Satellite observations and model simulations of harmful algae blooms in coastal waters

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Resumo

Após a proliferação da alga tóxica ("harmful algal bloom" – HAB) "Chrysochromulina polylepis" na costa Sul da Noruega, em 1988, foi iniciado um programa nacional de monitorização do desenvolvimento das algas. O seu objectivo é fornecer as informações sobre a situação e a possível proliferação de algas tóxicas. Mais de dez anos de experiência mostraram o interesse em utilizar conjuntamente os dados sobre a cor do mar, obtidos por satélites de observação da Terra, e os modelos numéricos de simulação e/ou de predição, para a monitorização, em tempo real, da proliferação dessas algas. A utilização - em sinergia - de dados «in situ», de dados de satélite e de modelos é demonstrada através de um exemplo operacional de monitorização do HAB no litoral da Dinamarca e da Noruega, na Primavera de 1998.

Palavras-chave: HAB, Detecção Remota, cor do mar, modelação, gestão de crise.

Abstract

After the severe toxic bloom of "Chrysochromulina polylepis" in southern Norwegian waters in 1988, a national operational monitoring program has been developed, which provides information about the algae bloom situation and its development. Experiences, gained from real-time monitoring of bloom events, emphasised the value of integrated use of remote sensing and numerical modelling in monitoring of algal blooms. This synergetic use of "in situ", modelled and satellite data are demonstrated through an operational example from a toxic algae bloom during spring 1998 in Danish and Norwegian waters.

Key words: HAB, Remote Sensing, ocean colour, modelling, crisis management.

Résumé

Suite à la prolifération de l'algue toxique (« harmful algal bloom » - HAB) « Chrysochromulina polylepis » sur la côte sud de la Norvège, en 1988, un programme national de suivi opérationnel des floraisons phytoplanctoniques a été initié. Son but *est de fournir des informations sur la situation et la possible prolifération d'algues nuisibles. Plus de dix ans d'expérience ont montré l'intérêt d'utiliser conjointement les données d'observations satellitaires de la couleur de la mer et des modèles numériques de simulation et/ou de prédiction, pour la suivi en temps-réel des proliférations d'algues. L'utilisation en synergie de données « in situ », satellitales et de modèles est démontrée à travers un exemple opérationnel de suivi d'un HAB survenu sur les côtes du Danemark et de Norvège au printemps 1998.*

Mots-clés : prolifération algale, Télédétection, couleur de la mer, modélisation, gestion de crise.

For several years the concern of toxic or harmful algae blooms along coasts has obtained more public interest as a consequence of increased awareness. Indeed, the impact has become more visible through aquaculture activities with cages fishes and shellfishes. It is particularly sensible in Norway where fisheries and aquaculture count for significant part of the export, representing 51% of the total market for Atlantic salmon (1996 figure). After the severe toxic bloom of *Chrysochromulina polylepis* in southern Norwegian waters in 1988 (Dundas *et al.*, 1989), an ad-hoc operational monitoring and guidance program was developed providing information about bloom situation and possible development. Since 1988 the national algae monitoring efforts has developed to system which produces a weekly bulletin based on a regular in situ observation network aiming for monitoring the bloom initiation, development and decay from early spring to fall. The use of satellite ocean colour and numerical modelling information in this service is under development and implementation. The current monitoring service is based on co-ordinated activities by public and private organisations in Norway.

Information on the distribution of algae along the Norwegian coast is provided (presently in Norwegian only) via the Internet at the regularly updated (weekly from March to October and less frequently in typically non-HAB periods) ALGEINFO web-site with the address, http://algeinfo.imr.no. The information at ALGEINFO consists of a station map (Figure 1) indicating the situation of HAB species along the coast and a short text for closer description. There are links to useful additional information such as description of various species and their effects. If acute HAB situations should occur more frequent updating is initiated as well as direct contact to management authorities and aquaculture industry in threatened areas.

At present, a 3D coupled physical and biogeochemical numerical model, set up and tuned for the North Sea, has been implemented and is used synoptically for simulating and forecasting of algae blooms and spreading.

Since 1997, SeaWiFS sensor, onboard the US satellite Orbview-2, delivers in quasi-real time, ocean colour data from which are derived maps of chlorophyll-a concentration and phytoplankton distribution in cloud free areas. This is a unique source of synoptic information, which can be used at four levels in the algae monitoring service: 1) daily acquisition and processing of satellite data for enhancement of early warning and planning of other field measures; 2) monitoring the growth and decay of blooms and ocean fronts; 3) forcing field for the numerical model; 4) data assimilation for improved estimates.

