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Monitoring and prediction of phytoplankton dynamics in the North Sea

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Chapter 3

Analysis of the Spatial Evolution of the 2003 Algal Bloom in the Voordelta (North Sea)

ABSTRACT

Phaeocystis blooms in the Southern Bight of the North Sea may cause damage to the aquatic ecosystem and to commercial mussel cultures at the entrance of the Oosterschelde estuary. In this paper the potential for early detection of *Phaeocystis* blooms in Dutch coastal waters is studied, using a combination of field data, satellite observations and hydrodynamic- and biological modelling. For the spring bloom period in the year 2003 MERIS chlorophyll-a maps, derived with the HYDROPT algorithm for coastal waters, were compared to in-situ measurements at stations off the coast in de Voordelta and the results of the GEM biogeochemical model.

The analysis shows that the spatial and temporal variability in *Phaeocystis* abundance and total biomass (expressed by the Chl-a concentration) during spring is large. It is confirmed that blooms may develop off shore and show a tendency to accumulate within 10 km from the coastline, giving rise to rapid biomass accumulation at the mouth of the multiple estuaries in the Voordelta. Based on the outcome of this study an early warning system is proposed that notifies local water managers and shellfish growers for potentially harmful *Phaeocystis* bloom formation.

This chapter is based on the paper: Van der Woerd, H.J., Blauw, A., Peperzak, L., Pasterkamp, R., Peters, S., 2011. Analysis of the spatial evolution of the 2003 algal bloom in the Voordelta (North Sea). Journal of Sea Research 65: 195-204.

3.1 INTRODUCTION

In the Southern regions of the North Sea and the Eastern English Channel the spring bloom of phytoplankton is dominated by diatoms and *Phaeocystis globosa* (Reid et al., 1990; Peperzak et al., 1998; Rousseau et al., 2002; Muylaert et al., 2006). At the *Phaeocystis* bloom maximum, colonies with diameters in excess of 200 μm and chlorophyll-a (Chl-a) levels above 20 mg m^{-3} are formed (Peperzak et al. 1998; Seuront et al., 2006). These colonies and associated foam formation on beaches are a nuisance to humans and ecosystems (Schoemann et al., 2005). *Phaeocystis* blooms are also harmful, because in shallow seas the sedimentation of decaying large colonies, at the bloom decline, may lead to sediment anoxia and massive mortality of benthic invertebrates (Peperzak, 2002). For example, in 2001 a massive bloom of *Phaeocystis* caused severe economic damage to the commercial shellfish industry near the entrance of the Oosterschelde at the Voordelta, part of the Southern Bight of the North Sea. Analysis of salinity and oxygen data revealed that the *Phaeocystis* bloom had developed off-shore and was transported towards the mussel beds near the Oosterschelde entrance. This was followed by anoxia and mussel death, most likely as a consequence of sedimentation of the colonies (Peperzak and Poelman, 2008). Problems as encountered in 2001 could be prevented in the future by relocating mussel cultures to waters less affected by high-biomass blooms. However, to apply such management options, reliable early confirmation of the onset of *Phaeocystis* blooms and subsequent spatial evolution is critical.

The intensity and frequency of *Phaeocystis* blooms has increased over the last decades (Cadée and Hegeman, 2002), likely coupled to higher nutrient loads (Gypens et al., 2007; Lancelot et al., 2009). In their review of the Continuous Plankton Recorder data from the second half of the last century, Gieskes et al. (2007) confirm that for the Southern North Sea the total phytoplankton biomass (expressed by the Chl-a related PCI) is related to river discharge. However, Gieskes et al. (2007) also suggest that the *Phaeocystis* abundance variation in the Southern North Sea is mainly correlated to the amount of Atlantic Ocean water flushed in through the Dover Strait. The bloom onset (between begin April to June) and intensity shows erratic behaviour from year to year and is, in addition, dependent on the geographical location (Muylaert et al., 2006; Gieskes et al., 2007; Blauw et al., 2010).

Therefore, the exact timing and abundance of the bloom formation in the Voordelta cannot be derived from historical data alone and other means must be considered. An obvious early detection method of high-biomass blooms is the use of satellite imagery (see the review by Stumpf and Tomlinson, 2005). Optical detection of elevated Chlorophyll-a (Chl-a) levels by the new generation ocean colour imaging spectrometers (SeaWiFS, MODIS and MERIS) is becoming an integrated part of off-shore HAB detection (Stumpf et al., 2003). *Phaeocystis* blooms have high cell concentrations (millions of cells per litre), contain high Chl-a densities, and are detectable by remote sensing. For example,

