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DECIDE FOR NEAR REAL-TIME USE OF OCEAN COLOUR DATA IN MANAGEMENT OF TOXIC ALGAE BLOOMS

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ANALYSIS DOCUMENT

in co-operation with

Centre for Coastal and Marine Sciences-
Plymouth Marine Laboratory
Plymouth, UK

Institute of Marine Research
Bergen, Norway

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ABSTRACT:

The importance of the aquaculture industry is significant for the Norwegian economy and the employment in coastal parts of Norway. The development of the industry over the last decades, placed Norway as the world largest export nation for aquaculture fish species, exporting in 1998 around 390,000 tonnes of farmed fish. The export market is world-wide and fresh fish are flown to e.g., the Japanese market several times per week.

The aquaculture suffers from many challenges in order to maintain profitable activities. Among these challenges are the treats from harmful natural algae blooms (HAB) in the seawater surrounding the aquaculture sites. However, in order to implement efficient mitigation actions an early warning of the harmful algae bloom events are essential. The Norwegian authorities also has important role in the advice and imposing regulations for mitigation strategies, which require first order information about threatening bloom situations.

The main objective of this study is to identify, demonstrate and validate the benefit of using satellite Earth observation information in support of the existing decision making processes for disaster management operations. This project specifically addresses the development and implementation of a pre-operational demonstration towards a sustainable service for harmful algae bloom monitoring and management decision support, related to the *effective management of fisheries/aquaculture, public health, and ecosystem problems related to marine biotoxins and harmful algae*.

In Norway, a national HAB monitoring service, operational during the main bloom season from March to October, has been build up. This ALGEINFO service publishes weekly its information about the algae bloom situation on a non-restricted web-site. During alert bloom situation the information frequency and efforts for monitoring are increased, and an operational co-ordination centre is established for performing analysis of the situation, making decisions and disseminating information to the industry, the public and media.

It appears that the early warning capability of the current monitoring system is limited due to the small number of offshore stations. A more regional approach including EO-derived environmental information may contribute achieving an earlier warning, which is necessary for successful mitigation actions. Potential benefits of including use of EO products is also acknowledged for (a) better integration of the regional dimension of the HAB, and (b) potential improvement of regional co-operation with neighbour countries. The limitations of EO-based monitoring technology such as dependence on cloud-free conditions and inability to sub-surface monitoring is compensated through use with the current *in situ* based monitoring techniques. Furthermore, integration EO product with numerical forecasting model has the potential to improve the quantitative predictions of development and decay of blooms.

These potential benefits can be regarded as sustainable since a number of spaceborne EO sensors are and will be operating during the next five years. It is foreseen that (1) the availability of data from several EO sources will stimulate competition and hopefully low cost in the data supply, as well as the generation of targeted value-added products, (2) improved sensor performances and continuous research on methods and algorithms for the applications of ocean colour data for estimation of the phytoplankton distribution, will contribute to improved future use of EO products in services for HAB monitoring.

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1. Introduction - HAB Monitoring in Norwegian Waters

This section gives an overview of the harmful algae bloom (HAB) monitoring protocol established in Norway, which to a large extent relies upon the operational information system ALGEINFO. The section is a brief summary of the project Requirements document [Pettersson et al., 2000] in which further details are given on the current HAB monitoring activities. Two cases of operational modes are also presented, which correspond to a regular monitoring situation during the algae growth season, and an emergency situation when a HAB has been detected and special monitoring and actions must be evaluated.

1.1 Regular monitoring and dissemination of information – ALGEINFO

Regular monitoring of algae and harmful algae blooms (HABs) is conducted at 27 stations along the coast (Figure 1) with a weekly sampling frequency in the main algae bloom period, from March to October. The observations include species determination and cell counts in surface layer and at the chlorophyll *a* maximum. The data are analysed within one day and aggregated and reported within 3-4 days. The published information is free of charge and available via the ALGEINFO system at a web-site administrated by the Institute of Marine Research (IMR), Bergen, Norway (http://algeinfo.imr.no). This monitoring service is a joint effort by more than seven institutions funded through public and private (aquaculture industry, insurance, etc.) budgets. The main objective of the monitoring program is to provide an early warning of algae blooms that may be a threat to the Norwegian coastal aquaculture industry along the entire coast of Norway, from the Swedish border in the south to the Russian border in the north.

The information at ALGEINFO consists of a map of the observation station locations indicating the situation of HAB species along the coast and a short text for clarification of the general situation and for each of five regions. During identified HAB situations more frequent updating of the public web-site as well as direct contact between management authorities and aquaculture industry in threatened areas are implemented through the contingency plan developed by the Directorate of Fisheries (FD). There are links to useful additional information from the web-site. One such link is to a web-site providing advice on the risk of shellfish toxicity (http://www.snt.no/nytt/blaskjell/).

Algae monitoring - The information on algae species distribution and concentrations (cell counts) reported in ALGEINFO is for all types of phytoplankton species, including potentially harmful algae blooms (HABs). Sampling, identification and quantification of algae are conducted by Norwegian state organisations (Directorate of Fisheries, the Institute of Marine Research, the Norwegian Institute for Water Research, the State Food Control Authority) and a private consultant company (OCEANOR AS). A large portion of the samples are collected at various aquaculture sites and then sent to one of the expert organisations for analysis. Through the experiences gained a network of algae experts has been built up, along the coast of Norway.

Reporting – The regular monitoring (sampling) and the reporting of data at ALGEINFO is conducted weekly from March to October at most of the stations, and every two weeks thereafter until winter, when the probability for the development of algae blooms along the Norwegian coast is negligible. A more frequent observation (three times per week) is done at the IMR station in Flødevigen. In general, it is the responsibility and interest of the aquaculture industry to keep themselves informed of the algae situation reported in ALGEINFO. It is the responsibility of the Directorate of Fisheries of Norway to submit public information in case of identified emergency HAB situations.

Database, web-site and web-site server - All information that are displayed in ALGEINFO, are archived in a database on the host server. This allows information in ALGEINFO to be updated online with the help of a normal Internet browser. Updates are performed by authorised personnel via a protected web page of ALGEINFO. Updating is simple and entails online uploading of new information to the database and some simple intermediate steps which then generates a new updated display of ALGEINFO, provides links to the algae database on the home server and archives the previous data. The authorised personnel responsible for updating information on ALGEINFO thus do not require particular expertise in networking and the Internet. Further, changes made to standard reporting routines e.g. HAB species to be described, are automatically indicated in previously archived sets of information. Links to other pages are also established using a normal web browser. The server is an Apache web server with an SQL database run on a Linux 5.2 computer (Pentium 200). The web-site structure is well suited to both include Earth observation images and give access to information products of public interest.