This demonstration study has been conducted in an operational context related to the monitoring of the 1998 bloom of the toxic dinoflagellate *Chattonella verrucu-losa* along the Danish and the Norwegian coasts, starting in late April (www.nersc.no/Decide-HAB). The main objectives were (i) to assess how Sea-WiFS-derived product can contribute to the monitoring of harmful algae blooms in the North Sea, (ii) to evaluate the capability of the coupled physical chemical biological model to simulate and forecast the bloom event, and (iii) to determine the strengths and weaknesses of both sources of information and their domain of synergy.

Figure 1 - The main ALGEINFO web page for July 1, 1999. The information content is provided by The Institute of Marine Research, Directorate of Fisheries, Oceanor AS and NIVA.

Data and methods

Satellite data

In this study we have used a time series of SeaWiFS data that has been acquired in near real-time between April and July 1998. During this period, several blooms took place, including a bloom of the toxic dinoflagellate *Chattonella verruculosa*, which caused the death of approx. 350 tons fish at an aquaculture site along the coast of south Norway.

The standard NASA SeaWiFS algorithm (O`Reilly *et al.*, 1998) derives the depth-integrated chlorophyll *a* (CHL) concentration in the range 0 - 64 mg·m^{-3}, with an accuracy of about 35 % in so-called case 1 open-ocean waters. Much lower accuracy is reached in turbid coastal waters (case 2), such as the North Sea, where the contribution of suspended sediments and yellow substance, to the signal measured by the satellite sensor, makes the standard algorithm fail.

Plymouth Marine Laboratory (PML, UK) has implemented a specific scheme for the retrieval of CHL in the North Sea (Moore *et al.*, 1999). On the one hand, the standard NASA atmospheric correction algorithm has been modified in order to account for the high load of sediment generally encountered in the North Sea, i.e., a correction based on *in situ* measurements and simulation of the North Sea optical properties, is applied, through an iterative process. On the other hand, a specific empirical relationship that relates chlorophyll concentration to the radiance ratio of two SeaWiFS band has been set up for the North Sea. The PML algorithm has shown to give the same level of accuracy in the North Sea case 2 waters than the NASA algorithm in case 1 waters.

Modelling

The NORWegian ECOlogical Model system (NORWECOM) is a coupled physical bio-chemical model for the North Sea that is applied to study primary production, nutrient budgets and dispersion of particles. The physical model (Blumberg and Mellor, 1987) is based on the 3D Princeton Physical Ocean Model. In the vertical a 12-levels sigma-co-ordinate representation is used, and the horizontal grid uses Cartesian co-ordinates with a resolution of 20x20 km. The prognostic variables are three components of the velocity field, temperature, salinity, turbulent kinetic energy, turbulent macro-scale, and water level. The model forcing makes use of six-hourly hindcast atmospheric pressure, surface heat flux (relaxation towards climatology), wind stress, tidal constituents and fresh water runoff. Initial values for velocities, water elevation, temperature and salinity are taken from monthly climatologies (Martinsen *et al.*, 1992).

The bio-chemical model (Aksnes and Lie, 1990) is coupled to the physical model through the subsurface light, the hydrography and the horizontal and vertical movements of the water masses. The prognostic variables are two groups of phytoplankton (diatoms, flagellates), inorganic nitrogen, phosphate and silicate, organic detritus. Model forcing is performed from user-supplied initial and boundary conditions, e.g., data obtained from ICES, for the six prognostic variables. Sources of nutrient are rivers runoff, the atmosphere (inorganic nitrogen only), and re-mineralisation.

All output numbers are given in nitrate-equivalent (mgN). Conversion into chlorophyll (CHL) concentrations is performed using a simple translation factor:

CHL = (diatoms + flagellates) / 11

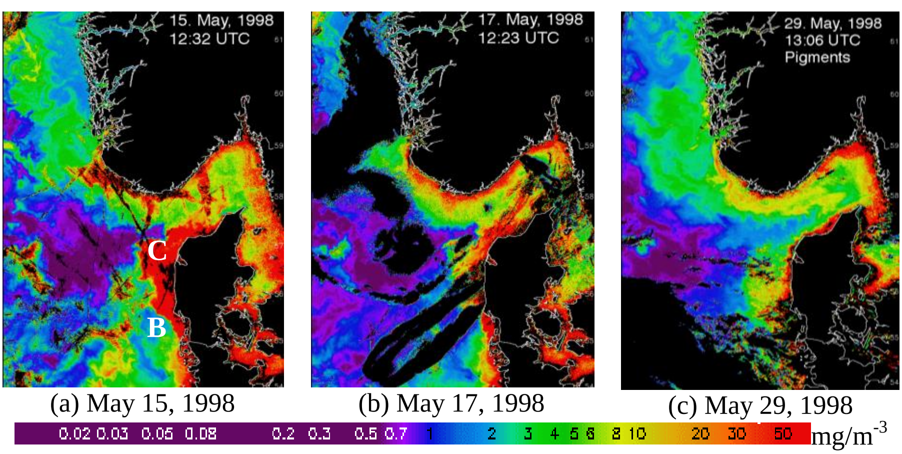
Results

First, we evaluate the two sources of information – model and ocean-colour data - independently. Then qualitative and quantitative comparisons are performed.

The blooms as observed by SeaWiFS

The images displayed in Figure 2 are SeaWiFS-derived chlorophyll concentration ($mg{\cdot}m^{-3}$), and show an area of high pigment concentration to the western coast of Denmark (white patterns), which was reported to be dominated by the dinoflagellate *Chattonella verruculosa*. Lands and cloud over the sea are masked in black. The time series shows the development and decay of the bloom between May 15 and May 29.

Figure 2 - Pigment concentration distribution in the North Sea and Skagerrak as derived from SeaWiFS data. (a) May 15 1998; (b) May 17 1998; (c) May 29 1998 (Data courtesy of S. groom, CCMS-PML, UK). Copyright NASA SeaWiFS project/Orbital image Corp.



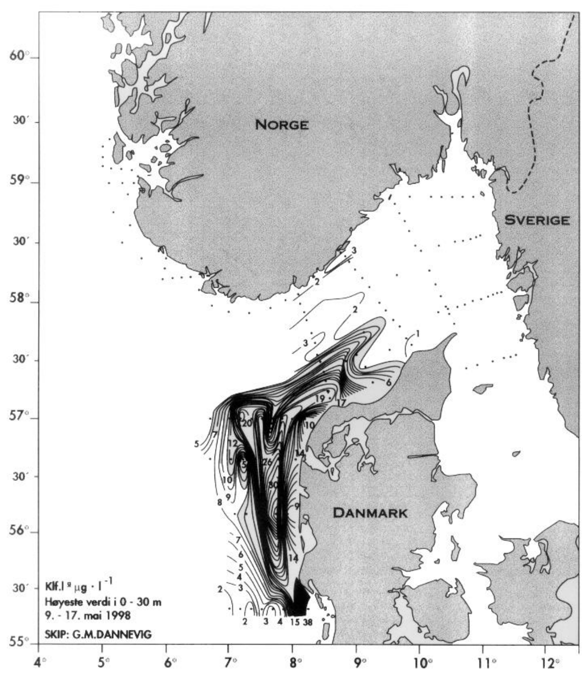
The concentration values range from 40 - 64 $mg{\cdot}m^{-3}$ (May 15) to 6-10 $mg{\cdot}m^{-3}$ (May 29). Actually, 64 $mg{\cdot}m^{-3}$ is the upper limit of the retrieval capability of the current algorithm, hence the data then were saturated. It is significant to note that the SeaWiFS data appears to overestimate the concentration of phytoplankton chlorophyll in this area as compared to the *in situ* observations (Figure 3). This overestimate is mainly due to the effects of bottom reflection and suspended sediments.

While comparing with *in situ* data collected during the same period (Figure 3), a good match can be observed in term of pattern shape and size of the bloom. Figure 3 shows the highest chlorophyll concentrations, observed *in situ*, in the interval of depth 0 – 30 m, which reach a maximum of 30 mg·m^{-3}, and which corresponds to an integrated value of 58 mg·m^{-3} on the interval 0-30 m.

The interpretation of the SeaWiFS images becomes however questionable when no field reference data are available. For instance, a highly productive area can be observed along the Dutch coast. Since no field measurements are available for this area, it is almost impossible to determine if the high values observed actually are due to a bloom or if it originates from a large amount of subsurface suspended sediments.

Along the southern coast of Norway, the time series clearly shows the development and advection of water masses from the Skagerrak to the Norwegian coastal current (Figure 2). On May 13, the bloom of *Chattonella* was reported along the western coast of Sweden and in the outer part of the Oslo Fjord. At many location, more than 10^6 cells/L were counted, and the surface water was observed discoloured brownish. From May 15 to May 17, the spreading of the bloom along the southern coast of Norway can be observed in the SeaWiFS data.

Figure 3 - In situ measurements (9 – 17 May 1998): highest concentration of chlorophyll-a in the interval 0 – 30 m (mg.m^{-3}).



