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INTER-COMPARISON OF SATELLITE OCEAN COLOUR DATA PRODUCTS DURING ALGAL BLOOMS IN THE NORTH SEA REGION IN 2004

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QUALITY ASSESSMENT OF THE MODIS DATA PRODUCTS DELIVERED BY KONGSBERG SPACETEC AS

by

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Bergen, October 18, 2004

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REPORT

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SUMMARY and **RECOMMENDATION**

Several satellite-borne ocean colour Earth observation (EO) sensors are presently collecting data on an operational basis. This study aims at quantifying differences in ocean colour EO sensor performances for ocean monitoring and in particular the study of algal bloom situations. The motivation for the present study is to explore how data from different sensors can be utilized in one system for HAB detection and monitoring. Ocean products from the MODIS/Terra, MODIS/Aqua, MERIS, and SeaWiFS sensors have been processed and inter-compared for data acquired during the development of an early spring algal bloom in 2004 in the North Sea region. The study assesses the comparability of these OC sensors in the cases of bloom and non-bloom situations. Particular focus has been on the assessment fo the quality of the MODIS/Terra data provided by Kongsberg Spacetec AS.

The conclusions are that the MODIS/Terra products processed and delivered by KSAT are inconsistent with equivalent products from derived from the other EO ocean colour sensors. We suspect the discrepancies to be mostly caused by the radiometric performance and the calibration procedure of the MODIS/Terra sensor used by Kongsberg Spacetec. Due to the discrepancies observed between the MODIS/Terra and the other sensors' products, the quality of the present product is not satisfactory for use of the data in an operational system for algae bloom monitoring in Norwegian coastal waters. A further harmonisation with the processing tools and algorithms used in Tromsø should be done using the similar tools being developed and validated by NASA. We suggests that Spacetec undertake parallel processing of MODIS-Terra and -Aqua data as well as SeaWiFS data using their implementation of the software. It should also be considered to use the NASA SeaDAS OC4 software or other operational software implemented and tested by NASA.

APPROVAL	
Lasse H. Pettersson, Project Leader	Ola M. Johannessen, Director

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1. INTRODUCTION

The Nansen Environmental and Remote Sensing Centre (NERSC) has since 1998 developed and operated a near real time system for algal bloom monitoring (http://HAB.nersc.no) based on ocean colour satellite data from the Sea-viewing Wide Field of View (SeaWiFS) sensor [1]. The system provides daily information about the abundance of phytoplankton in the North Sea and Skagerrak regions, provided via the web. In cooperation with Plymouth Marine Laboratory images of the surface distribution of chlorophyll *a* pigments are used in conjunction with other observations and data. In the event of harmful algal blooms (HABs) such information is essential for the national fishery authorities in order to implement mitigation actions as well as for the fish farming industry. The main goals of the system are to early detect and subsequently monitor the spatial distribution and intensity of phytoplankton bloom development and decay. In case of identified HAB events the satellite data are used to initiate and optimize dedicated field observations as well as modelling in order to improve the understanding of the specie specific triggering and growth mechanisms.

With the launch of several new ocean colour satellite sensors, an increased amount of Earth Observation (EO) data is available. However, the sensors have different design and specifications, all with the aim to among other map the Chlorophyll-*a* distribution. The Medium Resolution Imaging Spectrometer Instrument (MERIS) onboard Envisat was launched in 2002, and the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua and Terra satellites were launched in 2002 and 1999, respectively. SeaWiFS has been operational since 1997. By merging information from these sensors, improved temporal resolution and spatial coverage can be obtained, while an extensive time series of ocean colour EO data is gathered.

The motivation for the present study is to explore how ocean colour data from different sensors can contribute to improve an operational system for HAB detection and monitoring for Norwegian waters. Ocean products derived from the MODIS/Terra, MODIS/Aqua, MERIS, and SeaWiFS sensors have been processed and compared. In particular the consistency between the standard chlorophyll products of the three sensors have been evaluated. For the use of these data it is essential that regular and comparable information is available independent of the EO sensor used.

The validity of the used ocean colour products is limited to clear (Case 1) waters while the region under consideration contains sub-regions that often are optically complex (Case 2) waters. However, there are several reasons for restricting the present analysis to standard chlorophyll *a* concentration for Case 1 waters. For the HAB detection and monitoring system the most important task is to early identify the presence of elevated pigment concentrations as well as assess the potential harmful phytoplankton species. Therefore, our main goal is not to retrieve the best accuracy of the chlorophyll-*a* pigment concentrations, but rather to get information about the main chlorophyll distribution patterns and their temporal changes. Furthermore, an operational system for a region of this size requires quick and routine algorithms that are applicable for the entire region. For these purposes Case 1 water products are assessed to be acceptable. Accurate algorithms for retrieval of chlorophyll in Case 2 waters often requires specific local knowledge and parameterization of the optical properties of the water constituents. Identification of the various Case 2 water sub-regions will therefore be a complex task within an operational system. However, if necessary the data can be further consolidated with locally tuned algorithms in order to gain a better precision of the measurements.

2. DATA AND METHODS

2.1 Study area

The area covered by this study extends from 55.5°N to 60.0°N and from 4.5°E to 11.5°E, i.e. the North Sea, Skagerrak, Kattegat and the southern part of the Norwegian Coastal Current (NCC) (Fig. 1). For one scene (March 29 2004, Fig. 2b) the study area was extended to the region from 51°N to 66°N, and from 4°W to 14°E. Due to a complex and variable circulation pattern of the water masses in this region sub-areas with distinct optical complexity are present. Generally, the central part of the North Sea is poor on nutrients, and low density of phytoplankton is observed.

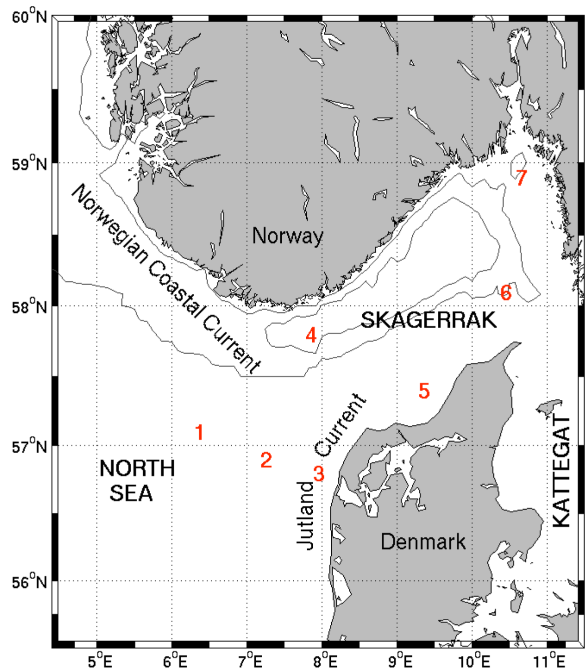


Figure 1: Map of study area. Isobaths for 200m and 400m depth contours are shown. The numbers indicate the fixed locations for inter-comparison of satellite ocean colour products used in this report.

The chlorophyll-*a* concentration is therefore low and the water is "clear". Due to sediment re-suspensions and river discharges the waters along the western coast of Denmark (Jutland Current) are often loaded with sediments. Nutrient-rich waters from river run-off in the German Bight cause high abundance of phytoplankton in this area as well as making the water optically complex. In central parts of Skagerrak, between Norway and Denmark, the Jutland current mixes with the water from central North Sea, and less saline outflow from the Baltic Sea. In the inner part of Skagerrak the waters are also influenced by coloured dissolved organic matter from river run-off primarily by the Glomma River, Norway. The NCC follows the Norwegian trench from central Skagerrak westwards and northwards along the western coast of south Norway.