Figure 1. Excerpt from the home page of ALGEINFO (http://algeinfo.imr.no) from July 1, 1999 showing map with 27 monitoring sites and status of phytoplankton concentration and potential HAB species as symbols and text. Closed circles indicated high algae concentrations.

1.2 Measures during emergency harmful-algae-bloom situations

The Directorate of Fisheries (FD) in Norway has the primary responsibility for public management of harmful algae blooms and providing warning and advice during HABs for the coastal waters of Norwegian interest. The Institute of Marine Research (IMR) is responsible for monitoring the algae situation at the shelf area and in the open-ocean waters. IMR is not the responsible organisation for coastal monitoring of HABs, which is performed directly under the FD, but supports the monitoring and gives expert advice during HAB situations. This role may be in the form of expert identification and evaluation of the possible HABs, initiation of dedicated cruise investigations, modelling of the HAB development and transport, and other supporting actions.

The Directorate of Fisheries has implemented an emergency-response plan with three-levels of action according to the HAB situation. The plan defines operational responses and lines of command and communication (on internal, national and communal levels, and to the marine aquaculture industry, fisheries authorities, the press, etc.), for each level of response. The plan also contains information about internal and external relevant expertise and experts at Norwegian institutions. Below is a summary of the emergency-response plan, as described in the document "Varslinggsplan for Fiskeridirektoratet ved Krisehåndtering i Kystsonen" – "Contingency plan for FD in management of emergency situation in the coastal zone" (2000), published by the Norwegian Directorate of Fisheries (revised annually).

The emergency-response plan with regard to HABs is provided for three algae situations, classified as follows:

1) The *normal* situation without indications of harmful algae blooms – The activities shall provide an overview of the algae situation, so that early warning of potential harmful situations can be made. ALGEINFO is instrumental for this task (see chapter 1.1).
2) The *critical* situation with indications of harmful algae species, but no related significant mortality of farmed fish. The plan shall provide an overview of the situation (distribution, toxicity), and all outgoing information to the press and mass media shall be co-ordinated by the Directorate of Fisheries via a designated *emergency-response group* defined in the plan document. The tasks of the group are to:
    - provide information directly to the regional directors of the Directorate of Fisheries,
    - assess the situation with help of regional directors,
    - arrange necessary field cruises with the coastal research vessels of the FD, R/V Munin, or other vessels to investigate the situation,
    - identify as quickly as possible the algae in question,
    - contact the Institute of Marine Research about possible need for support,
    - if necessary, orient the industry, press and mass media.
3) The *emergency* situation in which toxic harmful algae threaten farmed and wild fish and/or other marine life in combination with a significant mortality of farmed fish – The plan is the same as for the *critical* situation, above, with the following additional measures:
    - data on species specific harmful effects to farmed fish, wild fish and other organisms shall be collected,
    - the need to supplement the *emergency-response group* with additional expertise shall be evaluated and implemented as necessary. A list of contact persons and organisations for this purpose exists, which also includes external expertise in EO applications (i.e., The Nansen Environmental and Remote Sensing Center),
    - a command headquarter shall be set up at FD to emergency-related activities.

Following *critical* and *emergency* situations, the level of severity is officially declassified to *normal* when harmful algae have retreated or disappeared, and there are no indications for the development of new blooms. In this case the emergency-response group shall notify all partners and affected parties about the declassification of the HAB situation. The group shall also summarise damage and evaluate the handling of the situation.

In the past, the Institute of Marine Research has been commissioned by the Directorate of Fisheries to undertake field investigations to fulfil the tasks demanded by the emergency-response plan at all levels. IMR's activities in this respect have included redirecting research vessels to the HAB area, sampling of environmental variables, identification of the algal species, mapping the distribution of the HABs, recording damage to fish and other marine life and forecasting the development and distribution of the HAB using numerical models. The 3-dimensional biogeochemical numerical model, NORWECOM, is typically run in real time during critical and emergency situations and the model results are used to forecast the development and distribution of the HAB.

The role of ALGEINFO with respect to the distribution of information is instrumental, as described above. It is particularly noteworthy that in an emergency situation, ALGEINFO can represent a hub for the rapid dissemination of support-related information. For example, forecasting of HAB development may be graphically illustrated and made available to the public and/or authorities via a link to separate web-site or web page at IMR. Further, EO data in the form of graphic and numerical presentations of actual bloom distribution can also be made available by internet link to a source of value-added EO-information products currently being developed at the DeciDe-HAB project web-site.

2. EO capabilities for algae bloom monitoring

The goal of the HAB actions is *effective management of fisheries/aquaculture, public health, and ecosystem problems related to harmful algae*, including specific tasks such as:

1. Improvement of *in situ* sampling strategy.
2. Development of early warning and forecasting capabilities for the occurrence and impacts of harmful marine algae blooms.
3. Development of management and mitigation strategies to minimise the impacts of harmful algae.
4. Provision for rapid response to toxic and otherwise harmful marine algae blooms.
5. Identification and improvement of access to databases for bloom incidence, toxin occurrence in shellfish, mass mortality events, and epidemiology.

Earth Observation (EO) data have already proved valuable for early warning of some categories of algae blooms, and through use of information on front and gradients, a more efficient field sampling strategy can be implemented (task 1). A remote sensing system designed to monitor and track the formation and decay of HABs may improve an eventual forecast capability (task 2) that is necessary to the development of management and mitigation strategies (task 3) for rapid response to algal blooms (task 4). In addition, routine monitoring data required for a forecast system would provide a database containing information concerning the type, location, frequency, and duration of HABs. These data would support studies on the impacts of HAB on the fisheries/aquaculture industries, on public health, and for basic algae and oceanographic research (task 5). Information to be displayed through the World Wide Web which would allow the authorities, aquaculture industry, coastal managers, research community, educators, and the general public easy accessible updates of the most resent available information.