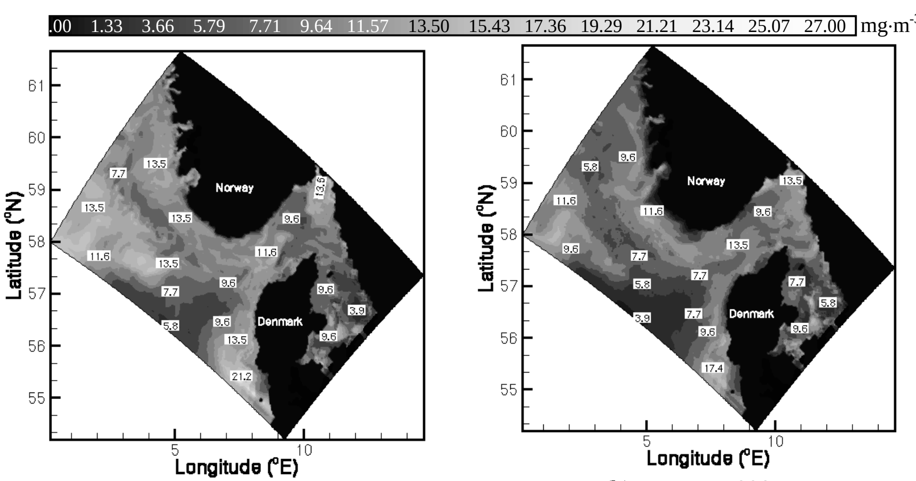
Low to medium concentrations of chlorophyll-a can be observed along the western coast of Norway, which correspond to small blooms of the coccolithophore *Emiliania huxleyi*.

Evaluation of NORWECOM

Ocean colour remote sensing give access to chlorophyll concentration, integrated over the upper ocean layer. In order to compare modelled and satellite-derived chlorophyll, modelled CHL have been integrated between 0 to 25 m. This is in accordance with euphotic depth values derived from light attenuation given by SeaWiFS light diffuse-attenuation products (K490). These modelled CHL estimates show a maximum of 25 mg·m^{-3} in the German coastal waters, between May 15 and 17 (Figure 4). The bloom development is reproduced by the model. High concentration patterns can be observed along the western Danish coast, as well as along the western coast of Norway. In particular, the model shows that the *Chattonella* bloom is decaying between May 17 and May 29 (Figure 4), while a possible new bloom is developing in the centre North Sea (0^{o}E; 58^{o}N).
When compared to *in situ* data, the general high and low concentration patterns in the model seem displaced southwards, although the main shapes are similar. A quantitative comparison reveals an underestimation of CHL by the model in bloom areas.

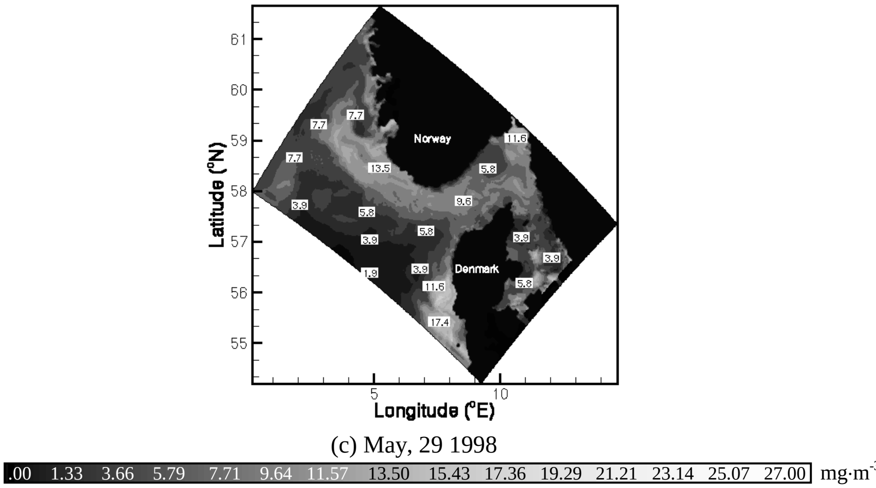
Only small variations in the model are observed along the Danish west coast between May 17 and May 29. Similarly, almost constant CHL values are predicted along the western coast of Sweden and Oslo Fjord (~13.5 mg·m^{-3}). Such high concentration can be explained by a continuous nutrient supply from the Oslo Fjord during this period of the year, as reported by others.