2.2 Ocean colour satellite data

"Cloud free" data from the ocean colour sensors MODIS/Terra, MODIS/Aqua, MERIS, and SeaWiFS were evaluated and acquired for the study area during the period from February 18 to April 1, 2004. Within this period, three days were identified for which data were available for all the four satellite sensors, and where the images contained large portions of cloud free areas in major parts of the study area of interest (Figs. 2a, 2c, and 2d). One day was identified for which MODIS/Terra, MODIS/Aqua and SeaWiFS data was available (Fig. 2b), and nine more days were identified for which MERIS, MODIS/Aqua and SeaWiFS data were available. Due to different orbit configurations the three satellites have different local overpass time, accordingly maximum differences in time between the three satellite passes was up to 3.5 hours around solar local noon time. During the specified time period the study area experienced at least two distinct phytoplankton blooms, neither were harmful to the environment.

2.2.1 MODIS/Terra from Kongsberg Spacetec

MODIS/Terra Level 2 (L2) data were obtained via ftp from Spacetec in Tromsø. The format of the data was in accordance with the NASA standard for MODIS files, including the standard MODIS ocean product suite. Two different chlorophyll products were analysed in this study; the "chlor *a* 2" and the "Chlor *a* 3" products retrieved by the OC-3M algorithm, and a semi-analytical algorithm respectively.

2.2.2 MODIS/Aqua

MODIS/Aqua L2 data were obtained from the NASA Ocean Data Processing System (ODPS) at http://oceancolor.gsfc.nasa.gov/. The standard MODIS L2 ocean product suite includes normalized water-leaving radiances in 6 bands (table 1), and chlorophyll *a* concentration (Chlor_a), providing the chlorophyll *a* concentration in Case 1 waters [2]. The algorithm used to obtain the Chlor_a product is identical to the algorithm used to obtain the MODIS/Terra "chlor *a* 2" product.

2.2.3 MERIS

For the present study processed MERIS Reduced Resolution (RR) L2 data were provided by the ESA ground segment processor using the latest revised algorithms for atmospheric correction and made available for calibration and validation purposes by Brockmann Consult, Germany. Further data analyses and image projections were performed using the BEAM freeware from ESA (Basic ERS & Envisat (A)ATSR and Meris Toolbox (BEAM) version 2.3).

MERIS L2 data products provide a number of geophysical ocean products. For this sensor we focused our study on the ocean products algal pigment index 1 (equivalent to chlorophyll *a* concentration in Case 1 waters) and the surface reflectance (MERIS bands 1-10). Detailed descriptions of the algorithms for retrieval of the selected products are presented in [3, 4].

2.2.4 SeaWiFS

SeaWiFS Local Area Coverage Level 1 data were retrieved from the NASA GSFC Distributed Active Archive Center (DAAC) together with ancillary meteorological and ozone data. The data were processed using atmospheric correction algorithm with multi-scattering with 765/865 model selection and NIR correction for non-zero normalized water-leaving radiance [5, 6]. Normalized water-leaving radiance in the first six bands (Table 1) was retrieved. The standard OC4 algorithm was used to retrieve the chlorophyll *a* concentration for Case 1 water [2, 7].

Table 1: Specifications of the spectral bands of MERIS, MODIS (Aqua and Terra) and SeaWiFS sensors relevant for the bio-optics.

MERIS	MERIS band #	1	2	3	4	5	6	7
	Band centre (nm)	412.5	442.5	490	510	560	620	665
	Bandwidth (nm)	10	10	10	10	10	10	10
MODIS	MODIS band #	8	9	10	11	12		13
	Band centre (nm)	412	443	488	531	551		667
	Bandwidth (nm)	15	10	10	10	10		10
SeaWiFS	SeaWiFS band #	1	2	3	4	5		6
	Band centre (nm)	412	443	490	510	555		670
	Bandwidth (nm)	20	20	20	20	20		20

2.3 AlgeInfo field data

The AlgeInfo web page (http://algeinfo.imr.no) provides weekly updated information on the algal situation in Norwegian coastal waters, based on water sampling and analyses. Updated information about the abundance of phytoplankton and species composition of the phytoplankton community is given. Most information is based on near shore data collection. Information on the algal situation from the time period covering the ocean colour datasets was collected from this web page. The phytoplankton abundance was given as cell counts and taxonomy, as such not fulfilling the criteria for a proper validation of ocean colour EO data products. However, these data indicate the general level of phytoplankton and dominant blooming species. This information was compared with the chlorophyll *a* concentrations retrieved from ocean colour data.

2.4 Methods of comparison - all EO sensors

For comparison of data from all the four sensors, the standard chlorophyll products were presented with identical projections and visualized using the same colour scale for the chlorophyll *a* concentration (Fig. 2). Visualization of the data in such a way enabled an overview of both the general consistency between the products from the three sensors, and also the smoothness/patchiness of the retrieved parameters.

2.5 Methods of comparison - MODIS/ Aqua, MERIS and SeaWiFS sensors

Due to lack of data and the low quality of the data available from the MODIS/Terra sensor (discussed in section 3.2) major efforts in comparison of data from the MODIS/Aqua, MERIS, and SeaWiFS sensors have been undertaken in this study. For comparison of data from these sensors, several methods of comparison have been used. For all sensors and for all the 13 selected dates, the standard chlorophyll products were visualized and compared (Fig. 3).

For all the 13 dates, the frequency distribution of the retrieved chlorophyll concentrations within each image was compared for the three sensors (Fig. 4). The data in each image were segmented in 20 bins each extending 1 mgm^{-3}. For some dates differences in swath coverage and the number of cloud covered pixels between sensors were large. For these dates it was necessary to limit this analysis to sub-regions of the image covered by all sensors, in order to exclude regions where data was lacking from one or more sensor.

Within the study area seven site locations were defined for sensor comparison (Fig 1). The locations were intended to represent areas with different types of water masses with different optical and biological properties. For all common 13 dates and for each location the chlorophyll concentration was extracted from a 5x5 pixel area for all the three sensors. The average chlorophyll-*a* values within these areas were thereafter calculated. The extraction of such information enabled a sensor inter-comparison of retrieved chlorophyll *a* concentration for the various locations, as well as a study of the time evolution of chlorophyll-*a* concentration for all locations.

Further, areas with homogeneous chlorophyll concentrations were identified for all 13 dates and for every date one to two such areas were defined. Pixel values of chlorophyll concentration were extracted from these areas. Due to differences in swath configurations between sensors, the number of pixels within the same area could vary. The criteria for selecting the areas were that they should be homogenous for all sensors (with standard deviation less than 30% of mean value), and that if multiple areas within the same image were selected they should represent different levels of chlorophyll *a* concentration (i.e. within the low, medium or high concentration ranges). In this way a total of 28 areas were selected. The size of these areas varied, and the number of pixels was generally in the order of 100 - varying between 56 and 1950. Mean values of chlorophyll *a* concentrations from every area were compared between the sensors. Because of the manual selection of these areas, the inter-sensor comparison of the retrieved results would not be influenced by dynamic effects like the changing of fronts between water masses or changing cloud coverage. Because of the size of the areas (as opposed to the 5x5 pixel box extraction as described above), the results would also be less likely to be sensitive to differences in the pixel-by-pixel processing and data quality.

The water-leaving optical signal (normalized water-leaving radiance (nLw) or surface reflectance) was compared between the three EO sensors. For the images from April 1, pixel values within a 5x5 pixel area for 7 selected locations were extracted for inter-sensor comparison. For MODIS/Aqua and SeaWiFS nLw in 6 comparable bands (table 1) were retrieved. For MERIS the standard product is the surface reflectance, which was retrieved in the 7 first bands (table 1). Due to differences in the definition of the water-leaving signal between MERIS and the two other sensors, a direct comparison of the products from the three sensors was not feasible. However, as the nLw is defined in the same way for MODIS and SeaWiFS, the spectral values from these two sensors were compared directly. The spectral values of the MERIS surface reflectance were also important for identifying variations of optical properties between the selected locations, and for evaluating the atmospheric correction procedure (e.g. whether the retrieved reflectance values in the blue part of the spectrum is positive or not).