In order improve the HAB monitoring efforts to increase the knowledge of the temporal and spatial distribution of blooms and front zones, remotely sensed imagery is an important source of frequent, synoptic information of the surface layer conditions. Near real-time (NRT) extraction of this information may be put to practical use in monitoring procedures of algae blooms and other oceanographic processes. In this respect EO techniques are identified to support the current command chain through:

- detection and monitoring of the distribution of photosynthetic pigment concentration, which is an estimate of phytoplankton biomass, using time-series ocean colour EO data sources;
- detection and monitoring of ocean fronts through use of sea-surface temperature (SST) imageries;
- contribute to an earlier warning of algae blooms (harmful or not) and to the understanding of the factors that influence the start of a bloom;
- identify, to a <u>very</u> limited extent, the phytoplankton categories, e.g., discrimination of coccolithophorid blooms (not harmful).

Although multi-spectral Earth observation sensors can be used to detect the optical characteristics of chlorophyll *a* and other pigments that characterise algae, efforts have been constrained by the limited ability of the present sensors to discriminate phytoplankton populations at the species level. This is, of course, a fundamental requirement of a HAB monitoring program [Anderson *et al.*, 1995]. However, integrated use of EO with other sources of information on HAB species and their exact concentration will increase the value of the complementary information sources.

Due to the limited level of own motion of phytoplankton, most blooms are advected with the water masses. The main progress has been made first linking specific water masses a bloom event, and then identifying and tracking that water mass with an appropriate remote sensing technique. In particular, remotely sensed sea surface temperatures (SST) have been used to follow the movement of fronts, currents, water masses or other physical features where HAB species accumulate. Pettersson *et al.* [1992] used SST data (Figure 2) from the NOAA AVHRR weather satellite to monitor the advection of the harmful *Chrysochromulina polylepis* bloom in the waters of southern Norway, in 1988 [Dunadas *et al*, 1989].

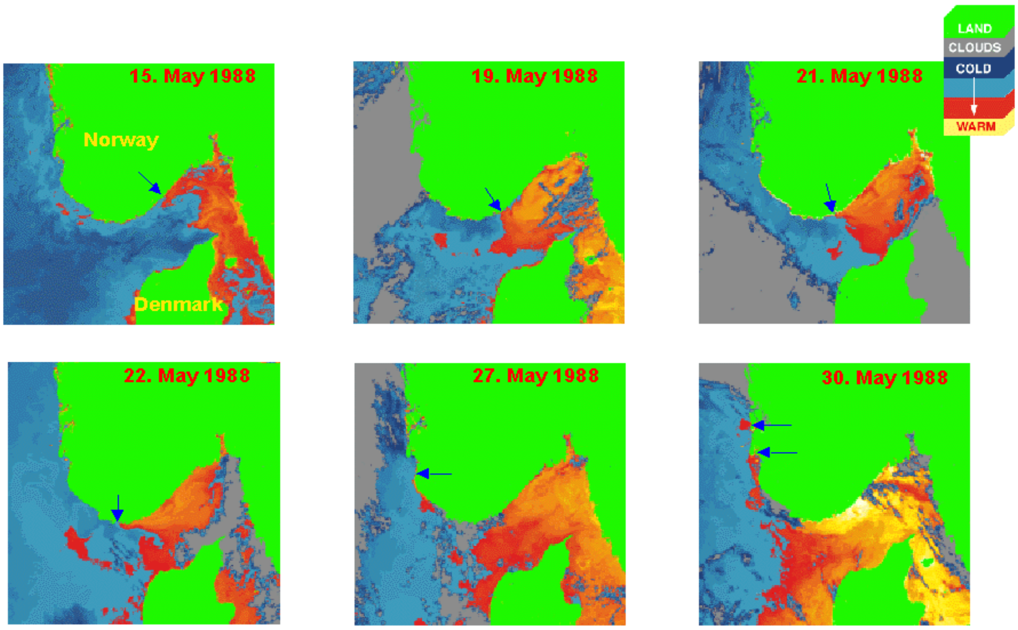


Figure 2. Time series of the AVHRR thermal infrared images during the toxic bloom of Chrysochromulina polylepis in Norwegian waters during May, 1988. During this event, the advection of the warm coastal water from the Skagerrak basin turned out to be coherent. The arrows indicate the position of the warm water-front [Pettersson et al., 1992].

Kahru *et al* [1994] used AVHRR imagery of the Baltic to compare the total annual coverage from 1982 to 1993 and concluded that there had been an increase in abundance over time. Figure 3 shows a *cyanobacteria* bloom in the Baltic, 1 August 1999, using a SeaWiFS Rayleigh corrected colour composite (the 670, 510 and 412 nm bands as red, green and blue) and AVHRR rayleigh corrected visible (580-680 nm) band image. Similar types of EO data are also available from the ERS ATSR sensor, which has been in operation on two satellites since 1991 and is scheduled continued on the ENVISAT mission from 2001.

In August 1997 Orbital Sciences Corporation (OSC) launched the OrbView-2 satellite, carrying the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). SeaWiFS was designed to measure ocean colour in eight spectral bands, the spectral variation of water-leaving radiance that can be related to concentrations of phytoplankton pigments, coloured dissolved organic material, and suspended particulate material [Hooker et al., 1992]. NASA funded the instrument development and purchased the right to use SeaWiFS data for academic research. Investigators wishing to use imagery must register with NASA (http://seawifs.gsfc.nasa.gov/SEAWIFS/LICENSE/checklist.html). NASA licenses permit SeaWiFS data to be supplied in 'near-real time' to support oceanographic research cruises and with a two week delay, for all other research users. For commercial and other regular near real-time applications SeaWiFS data are distributed on commercial terms by Orbimage Corp..

a)

b)