Figure 4 - Chlorophyll concentration distribution in the North Sea and Skagerrak as derived from NORWECOM. The value displayed are the chlorophyll concentration in mg·m-3, integrated over the depth 0 –25 m. (a) May, 17 1998; (b) May 22 1998; (c) May, 29 1998.



(a) May, 17 1998

(b) May, 22 1998



(c) May, 29 1998

Comparison

A comparison between satellite- and modelled-derived CHL has been performed. In Figure 5, we present the modelled and satellite-derived CHL at three locations (see Figure 2a for locations), which are representative of the main bloom areas.

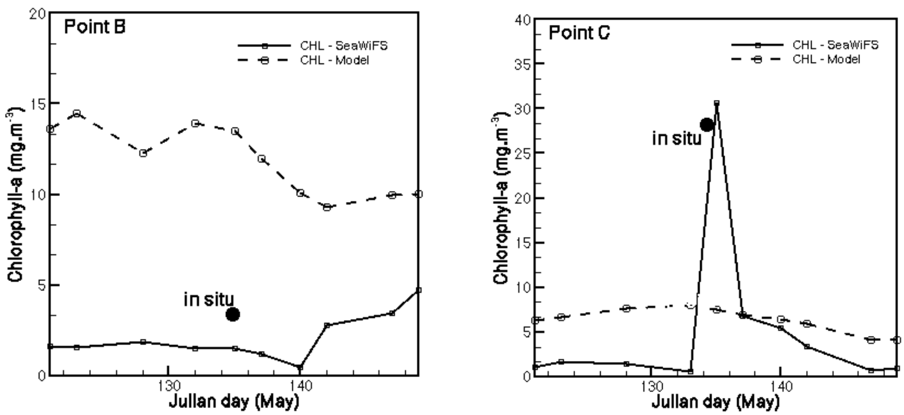
We may notice that, even if the entire region were under exceptionally good weather conditions in May 1998, only a few locations of synoptic satellite and *in situ* observations were obtained for comparison. The model curves in Figure 5 appear smoothed because data are available at all dates. At contrary, the SeaWiFS-derived chlorophyll curves are irregular because data are only available while the sky is clear.

From the evolution of CHL (Figure 5), it is seen that the bloom starts earliest close to the continental coast and in the southern part of the North Sea (point B in figure 2a), where continuous supply of nutrients by rivers keeps the production up. At point C, the model maximum is obtained for May 10 (Julian day: 131), whereas SeaWiFS CHL peak is reached May 15 (Julian day: 136).

It is worth noticing how SeaWiFS-derived CHL are consistent with *in situ* data, for these three points, whereas the model does not quantitatively reproduce the actual concentration in the bloom.

This analysis shows that both source of information are complementary since the model gives smooth and regular time series, while ocean colour data are closer to *in situ* measurements, and allow a better identification and synoptic view of the extension of specific events.

Figure 5 - Bloom evolution during May 1998 as derived from SeaWiFS (solid line), as and predicted by NORWECOM (dashed line). See Figure 1-a for point locations. In situ measurements acquired between May 15 (Julian day: 136) and May 18 are given.



Conclusions

SeaWiFS satellite ocean-colour data have been processed with an algorithm that is tuned for the North Sea. Reliable estimates of pigment concentration and distribution are found, with the exception of shallow near shore areas and of sediment-loaded waters where systematic overestimation is observed.

Furthermore, algorithm saturation has been observed for extremely high chlorophyll concentration (CHL > 50 mg.m^{-3}). However ocean-colour data have proven valuable for monitoring of the dynamic and the advection/development of the bloom.

The NORWECOM model shows reliable results in term of bloom patterns. However quantitative errors have been found, particularly in the core bloom areas. However, the model predicts several other variables, such as temperature, nutrient concentration, oxygen consumption, and primary production, which are very valuable for the understanding of spreading and decay of the blooms. It is therefore believed that quantification of these parameters must be achieved through modelling, and that remote sensing should primarily be used for model's initialisation and validation, and possibly assimilation into models. Clearly also the ocean colour data are of great value for the study of meso-scale features in order to obtain a synoptic view of the bloom.

Benefit has been demonstrated from the application of remote sensing data in monitoring of an extreme algae bloom in coastal waters. The coming generation of ocean-colour sensors, such as the ESA Medium Resolution Imaging Spectrometer (MERIS) is designed with improved capability for synoptic monitoring of algae bloom under cloud-free conditions. We can expect within two years, to have access to at least four spaceborne ocean colour sensors with complementary characteristics. This should improve our capability for integrated *in situ* and EO-based monitoring of harmful algae bloom in coastal waters.

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