3. RESULTS & DISCUSSION

3.1 *In situ* observations

Between February 23 and 29, a massive bloom of *Skeletonema costatum* occurred in Skagerrak. Observed cell concentrations were 6mill./l (*AlgeInfo,* March 19, 2004). This bloom decayed rather quickly and was followed by a moderate bloom of the harmful species

Chattonella during the period of March 8-14. In the last week of March and the early days of April, only low concentrations of algae populations were reported from the *in situ* sampling network along the coast (*AlgeInfo,* April 2, 2004).

3.2 Comparison of chlorophyll a distribution patterns – all sensors

The general quality of the MODIS/Terra products is evaluated by comparison with the equivalent products from the other ocean colour sensors (Fig. 2). Two main features are seen when performing the comparison. Firstly, the number of processed pixels in the MODIS/Terra images are for certain scenes significantly less than for the other sensors. This causes in some cases a total absence of the chlorophyll product, even for regions where the same product is properly retrieved by the other sensors. The reason for this is not clear, however the threshold for allowing data to be flagged accepted may be set too low. The quality of the raw and calibrated data should be further inspected. However, for some scenes (Fig. 2a and c) the reason may be that the study area is very close to the outer parts of the sensor swath (Fig. 2d). The parameter settings used to run the retrieval algorithms might also be different from those used for MODIS/Aqua data, since the algorithm should be the same. Restrictions on the quality of each pixel may also apply to determine whether the pixel is processed or not. These restrictions may have been set to be too restrictive for the MODIS/Terra compared to the other sensors, causing the number of processed pixels to be significantly less for MODIS/Terra.

The other main feature observed, is that the retrieved values of chlorophyll concentrations are generally lower than for the other sensors (Fig 2a, b). As this is a purely relative inter-comparison of the different sensors, we cannot say what are the true values of retrieval. However, as the MERIS, SeaWiFS and MODIS/Aqua are seen to agree very well, the low values retrieved by MODIS/Terra seems suspicious. Furthermore, some of the MODIS/Terra scenes are contaminated by stripes. The same problem is sometimes observed also for MODIS/Aqua. This phenomenon may come from the radiometric performance of the sensor and accordingly not due to the data processing.

To determine the causes for the discrepancy between results from the MODIS/Terra and the other sensors, a more detailed analysis is still required. We suggest that this analysis would include an inspection of the quality of the raw MODIS/Terra data, i.e. the radiometric performance of the sensor, and a revision of the procedures for calibration of the sensor. In the data processing chain from the raw calibrated data to the ocean products, discrepancies between sensors may occur if the atmospheric correction schemes are different. The MODIS/Aqua and MODIS/Terra data should be subject to identical algorithms for retrieval of the chlorophyll product. However, the observed discrepancies may be caused by different parameter settings and thresholds etc. are used for running the retrieval algorithm.

3.3 Comparison of chlorophyll a distribution patterns –MODIS/Aqua, MERIS, and SeaWiFS sensors

A set of images from the three EO sensors MODIS/Aqua, MERIS, and SeaWiFS is presented for three dates (Fig. 2) as they illustrate the main features observed when comparing the data from all 13 dates. The selected images represent different stages of the phytoplankton bloom events that took place during this period. In the images from February 23 (Fig. 3 –row 1), the main chlorophyll distribution pattern looks similar for all sensors. The algae bloom along the Norwegian Skagerrak coast (Sørlandskysten) can be seen. High concentrations are also present in Kattegat between Denmark and Sweden. MERIS shows slightly higher concentrations along the Norwegian coast than the two other sensors. Also, the chlorophyll *a* concentrations retrieved by MERIS in central Skagerrak is around 2mgm^{-3} which is twice as high as values retrieved by MODIS/Aqua and SeaWiFS.

For the same dates, the frequency distribution of the retrieved chlorophyll *a* concentration from all sensors is shown (Fig. 4). Due to differences in swath and cloud cover contamination between images from the three sensors, only data from selected sub-regions of the original images (Fig. 3) were used for estimating the frequency distribution. The frequency distribution of chlorophyll *a* concentrations shows that on February 23 the number of pixels that retrieve values between 0 and 1mgm^{-3} is 4-5 times lower for MERIS than for MODIS/Aqua and SeaWiFS (Fig. 4a). Furthermore the number of pixels that retrieve values between 4 and 8mgm^{-3} is 2-5 times higher for MERIS than for the other sensors. This is mainly because of the higher values retrieved off western Jutland in the MERIS data. However, a very good agreement between SeaWiFS and MODIS/Aqua sensors is observed. The MODIS/Aqua image is contaminated by stripes that most probably are originated by failure in the sensor's radiometric response, and not the data processing.

For March 9, the agreement between MODIS/Aqua and SeaWiFS are still very good, while MERIS shows generally lower values along the Norwegian Skagerrak coast (Figs. 3 - row 2 and 4b). Both MODIS/Aqua and SeaWiFS retrieve high pigment concentrations in central Skagerrak. Whether these observations are consistent with the *in situ* observed blooms of *Chattonella* for the same time period is uncertain, due to the lack of offshore field observations. For this date the MERIS Case 2 water flags indicated the presence of Case 2 waters in large parts of the area. Using the MERIS Algal 2 product, which should be more adequate for this type of water, improved the agreement between MERIS and the other sensors for some areas. As already indicated this study intends not to evaluate Case 2 water algorithms for the different sensors. Such an evaluation is however needed. Images from April 1 (Figs. 3 – row 3 and 4c) show generally good agreement between all three sensors. However, due to atmospheric correction contamination around the southern part of Norway, the number of unprocessed pixels for MERIS and SeaWiFS are rather high. Increased levels of chlorophyll *a* are again observed along the Norwegian coast east of Lindesnes (Skagerrak Coast).

3.4 Comparison of larger homogeneous areas

The consistency between standard chlorophyll-*a* products for all sensors have been evaluated by comparing averaged data from manually selected homogeneous areas, as described above. The retrieved chlorophyll *a* concentrations ranged from 0.1 to 12mgm^{-3}. Scatter plots of averaged values of chlorophyll *a* concentrations derived from pairs of the three sensors are shown (Fig. 5), as well as the coefficients of determination, r^2, between data retrieved by pairs of the three sensors (Table 2). The correlation is shown for the entire concentration range, as well as for respectively high (Chlorophyll *a* >2mgm^{-3}) and low (Chlorophyll *a* <2mgm^{-3}) concentrations. These ranges are assumed to represent bloom and non-bloom areas respectively. The agreement between MODIS/Aqua and SeaWiFS sensors is very good (r^2=0.99) with no distinct difference between low and high concentration ranges. The coefficients of determination between MERIS and MODIS/Aqua (r^2=0.92), and between MERIS and SeaWiFS (r^2=0.93) are slightly lower, however still acceptable. The difference between MERIS and the other sensors are most significant in the higher chlorophyll range. However, there is no trend in these data that shows a relative systematic over or under estimation of chlorophyll in SeaWiFS and MODIS/Aqua data as compared to MERIS.

The fact that the best correlation is found for MODIS/Aqua and SeaWiFS can be explained by several reasons. The algorithms for atmospheric correction and for the retrieval of chlorophyll *a* concentration are both similar for the two sensors, i.e. the algorithms originally designed for SeaWiFS have only been modified to handle the MODIS band specifications. Also, the typical time gap between overpass of the MODIS/Aqua and SeaWiFS sensors are less than between MERIS and the other two sensors. The maximum observed time span between MODIS/Aqua and SeaWiFS was 1.5h, while it was 2.8h between MODIS/Aqua and MERIS, and 3.5h between MERIS and SeaWiFS. A natural change in the measured parameters could take place in between the overpass of the different satellites. This change will of course be expected to increase with the time difference and the diurnal variation.