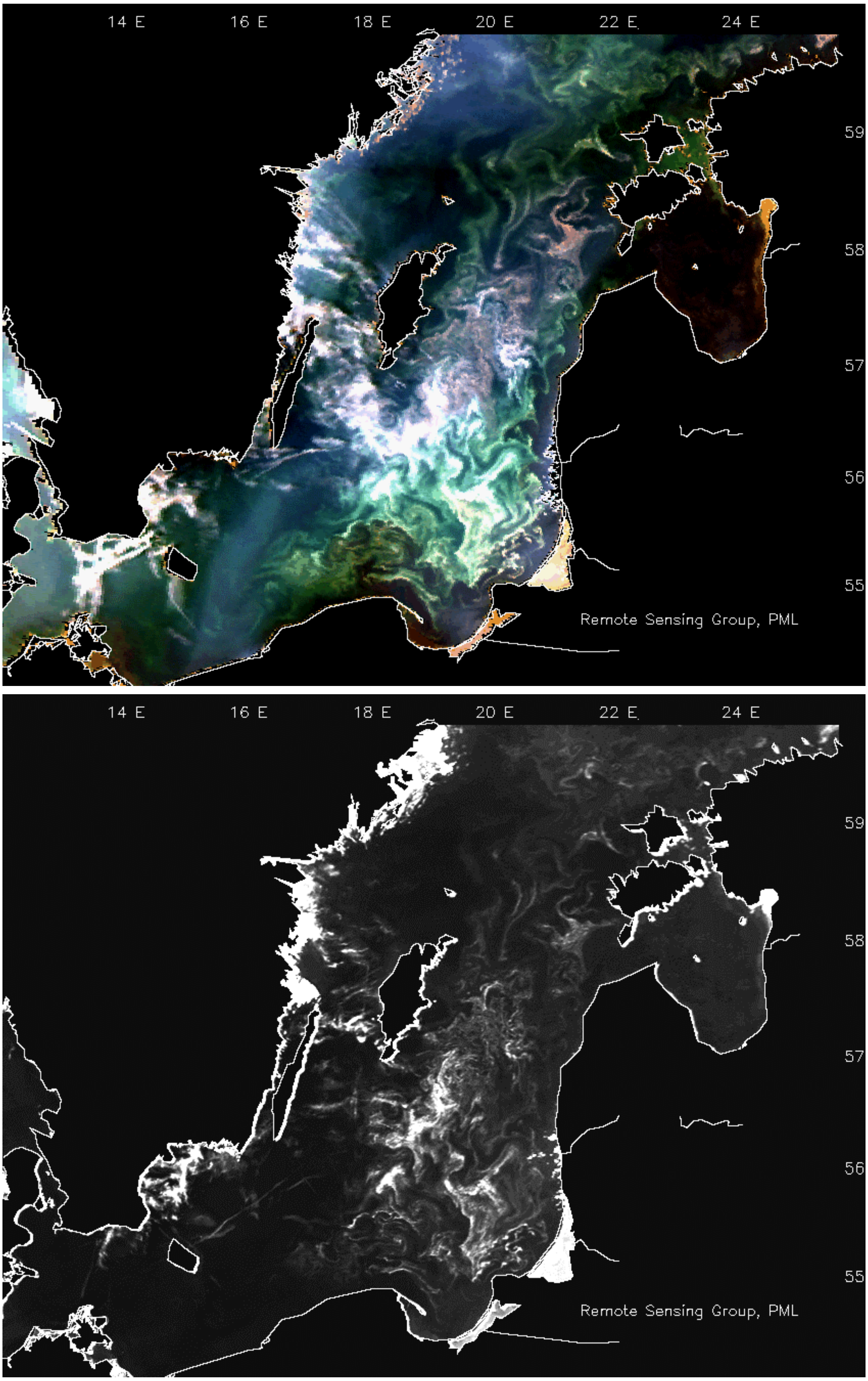


Figure 3. (a) SeaWiFS Rayleigh corrected colour composite (the 670, 510 and 412 nm bands as red, green and blue) and (b) AVHRR Rayleigh corrected visible (580-680 nm) band image for 01 August 1999 showing a cyanobacteria in the eastern Baltic. Imagery processed by CCMS-PML RSG and SeaWiFS imagery copyright of Orbital Imaging Corps and NASA SeaWiFS project.

This type of visual/optical and IR satellite EO sensors covers typically swath widths of some hundred to thousand kilometres. The swath width covered is a trade-off of the spatial resolution of the data, which typically are between some hundred meters to approximately one kilometre. For SeaWiFS the swath width is 2 800 km and the spatial resolution 1.1 kilometre. The orbital repeat coverage of the same location is usually several times per day, but for EO data in the visible spectral range, which are pending on the solar illumination conditions, one or two potential useful orbits per day may be available at high latitudes. Thermal infrared EO data are also applicable during the night passes and typically four passes are acquired per day. These spatial and temporal scales for coverage of information are warranted because oceanographic features that initiate blooms and the blooms themselves occur at such or larger scales.

However, cloud cover and haze prevents use of the optical satellite sensors described so far, to observe the surface of the earth. Hence, the nominal "daily coverage" may in reality become significantly less, in some regions "non-existent", for actual applications, with significant seasonal and geographical variations. However, some algae blooms are associated with strong solar radiation and hence during such periods one may have more favourable atmospheric conditions for this type of EO observation.

2.1 Applications of ocean colour EO data - Chlorophyll and other Pigments

The photosynthetic pigment, chlorophyll *a*, in the phytoplankton cells affects the colour of the water differently than for pure water. Ocean colour EO instruments can detect these colour changes from their orbit in space. However, deriving chlorophyll concentration is not a straight-forward problem, and requires complex atmospheric correction algorithms, particularly in order to satisfactorily retrieve the water-leaving signal, which only accounts for about 10% of the total signal reaching the satellite sensor. Moreover, determination of the phytoplankton species and the eventual harmful species requires analysis of water samples in the laboratory.

According to the requirements to HAB information the most relevant EO information is related to the so-called "water quality" parameters. This includes information on the physical, biological, ecological and partly chemical conditions of the oceans (Table 1). These so-called "water quality" parameters are usually derived via intermediate parameters, which are directly measured by the ocean-colour remote sensing instruments. Models and other *a priori* information are needed to derive the water quality parameter. The basic technical terms for some of the key ocean optical parameters (used in Table 1) includes:

a, b, c	are the coefficients of absorption, scattering and attenuation of light by bulk water
K_d	is the coefficient of down-welling irradiance diffuse attenuation
R	is the water volume reflectance
C_{chl}, C_{sm}, C_y	are the concentrations of chlorophyll, suspended minerals and coloured dissolved organic matter (yellow substance), respectively
λ_{dom}	water colour in terms of dominant wavelength

Table 1: Basic physical, biological, ecological and chemical parameters observable by satellite earth observation techniques.

Physical parameters	**Intermediate parameter derivable by remote sensing**	**a priori information required**
water transparency	*a, b, c*, K_d	hydro-optical model[(1)] or statistically-significant correlation between an up-welling radiance ratio and K_d
water colour	*R*, colour co-ordinates, dominant wavelength, colour purity	hydro-optical model
photic depth	K_d	hydro-optical model, actual or at least statistically significant (for a given season and weather pattern) vertical profiles of major optically active components
Biological parameters	**Intermediate parameter derivable by remote sensing**	**a priori information required**
Chlorophyllous pigments	a	hydro-optical model
Auxiliary pigments	a	hydro-optical model
Ecological parameters	**Intermediate parameter derivable by remote sensing**	**a priori information required**
Primary production rate	C_{chl}	vertical profiles of major optically active components, area specific primary production model parameters
Phytoplankton diversity	a	hydro-optical model
Chemical parameters	**Intermediate parameter derivable by remote sensing**	**a priori information required**
Suspended sediments	C_{sm}	hydro-optical model
Dissolved organic carbon	C_y	hydro-optical model

(1): hydro-optical model is defined as *a priori* information as it is based on *a priori* knowledge of the inherent and apparent optical properties of the water.

