments



Monthly mean SeaWiFS Chlorophyll-a images, September to December 1999.