Table 2: The coefficient of determination, r^2, for the data presented in Figs 4 and 5 are shown. For the large homogeneous areas correlation is shown for the entire data range (0-12mgm^{-3}), for the low concentration range (0-2mgm^{-3}) and high concentration range (2-12mgm^{-3}). For the fixed locations correlation is shown for datasets with and without the inclusion of data from inner Skagerrak (#7).

	Large homogenous areas			Small fixed areas	
Sensors compared	All	Low	High	#1-7	#1-6
MERIS-MODIS/Aqua	0.92	0.91	0.75	0.60	0.76
MERIS-SeaWiFS	0.93	0.88	0.81	0.15	0.44
MODIS/Aqua–SeaWiFS	0.99	0.97	0.98	0.82	0.91

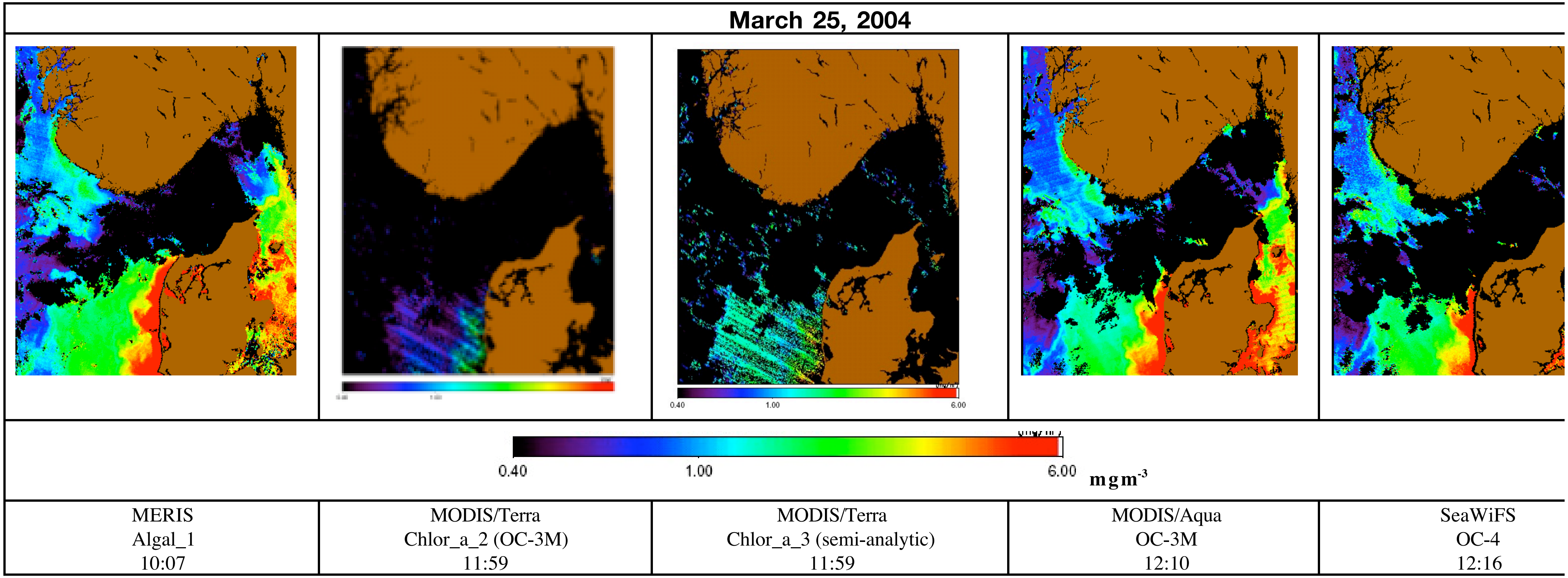
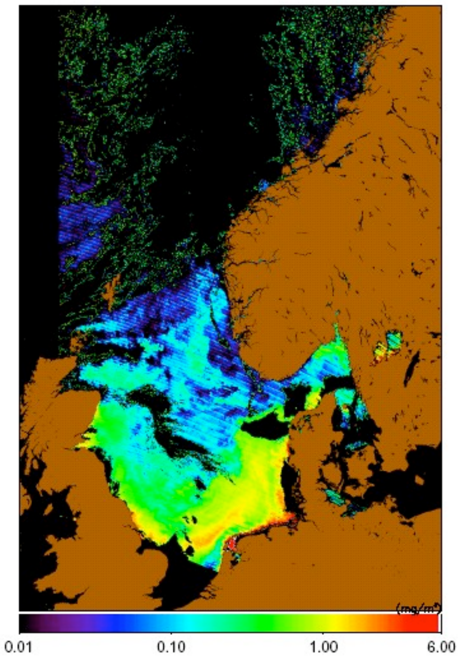
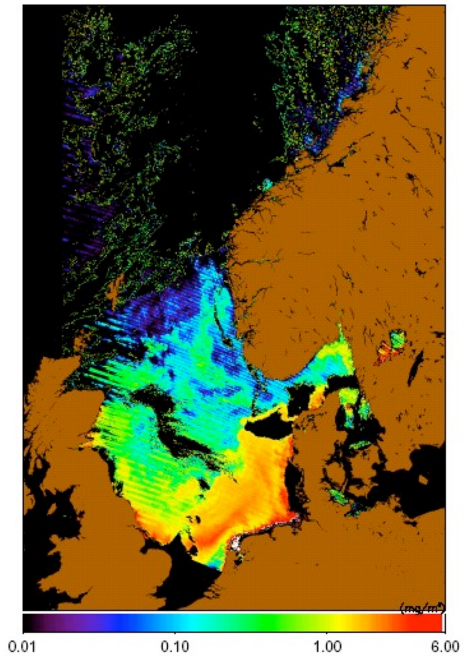


Fig. 2a: Distribution of chlorophyll in the North Sea/ Skagerrak region on March 25, 2004 as retrieved by the MERIS, MODIS/Terra, MODIS/Aqua, and SeaWiFS sensors. The satellite overpass time is indicated (UTC time). The name of the products and/or the name of the algorithms are given. For MODIS/Terra products resulting from two different retrieval algorithms are shown.

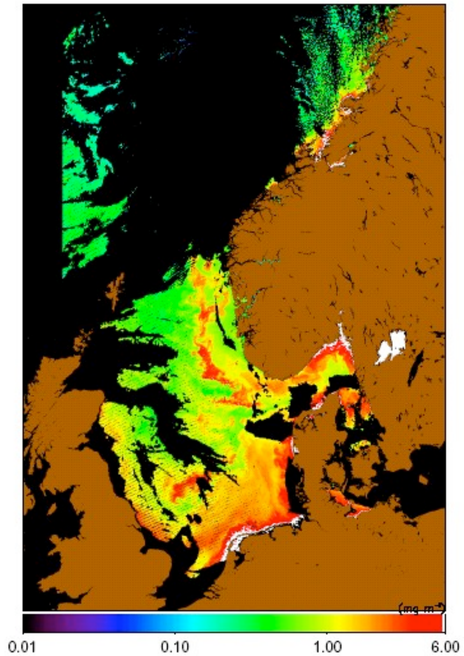
March 29, 2004



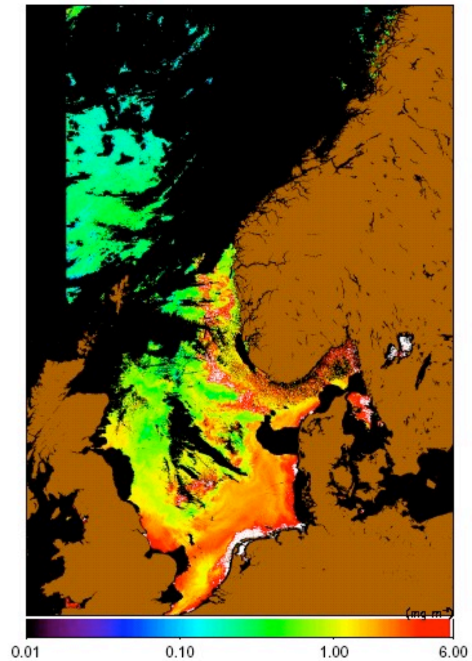
MODIS/Terra
Chlor_a_2 (OC-3M)
11:35



MODIS/Terra
Chlor_a_3 (semi-analytic)
11:35



MODIS/Aqua
OC-3M
11:45



SeaWiFS
OC-4
13:21

Fig. 2b: Distribution of chlorophyll in the North Sea/ Skagerrak region on March 29, 2004 as retrieved by the MODIS/Terra, MODIS/Aqua, and SeaWiFS sensors. The satellite overpass time is indicated (UTC time). The name of the products and/or the name of the algorithms are given. For MODIS/Terra products resulting from two different retrieval algorithms are shown.