Atmospherically corrected SeaWiFS data provides normalised water-leaving radiance at five key wavelengths in the visible region of the spectrum. These basic measurements are used in the derived products include chlorophyll *a* concentration, as a phytoplankton biomass parameter (Figure 4), the diffuse attenuation coefficient at 490 nanometer (nm), as indicators of water transperancy as well as water reflectance.

Advantages:

SeaWiFS images provide data with a horizontal swath width in the order of 2800 km with spatial ground resolution of 1.1 km; nominal repeat coverage of an area occurs approximately every day at high latitudes (60°).

Limitations:

(a) Useful data are pending on cloud-free conditions to detect the ocean surface signal.

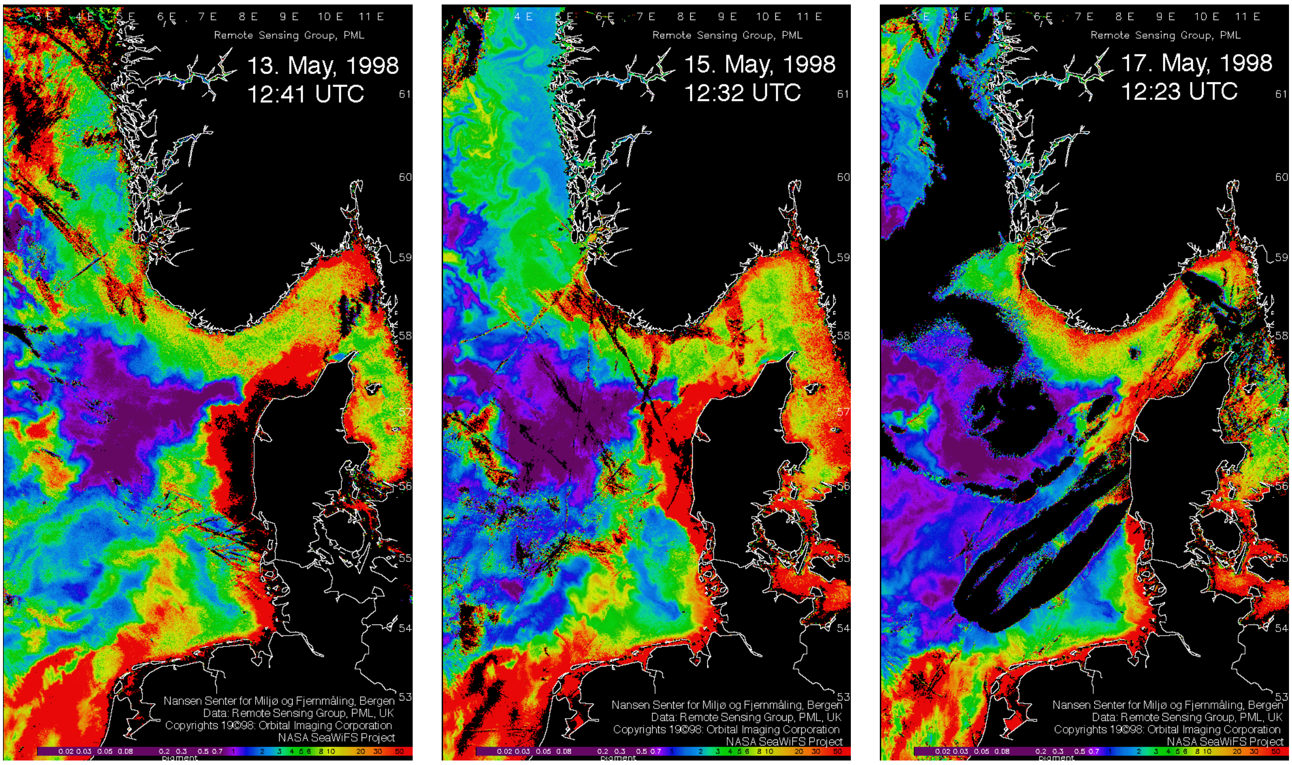
(b) Algorithms to derive phytoplankton pigments from the ocean colour signal are still a field of significant research and improvements in particular in coastal waters for accurate observations.

(c) Spatial resolution (1.1 km) of currently available sensors is too coarse for near coast and fjord observations.

(d) High chlorophyll *a* concentrations do not necessarily indicate a harmful bloom and currently no species-specific algorithm to determine harmful algae blooms from water-leaving radiance has been developed, however identification of Coccolithophorid blooms have been successfully performed [Pettersson *et al.*, 1995].

(e) Only surface layer characteristics are visible to satellite sensors, and deeper sub-surface bloom may be hidden.

(f) Currently, SeaWiFS has a two-week embargo on data availability that limits near-real-time access to data unless commercial prices are paid for the data.



(a) (b) (c)

Figure 4. Chlorophyll pigment concentration product from SeaWiFS over the North Sea and the Skagerrak, on (a) May 13, (b) May 15 and (c) May 17, 1998. © Orbital Imaging Corps and NASA SeaWiFS project. The time series shows the increases and demise of a Chattonella spp. *bloom, along the Danish coast. Blue indicates low pigment; red indicates high pigment. Data courtesy: Remote Sensing Group, Centre for Coastal and Marine Sciences – Plymouth Marine Laboratory.*

2.2 Applications of Infrared EO data - Sea surface temperature

Sea surface temperature (SST) as retrieved from satellite sensors has proved valuable for deriving important indirect information of the movement and possible extent of algae blooms. Such images that exhibit ocean dynamical features such as fronts, main currents, up-welling zones near the shelf-edge, and other large-scale physical oceanographic features, which are related to the initiation and advection of algae blooms. The Advanced Very High Resolution Radiometer (AVHRR) sensor is used to identify physical oceanographic features through the in surface water temperature gradients (Figure 5, left). Other EO sensors are also available that give access to the same type of information, such as ERS-ATSR (Along Track Scanning Radiometer).

The microwave synthetic aperture radar (SAR) EO sensors onboard the ERS and RADARSAT satellites do not have any limitations with respect daylight and cloud cover. These microwave sensors provide information on surface roughness (capillary waves), which under given conditions can be interpreted for information about ocean current fronts, meso-scale circulation patterns, and surface films, including biologically caused natural films (Figure 5, right). Since, these microwave EO sensors do not provide any direct information about algae bloom situation, and their use in this respect is still a topic of scientific research and their applications will not be further elaborated in this project.

Advantages:

AVHRR data processing is highly automated and occurs in near real-time with world wide coverage of stations. Data access occurs at least four times daily and is relatively inexpensive on a subscription basis.

Limitations:

Data are pending on cloud-free conditions. Spatial resolution is 1 km and near-shore data may be questionable due to pixels affected by the signal from land. Provide only indirect information about algae blooms and other sources is needed for the bloom identification and characterisation.

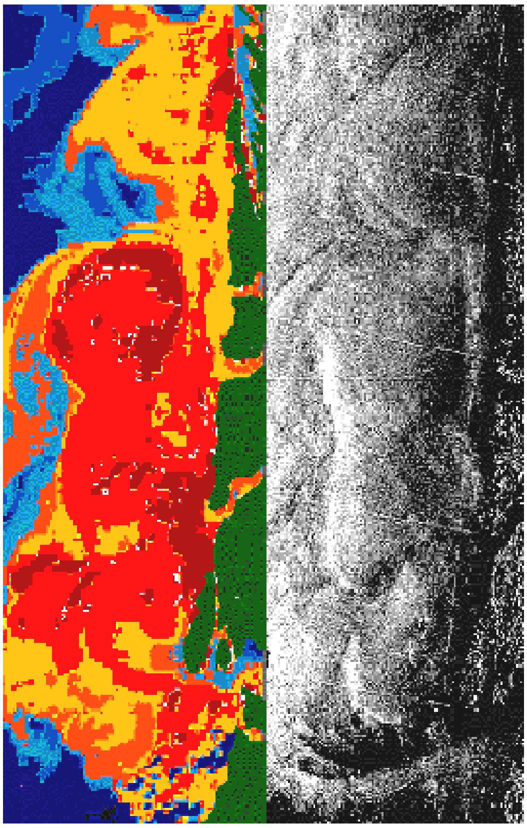


Figure 5. Expression of the Norwegian coastal front on October 3, 1992 in a NOAA-AVHRR image at 14:20 UTC (left) and a ERS-SAR image acquired at 21:35 UTC (right). Both images cover the same 100-km region. © ESA/NERSC.

2.3 EO applications in coupled bio-physical forecasting models

IMR performs model simulations and forecasting of algae bloom spreading and advection during emergency bloom situations, using their "Norwegian Ecological Model (NORWECOM)" tool. Due to insufficient knowledge of the mechanisms that triggers the initiation and development of algae blooms, the current model is not able to predict the initiation of new bloom developments. The forcing and interpretation of the model results is thus strongly dependent on other observations from *in situ* or EO sources to initiate the bloom situation in the model.

Integration of satellite-derived bio-physical parameters, such as sea surface temperature and chlorophyll pigment concentration, with the numerical model is a way to improve its forecasting capability. In particular, a recent study reports that even if NORWECOM was able to qualitatively reproduce the *Chattonella* bloom in 1998 [Lekve, 1998], the quantitative estimates were far from the *in situ* observations of the bloom [Durand *et al.*, 1999b].

Integration of chlorophyll *a* distribution map based on EO and *in situ* information sources, as a biological field after the physical model spin-up could constrain the model with unbiased data, and thus improve the quantification of the model variables. More advanced coupling between EO data and model can be achieved through assimilation scheme, which performs a dynamical and controlled adjustment of the model variable as a function of time [Evensen *et al.*, 1997].

2.4 Validation and Accuracy

Naturally EO derived parameters requires to be validated against *in situ* high-accuracy measurements used by the current service. Practical realisation of this is a scientific challenge, due to the different observation characteristics of the two types of data sources. The various algorithms developed for retrieval of in-water parameters from ocean colour data has been validated. A general summary of the quantitative achievements of EO techniques regarding the geophysical parameters of relevance of HAB monitoring is given in Table 2. The values indicated in the table correspond to the best results expected under favourable observation conditions.

Table 2. Quantitative achievements of state-of-the-art ocean-colour algorithms relevant to use in ALGEINFO. The values reported in the table result of a compilation of various algorithms, and are representative of the best achievement that can be expected for EO [revised from Durand et al.*, 1999a].*

Remotely sensed derived parameters		Algorithms		Satellite / sensor		
	Units	Range of value	Relative/ absolute accuracy	Spatial resolution (km)	Frequency of sampling (days)	Delay* (days)
Water constituents						
C_{chl} [Chl-a]	$mg.m^{-3}$	0.01 - 60	30 - 40 %	1.1	1	NRT
Primary production	$gC.m^{-2}.d^{-1}$	0.5 - 3.0	40 %	1.1	1	NRT
C_{sm}	$mg.l^{-1}$	0.1 - 30	30 - 50 %	1.1	1	NRT
C_y / a_y(380 or 440 nm)	$mgC.m^{-3}$	0.1 - 20	50 %	1.1	1	NRT
Optical properties						
Absorption coef.: a	m^{-1}	all	NS	1.1	1	NRT
Scattering coef.: b	m^{-1}	all	NS	1.1	1	NRT
Diffuse attenuation: K_d	m^{-1}	0- 6.5	0.1	1.1	1	NRT
Turbidity/Secchi depth	m	0.25 - 5.0	50 %	1.1	1	NRT
Surface Temperature						
SST	°C	all	Rel. 0.2°C	1.1	<0.5	NRT

***Delay**: Time delay of availability of products, **NS**: not specified, **NRT**: Near real-time

In the regular ALGEINFO Service, phytoplankton cell counts and algae taxonomy are adopted as suitable parameters for characterisation of (harmful) algae blooms. Both regular and dedicated cruises are carried out under the general IMR monitoring programs, for *in situ* measurements of a number of biogeochemical parameters relevant for HAB monitoring. Sampling and analysis for chlorophyll concentration depth-profiles, phytoplankton cell counts, nutrient concentration, suspended sediment, numeration and identification of algae species are performed both during these cruises and from near shore station locations. The near real-time availability of this information is however limited to some of the parameters. The monitoring cruises are organised along the southern coast of Norway and across the Skagerrak between Norway and Denmark during the bloom period from April to July, each year. The data sets collected during these campaigns will be delivered to NERSC for use in the validation and tuning of EO-derived parameter.