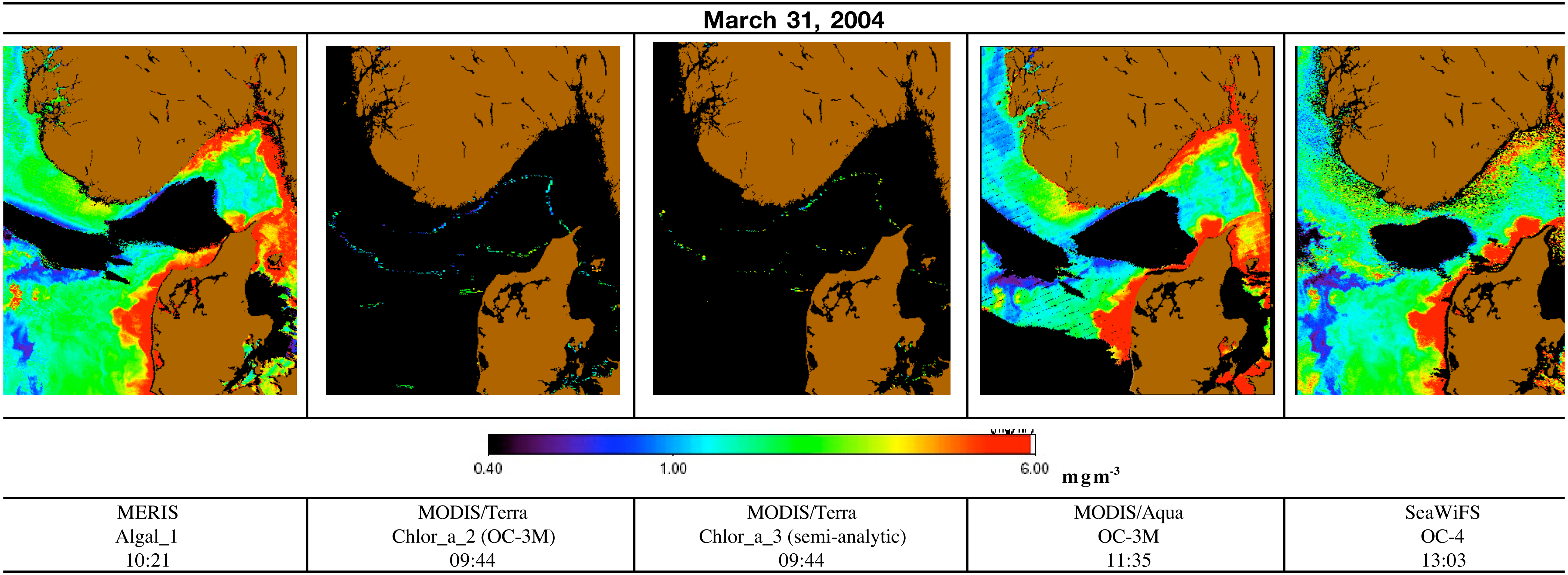
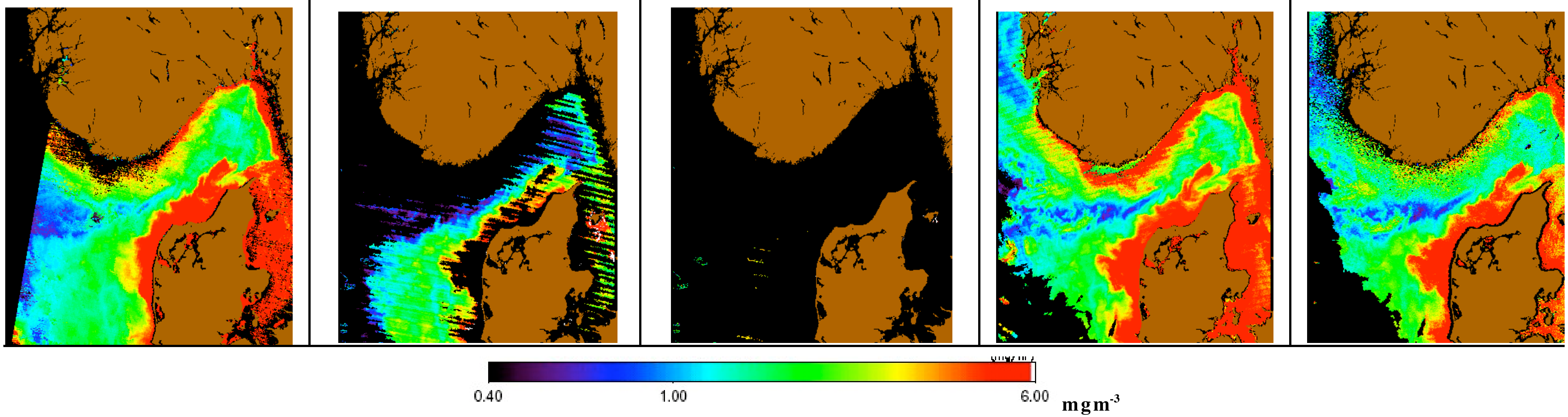


Fig. 2c: Distribution of chlorophyll in the North Sea/ Skagerrak region on March 31, 2004 as retrieved by the MERIS, MODIS/Terra, MODIS/Aqua, and SeaWiFS sensors. The satellite overpass time is indicated (UTC time). The name of the products and/or the name of the algorithms are given. For MODIS/Terra products resulting from two different retrieval algorithms are shown.

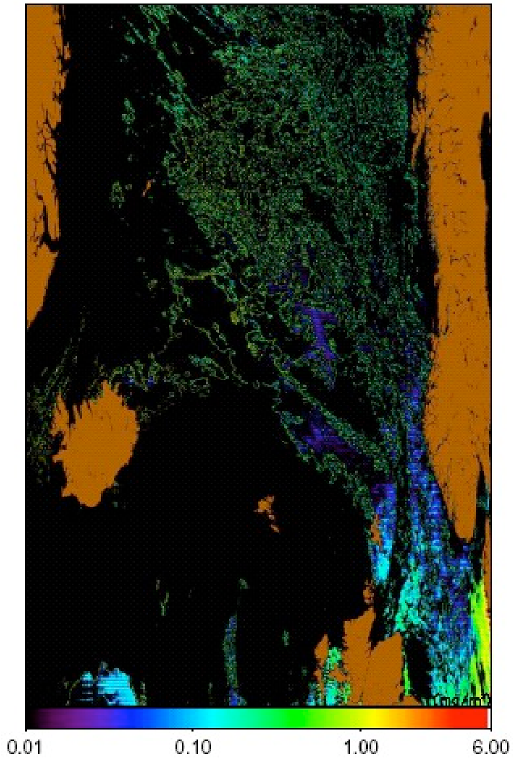
April 1, 2004



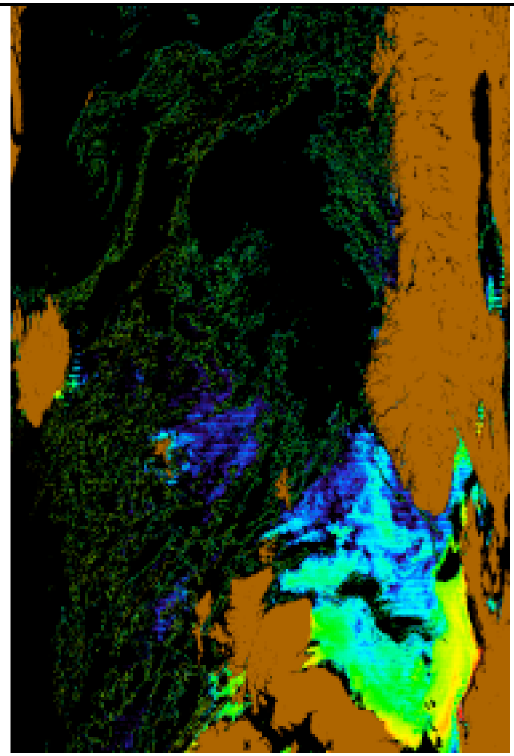
MERIS	MODIS/Terra	MODIS/Terra	MODIS/Aqua	SeaWiFS
Algal_1	Chlor_a_2 (OC-3M)	Chlor_a_3 (semi-analytic)	OC-3M	OC-4
09:52	10:29	10:29	12:15	12:05