3. Availability of EO sensors for algae monitoring

The longer term sustainability of an Earth Observation relevant to algae monitoring depends on continued future access to ocean colour data of sufficient spectral, temporal and radiometric resolution, and appropriate signal/noise ratio. It further depends upon the terms of access allowed by the satellite operating authorities to a self-funding or commercial system. This section considers option for continued access to the current SeaWiFS and future access to current planned satellite systems most notably the ESA's MERIS (launch, summer 2001) and NASA's MODIS (launched 18. December 1999) instruments.

3.1 Current spaceborne ocean colour sensors

The current spaceborne Ocean Colour Sensors is summarised in Table 3. SeaWiFS is a commercial satellite owned by Orbimage Inc, USA, with access to research usage purchased on behalf of the scientific community by NASA. The German/Indian MOS sensor has a poor repeat cycle, but may complement other more frequent observations. The Japanese Ocean Colour Imager (OCI) was launched into an orbit (±30° Latitude) which does not provide observation over most European waters. The Indian Ocean Colour Monitor (OCM) sensor has no onboard recording and the data are currently only received by the Indian National Remote Sensing Agency at Hyderabad. However, it is envisaged that there will be a global network of international ground stations in the future, which may also provide near real-time data access to users.

Table 3. Current spaceborne ocean colour sensors. Source: http://www.ioccg.org/sensors/500m.html

SENSOR	AGENCY	SATELLITE	LAUNCH DATE	SWATH (km)	RESOL-UTION (m)	NUMBER OF BANDS	SPECTRAL COVERAGE (nm)
MOS	DLR (Germany)	IRS-P3 (India)	21/3/96 -	200	500	18	408-1600
SeaWiFS	NASA (USA)	Orbview-2 (USA)	01/8/97 -	2806	1100	8	402-885
OCI	NEC (Japan)	ROCSAT-1 (Taiwan)	1/99 -	690	825	6	433-12500
OCM	ISRO (India)	IRS-P4 (India)	26/5/99 -	1420	350	8	402-885
MODIS	NASA (USA)	Terra (USA)	18/12/99 -	2330	1000	36	405-14385

3.2 Scheduled Ocean Colour satellite sensors

There are a number of future ocean color sensors planned (see Table 4), however the main consideration for EO data in the algae bloom monitoring system is the near-real time access to the data. In this respect the European MERIS and US MODIS sensors will offer near-real-time data access.

Table 4. Scheduled spaceborne ocean colour sensors. Source: http://www.ioccg.org/sensors/500m.html

SENSOR	AGENCY	SATELLITE	LAUNCH DATE	SWATH (km)	RESOL-UTION (m)	NUMBER OF BANDS	SPECTRAL COVERAGE (nm)
GLI	NASDA (USA)	ADEOS-2 (Japan)	Scheduled June 2000	1600	250/1000	36	375-12500
MERIS	ESA (Europe)	ENVISAT (Europe)	Scheduled Summer 2001	1150	300/1200	15	412-1050
OSMI	KARI (Korea)	KOMPSAT (Korea)	Scheduled Dec. 1999	800	850	6	400-900
POLDER-2	CNES (France)	ADEOS-2 (Japan)	Scheduled June 2000	2400	6000	9	443-910
MODIS-PM	NASA (USA)	EOS-PM1	Scheduled Dec. 2000	2330	1000	36	405-14385
S-GLI	NASDA (USA)	ADEOS-3 (Japan)	Scheduled March 2003	1600	750	11	412-865
OCTS	CNSA (China)	Hai Yang-1 (China)	Scheduled 2001-2003	1400	1100	10	402-12500

3.2.1 Moderate Resolution Imaging Spectrometer (MODIS)

MODIS, the "next generation" optical EO scanner, was launched on NASA's "Terra" (formerly AM-1) spacecraft on December 18, 1999. It is the first MODIS sensors to be launched on NASA Earth Sciences Enterprise satellites including "Aqua", formerly PM-1, in 2000. The dual operation of Terra and Aqua (with descending nodes at 10:30 LST and 14:30 LST) will offer greater opportunities for observing phenomena in cloudy conditions, and possibly short-term temporal variability.

MODIS also provides a number of advantages over SeaWiFS:

- MODIS data will direct broadcast over X-band and can be used freely for any application; the University of Dundee (the current suppliers of SeaWiFS data to DeciDe HAB project) has developed X-band reception capabilities and similar capabilities will be at a number of ESA and non-ESA ground stations world wide.
- Simultaneous observation of ocean colour (visible spectral range), temperature (SST) and atmospheric parameters (36 spectral bands fixed).
- Extensive on-board calibration facilities.

Compared to MERIS, MODIS only has 1-km resolution and is not spectrally programmable; like MERIS it does not tilt away from the sun and so the imagery will be affected by sun glint.

3.2.2 Medium Resolution Imaging Spectrometer (MERIS)

MERIS is due for launch on ESA's Envisat platform during summer 2001. The instrument offers significant advantages over current ocean colour satellites such as SeaWiFS including:

- Spectral bands: MERIS has 15 wavebands that can be programmed in width and location, which means that specific channels can be modified to observe specific phenomena e.g. red tides,

- Spatial resolution: MERIS has two resolutions, 300m regionally (Full Resolution) and 1.2km globally (Reduced Resolution); this will mean that smaller features such as algae blooms in fjords may be detected,
- Radiometric resolution: data are digitised to 16 bits and the S/N ratios are very high (noise equivalent radiance of below 0.033 W m^{-2} sr^{-1} μm^{-1} in the visible and 0.025 in the NIR),
- Calibration: MERIS has a number of on-board calibration mechanisms to measure potential system response degradation and wavelength stability,
- Synergy with other instruments: the Envisat spacecraft will carry a suite of instruments which will enable simultaneous observation of ocean colour, sea-surface temperature, surface elevation and surface roughness. This will enable the ocean colour biological information to be tied more closely to physical structure of the oceans.

A disadvantage of MERIS is that it does not tilt away from the sun and so images will be affected by sun glint, which may affect observation when the area of interest is on the eastern part of the sensor swath.

MERIS data will be accessed via two main routes:

- Pre-operational research requirements are classified at Category 1 and will be supported directly from ESA User Services.
- Operational applications, so-called Category 2, will obtain data through ESA delegated “distribution entities”.

Access to EO data in near-real time is crucial for the algae monitoring service and ESA quote the delivery of Fast Delivery (FD) products at three hours for the low-resolution products; high resolution, including presumably MERIS-FR are processed on request and may take 1-3 days to deliver. Clearly the delivery of FR products in near-real time is a major challenge for the distribution entities, in order to provide services related to HAB monitoring services.

3.2.3 Global Imager (GLI)

GLI will be launched on Japanese ADEOS-2 in 2001 and has the following advantages over SeaWiFS:

- Has more spectral channels: 36 VIS and IR spectral channels, inclusive 15 for ocean colour
- Tilt function to avoid sun glint in middle latitudes
- Spatial resolution of 1km with six channels at 250m spatial resolution (including channels at 460, 545, 660 and 825 nm which could be used for monitoring coastal regions).

Compared to MERIS and MODIS the problems could be access to near-real time products.

4. Summary and Conclusions

Remote sensing information have a valuable function in defining the baseline conditions, against which the impact of HAB can be evaluated. Although measurements from water samples are more accurate and allow deriving more specific parameters, they have their limitations when extrapolated in time and space. The synoptic picture obtained by EO data sources are in this respect unique.

The current algae monitoring system (ALGEINFO) have limited the early warning capabilities. A more regional monitoring approach including EO-derived environmental information may contribute to achieving earlier warning of potential HAB, which is necessary for successful mitigation actions and efficient public control and management during emergency situations.

Potential benefits of including EO based information is identified for:

- Potential earlier warning of algae blooms
- Better integration of the regional dimension of the HAB
- Potential improvement of regional co-operation with neighbour countries, e.g., Sweden and Denmark, by providing regional information.

Furthermore, integration EO product with numerical forecasting model has the potential to improve significantly quantitative predictions of bloom spreading, development and decay.

Combining EO data from similar sensors from different satellites (e.g., SeaWiFS and MODIS) may lead to improved, albeit irregular temporal/sensor sampling. Nonetheless, it is apparent that the present spaceborne sensor systems have spatio-temporal sampling capabilities that are adequate to meet the monitoring requirements for HAB. However, cloud cover is a limiting factor with increasing importance at the high latitudes.

4.1 Reliable detection of algae blooms

The most useful parameter derived from ocean colour sensor is the chlorophyll pigment concentration (CHL) directly related to the intensity of the bloom. Most of the algorithms implemented for the retrieval of chlorophyll concentration are based on empirical models that are tuned for Case I oligotrophic waters, and then not sufficient accurate for coastal waters. These empirical models are based either on world-wide open ocean data sets or local data sets that only representative of a region. Moreover, these algorithms are not robust. Therefore, it is difficult or impossible to predict the accuracy that could be obtained by using one of these models in a different region like the DeciDe-HAB area. However, in the context of HAB monitoring in the Skagerrak and the Norwegian coastal waters, the processing system developed at CCMS/PML [Moore *et al.*, 1999] may be confidently applied, since it has been tuned for the North Sea waters with similar optical properties. In view of the users required accuracy to the distribution of and changes in phytoplankton concentrations, it is envisaged that the state-of-the-art processing algorithms can provide complementary information to the current monitoring activities.

The critical range of chlorophyll concentration is determinable with space sensors. These algorithms overflow when the chlorophyll concentration is greater than about 60 $mg \cdot m^{-3}$, however during such conditions the level of accuracy is not critical since the situation is treated as a high concentration algae bloom.

The presence of other optically active compounds, such as sediments and CDOM, in the water column reduces the reliability of the EO detection algae blooms. However, it is anticipated that use and interpretation of several ocean colour derived products, may help in encompassing this limitation.

Present EO capability may not cover the entire range of possible CHL values in case of algae bloom, and do not give the capability to detect and predict the occurrence of the bloom of a particular algae species. Nevertheless, satellite data is certainly valuable in many cases of blooming conditions. In particular, EO-derived chlorophyll concentration may be adequate for detecting those blooms that are characterised by a rapid and significant increase in phytoplankton biomass. However it is clearly stated that EO and model technology are yet not suitable for monitoring of low concentration highly toxic algae blooms.

The last years have seen the emergence of algorithms for Case II. Solution are mathematically more complex, often more computer-time consuming. Therefore, performance regarding operational applications must be assessed. Most of these new methods are based on inverse techniques, and involve the retrieval of all optically active components simultaneously.

4.2 Early warning

In the present state of the art, EO technology is certainly one of the best candidate to improve early warning capability of some types of algae blooms. As a matter of fact, densifying the *in situ* observation network would increase dramatically the cost of operations, and present knowledge of mechanisms that trigger algae blooms is insufficient to achieve model prediction of bloom initiation.

The main advantage of EO-based information resides on near real-time synoptic view of coastal processes, and on the possibility to get access to daily updated data. However, a major restriction concerns the frequency of availability of this information, due to frequent cloud cover in the Northern Europe.

4.3 Regional monitoring

A third major contribution of EO data in an operational HAB management system concerns the regional transboundary aspects of monitoring of algae blooms.

Physical processes in the coastal waters contribute to the development and advection of biological compound. In particular, meso-processes such as fronts, eddies and coastal currents determine when and where a particular water masses would reach the coast. Therefore, estimates of such parameters are essential to improve the predictability and risk assessment concerning HAB. EO products may help understand and/or visualise the marine physical and biological surface structure at regional scale, and are therefore complementary to high-resolution *in situ* sampling in this respect. This may be used on more representative and cost efficient planning of the *in situ* observation strategy.

Ocean fronts and main waters masses can be detected from the surface temperature (SST) and from ocean colour maps derived from EO sensor data. SST is certainly the most extensively used geophysical parameter from EO sources. Requirements are meet in terms of range of value, accuracy and temporal resolution for applications related to HABs.

4.4 Future perspectives

These benefits can be regarded as sustainable and reliable since a number of satellite EO sensors are and will be operating during the next five years, which can provide operational ocean colour data and redundancy in terms of individual sensor failure. ESA’s MERIS offers possibly the best sensor system in terms of flexibility and capability for improved HAB monitoring, however near-real-time access to data may be a limiting factor. The NASA MODIS system provides unencrypted X-band direct broadcast data and will stimulate competition and hopefully low cost in the data supply, and stimulate the generation of useful value-added information products.

Improved sensor performances and innovative research on the methods/algorithms for the applications of ocean colour data for estimation of the phytoplankton distribution will contribute to improved future use of ocean colour information products in services for HAB monitoring.

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