Fig. 2d: Distribution of chlorophyll in the North Sea/ Skagerrak region on April 1, 2004 as retrieved by the MERIS, MODIS/Terra, MODIS/Aqua, and SeaWiFS sensors. The satellite overpass time is indicated (UTC time). The name of the products and/or the name of the algorithms are given. For MODIS/Terra products resulting from two different retrieval algorithms are shown.

MODIS/Terra Chlor_a_2 product



March 25, 2004



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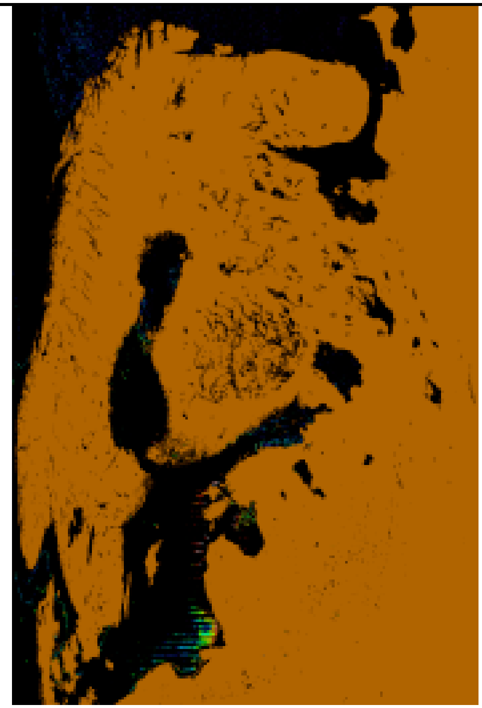
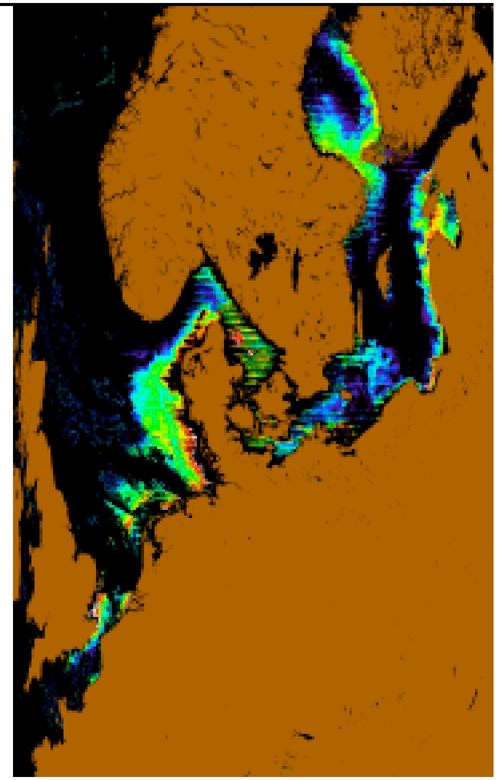


March 31, 2004



April 1, 2004

Fig. 2e: Distribution of chlorophyll in the North Sea/ Skagerrak region as retrieved by the MODIS/Terra sensor. The images show the un-projected scenes for the four dates available for this study.

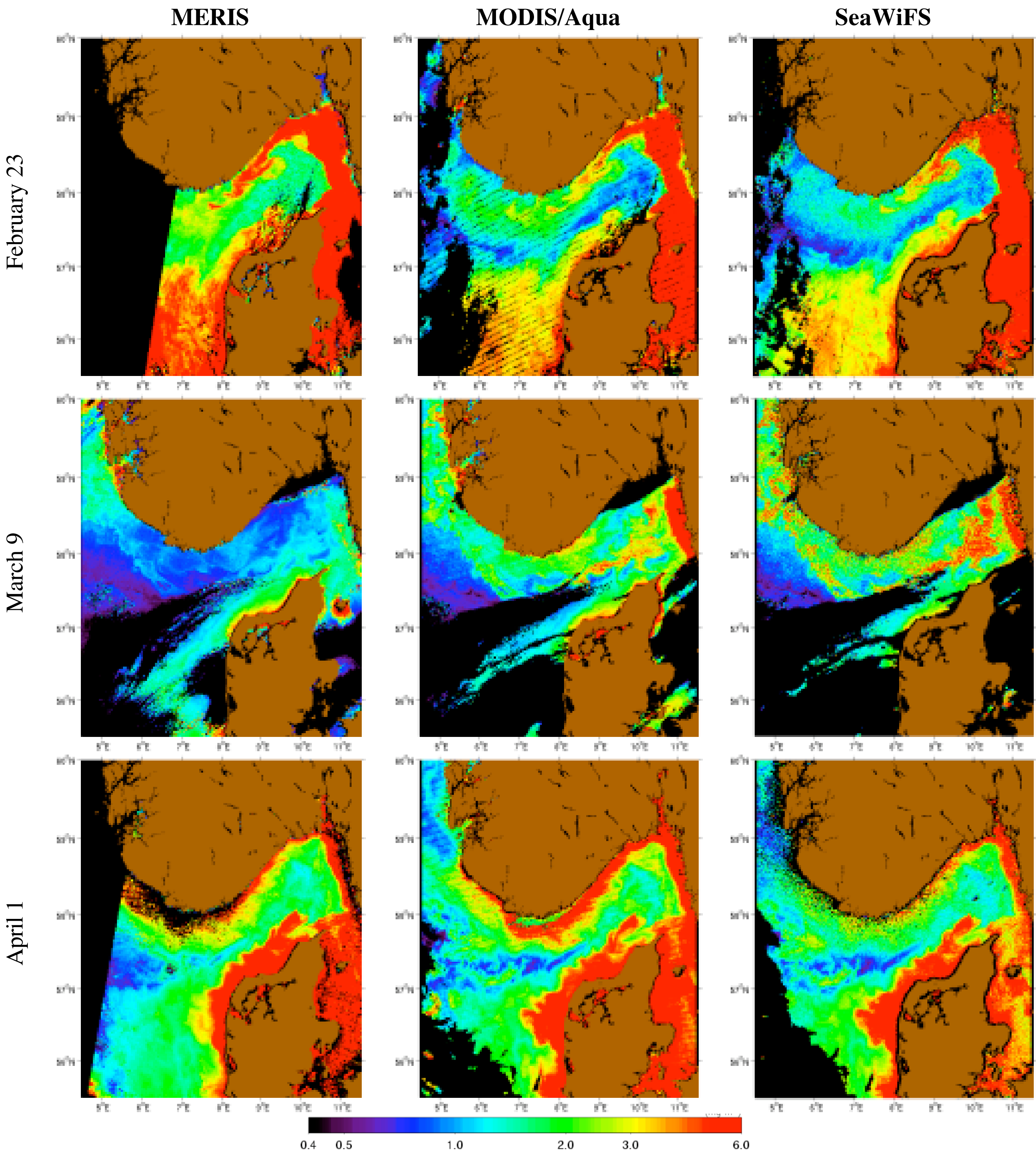
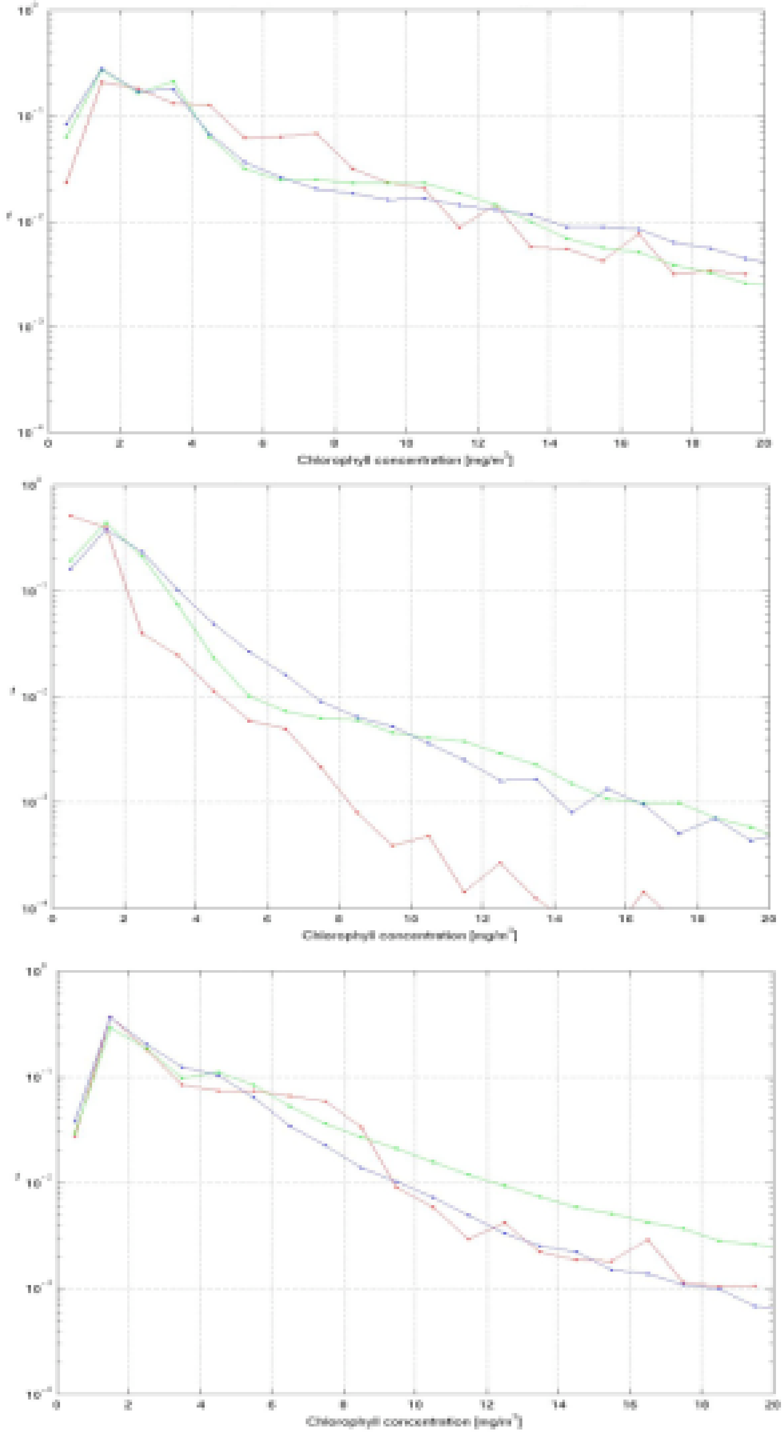


Figure 3: Chlorophyll distribution in North Sea and Skagerrak region as retrieved by the MERIS, MODIS/Aqua, and SeaWiFS (from left to right) for February 23, March 9 and April 1, 2004 (from top to bottom). Black areas indicate unprocessed pixels (clouds, corrupt atmospheric correction, or out of swath areas). Data are plotted with the same logarithmic colour scale, as indicated by the colour bar. The unit is mgm^{-3}. Copyright: ESA/NASA/Orbimage..



(a)

(b)

(c)

Figure 4: Frequency distribution of levels of retrieved chlorophyll a concentrations in sub-regions of the images shown in Fig. 3. The sub-regions are specified in the text. Results are shown for MERIS (red line), MODIS/Aqua (green line) and SeaWiFS (blue line), from February 23 (a), March 9 (b) and April 1 (c). The chlorophyll a concentration is represented along the x-axis. The bin size is 1mgm^{-3}, and the number of bins is 20, representing the concentration range 0-20mgm^{-3}. The y-axis represents the fraction, f, of the number of pixels within each bin, n_b, to the total number of pixels in the image, n_{tot}, i.e. $f=n_b/n_{tot}$.

3.5 Comparison of variability at fixed locations

The average chlorophyll *a* concentration at the seven fixed locations (Fig. 1) mapped by the three sensors were compared (Fig 6, Table 2). The higher correlation was found between the MODIS/Aqua and SeaWiFS sensors, where the coefficient of determination, r^2=0.82. The correlation between MERIS and MODIS/Aqua was rather low (r^2=0.60). No significant correlation was found between MERIS and SeaWiFS (r^2=0.15). However, it was observed that the data discrepancies were mainly caused by results from 2-3 of the selected locations. Especially the data from inner Skagerrak (#7) showed no clear correlation between any of the sensors. Furthermore, locations in North Sea water and in Central Skagerrak (#1 and 6) also showed to lower the overall correlation. By excluding data from inner Skagerrak, the correlation between the sensors improved significantly (Table 2).

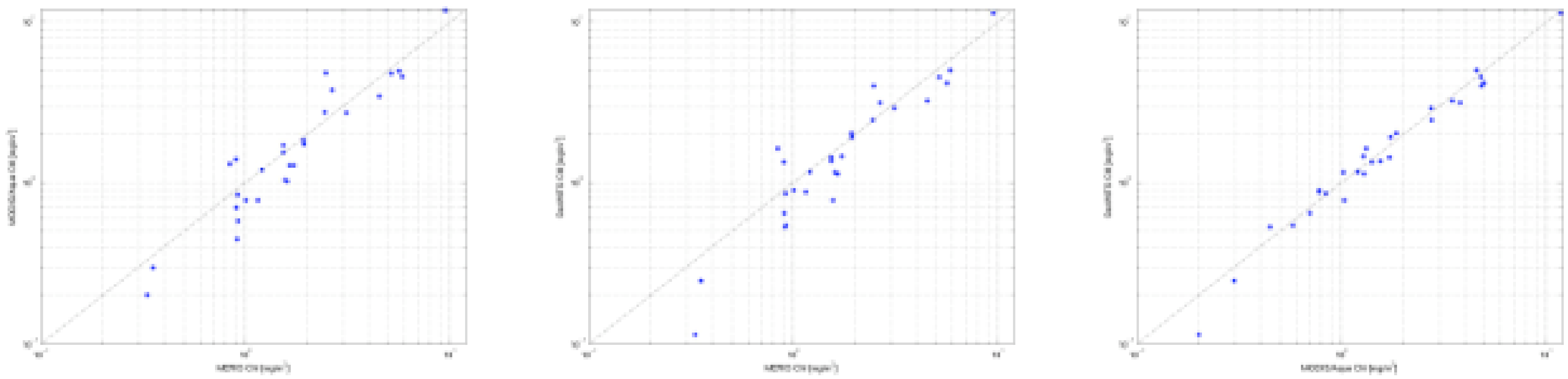
The MERIS Case 2 water flags were used to determine whether the locations for sensor inter-comparison were Case 1 or Case 2 waters. The validity of the algorithms used for retrieval of the standard chlorophyll products is limited to Case 1 waters. The correlation between the sensors was therefore estimated for data from Case 1 water locations only. However, the results showed no significant improvement in the correlation when the analysis was restricted to Case 1 waters only.

There are several factors that could explain why the agreement between the sensors was not as good for the fixed stations as for the individually selected homogeneous areas. First of all the number of averaged pixels were much higher for the homogeneous areas, and high variations between neighbouring pixels would then be more likely to be removed. Furthermore, as the homogeneous areas were specially selected from image to image, obvious gradients of chlorophyll *a* concentrations were not included in the selected area. Dynamic effects that could cause natural differences would thereby be reduced. Such effects could include the moving of high chlorophyll *a* concentration gradients due to hydrodynamics, and changing atmospheric conditions, and could cause high temporal variability for small areas, especially on a time scale of 2-3 hours, as is the typical maximum time difference between the three satellite overpasses.

3.6 Evaluation and comparison of the atmospheric correction

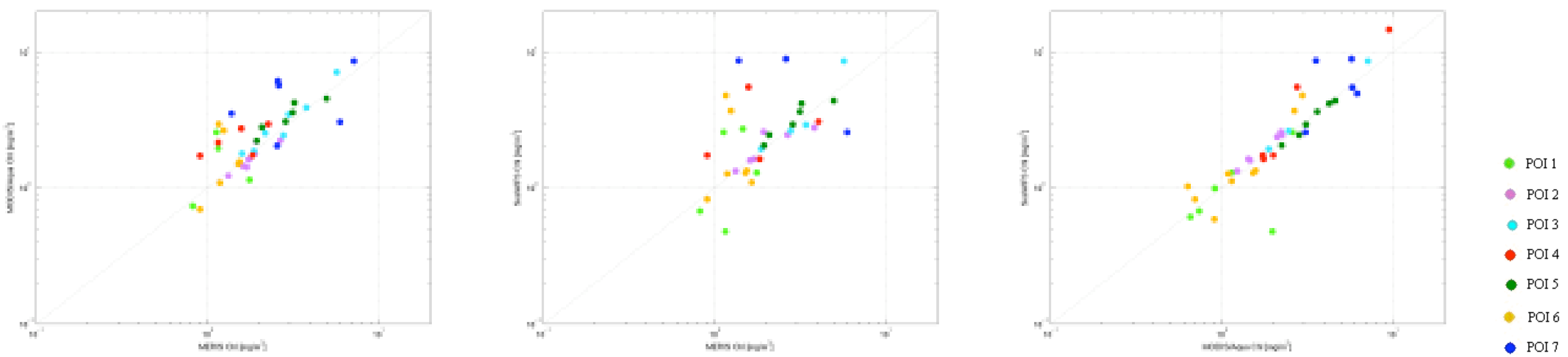
The spectra of the water-leaving optical signal were analyzed for seven locations. The physical conditions ranged from near-shore highly dynamic water masses to open ocean waters, and the biological conditions ranged from low to high chlorophyll concentrations. As the normalized water-leaving radiance is defined in the same way for MODIS/Aqua and SeaWiFS they could be directly compared. For offshore locations (more than 10 kilometres away from land), the two sensors retrieved almost identical spectra of water-leaving radiance. Only for two locations very close to land along the Norwegian Skagerrak Coast significant differences in the spectra from the two sensors were observed. However, for both MODIS/Aqua and SeaWiFS positive values of water-leaving radiance in the first band (412nm) were retrieved for one of the seven locations only. In contrast, MERIS retrieved positive values of surface reflectance in all bands for six of the seven locations. Negative values in the blue were observed only for one station close to land.

It is a well-known fact that the atmospheric correction scheme for SeaWiFS often leads to an overcorrection in the blue for coastal waters. Since the same scheme is used for the processing of MODIS/Aqua, the fact that the two sensors' spectra shows good agreement (even for negative values) is not surprising. However, the MERIS atmospheric correction looks more robust in the sense that it retrieves meaningful values for almost all conditions. The algorithms for retrieval of chlorophyll *a* concentrations in Case 1 waters are not for any of the sensors directly dependent on the spectral values retrieved in the blue band at 412nm. However, spectra with negative values in the blue indicate questionable atmospheric correction that may include bands used for retrieval of chlorophyll *a* concentrations.



(a) (b) (c)

Figure 5: Scatter plots of averaged chlorophyll values within a total of 30 homogeneous areas selected from 13 images between February 18 and April 1, 2004. Results are shown for MERIS versus MODIS/Aqua (a), MERIS versus SeaWiFS (b), and MODIS/Aqua versus SeaWiFS (c). Number of averaged pixels within the regions varies between 56 and 1950.



(a) (b) (c)

Figure 6: Scatter plots of averaged chlorophyll a concentrations within 5x5 pixel boxes around fixed locations (Fig. 1). Results are shown for MERIS versus MODIS/Aqua (a), MERIS versus SeaWiFS (b), and MODIS/Aqua versus SeaWiFS (c).

4. CONCLUSIONS

The present study has shown that the MODIS/Terra products processed and delivered by Kongsberg Spacetec AS are inconsistent with equivalent products from derived from the other ocean colour satellite EO sensors. The major discrepancy is that a significant larger portion of the MODIS/Terra data remains unprocessed in comparison to the other OC colour data from other sources and/or processed in house at the Nansen Center. Thus, there is a need for further investigations of the causes of these observed discrepancies, and subsequently an improvement of the product delivered from Kongsberg Spacetec. We suspect the discrepancies to be mostly caused by the radiometric performance and the calibration procedure of the MODIS/Terra sensor used by Kongsberg Spacetec. Due to the discrepancies observed between the MODIS/Terra and the other sensors' products, the quality of the present product is not satisfactory for use of the data in an operational system for algae bloom monitoring in Norwegian coastal waters. A further harmonisation with the processing tools and algorithms used in Tromsø should be done using the similar tools being developed and validated by NASA. We suggests that Spacetec undertake parallel processing of MODIS-Terra and -Aqua data as well as SeaWiFS data using their implementation of the software. It should also be considered to use the NASA SeaDAS OC4 software or other operational software implemented and tested by NASA.

Regardless of the poor quality of the MODIS/Terra data, the presented results have shown a generally good consistency between the products from the MERIS, MODIS/Aqua and SeaWiFS sensors. The atmospheric correction scheme has shown to be more robust for MERIS than for the other two sensors, avoiding negative (non physical) values in the blue part of the spectrum. Agreement between the major patterns of chlorophyll distribution as retrieved by the different sensors has been shown. However, some discrepancies between retrieved chlorophyll *a* concentrations have been observed. The discrepancies have been most obvious when comparing values averaged over small areas and become less pronounced when averaging over larger areas. The study shows better agreement between MODIS/Aqua and SeaWiFS, than between MERIS and any of the other two sensors. This is most likely due to the similarity in atmospheric correction scheme and chlorophyll retrieval algorithms that are used for these two sensors, as well as a minimum difference in the overpass time between the two sensors. The present conclusion is restricted to a relative inter-comparison of the three sensors, and does not include any *in situ* validation of the satellite data. Therefore the results could not conclude which of the three sensors retrieves the best results with regards to ground truth data. Such a study requires the use of Case 2 water algorithms for all sensors where such areas are identified. The present study shows how different areas and different methods of comparison influence the correlation between data products from the different sensors. Locations that show a minimum of correlation between sensors will be especially interesting sites for an *in situ* validation of the ocean products.

The main focus of this work has been to evaluate the consistency between the standard chlorophyll products valid for Case 1 waters. This study shows that all sensors evaluated, with the exception of MODIS/Terra, provide the information required for a system for detection and monitoring of harmful algal blooms (HABs). For the system to be functional with a daily updated analysis of the phytoplankton situation, satellite data needs to be available in near real time. For the user it should be transparent whether the satellite data originates from one or another sensor system. In order to obtain such consistency inter-calibration and product assessment between similar EO sensors such as MERIS, SeaWiFS and MODIS are needed to be done on a regular basis throughout the missions life time.

5. REFERENCES

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