Tang et al. (2004) demonstrated that SeaWiFS is able to detect *Phaeocystis* by its optical signature in clear oceanic (case 1) waters off the South-Eastern coast of Vietnam in 2002. However, the simple algorithms developed for case-1 waters greatly overestimate the Chl-a concentrations in estuaries and deltas (D'Sa and Miller, 2005), thereby mimicking spurious bloom phenomena. This drawback was recently overcome with the development of reliable Chl-a retrieval algorithms for the North Sea (case 2), that take into account the influence of highly-variable concentrations of suspended particular matter and coloured dissolved organic matter on the measured signal (Schiller and Doerffer, 2005; Van der Woerd and Pasterkamp, 2008). Also more information becomes available on the inherent optical properties in coastal waters that underpin the bio-optical models of coastal waters (Babin et al., 2003; Tilstone et al., 2010).

Additional information on the exact timing of the bloom formation in the Voordelta can be derived from complex hydrodynamic biogeochemical models, combined with satellite and in-situ data (Schofield et al., 1999). With the MIRO model Lancelot et al. (2005) and Lacroix et al. (2007) could model the timing of the spring bloom in the years 1989-1999 within a few weeks. They found that typically a *Phaeocystis* bloom is preceded by a bloom of diatoms, separated by 20-40 days. The MIRO model tends to underestimate spring Chl-a concentration (Lacroix et al., 2003). In our study, the GEM model used (Los et al., 2008; Blauw et al., 2009) has a model domain that includes the Southern Bight of the North Sea and the delta estuaries of Rhine and Scheldt and has been extensively validated for Dutch coastal waters.

In this paper we describe the spatial and temporal evolution of an algal bloom in spring 2003, based on an analysis of four data sources (Van der Woerd et al., 2005): Field data that include Chl-a measurements and flowcytometer cell counts, MERIS satellite measurements and GEM-model output. A priori it was recognized that none of these data sources is likely to provide a sufficiently reliable early detection and forecast of *Phaeocystis* levels by itself for the following reasons: (1) The collection and analysis of field data is an expensive and time-consuming procedure to monitor the spatial and temporal development of blooms offshore, (2) Remote sensing data give synoptic information, but can have temporal under-sampling because of cloud cover and (3) dynamic modelling information is prone to uncertainties, considering the complexity in the many biological and hydrodynamical processes that operate in the Voordelta. In this paper it is shown to what extent the information from the four data sources support the early detection of algal blooms and to what extent the data provide consistent or conflicting information.

In section 2 the Voordelta area is introduced. In section 3 the description of the remote sensing data and the retrieval of Chl-a are provided, together with an introduction to the GEM model. Also the *Phaeocystis* cell count by the flowcytometer and Chlorophyll-a (Chl-a) concentration measurements by HPLC are described. In the result section (4) all data are compared, mainly the spatial patterns with elevated Chl-a levels and the

temporal evolution at stations in the Voordelta. The paper finishes with a discussion of the uncertainty in information and differences between data sources (section 5) and consequences for the implementation of an early-warning system (section 6).

3.2 STUDY AREA DESCRIPTION

This study focuses on the southern part of the Dutch coastal zone, the Voordelta and adjacent (former) estuaries and inlets (Figure 3.1). This part of the North Sea is characterized by OSPAR (2010) as problem area with regard to eutrophication. Rivers such as the Rhine, Meuse and Scheldt discharge nutrient-rich fresh waters in a relatively shallow shelf sea, enclosed between the United Kingdom and continental Europe.



Figure 3.1: Graph of Voordelta and the province of Zeeland. The inset shows the location in the Southern North Sea and the West English Channel. The dark-grey areas are recognized as eutrophied. The names denote important cities, water bodies and measuring stations. The exact location of the measuring station is indicated by (*). Sources of freshwater input are indicated by (F).

The main fresh water (F) and nutrient input in the area is via the Nieuwe Waterweg (outlet of the harbour of Rotterdam) and via the Haringvliet, which discharge freshwater from the rivers Rhine and Meuse. Further south is the saline lake Grevelingen that is connected to the North Sea via a sluice in the Brouwersdam. The Oosterschelde, also connected by a tidal inlet dam (storm surge barrier) to the North Sea, is an area of intense mussel cultivation. The most southern estuary is the Westerschelde. In fact, all these shallow coastal waters, with depths less than 20 meters, are usually well mixed due to strong tidal currents. In addition to the Brouwersdam station, in-situ data from the stations Goeree 6 (51°52.2' N, 3°52.4' E), Walcheren 2 (51°32.9' N, 3°24.6' E) and Wissenkerke (51°36.2' N, 3°43.2' E) have been used in this study. Note that station Goeree 6 is sometimes influenced by the fresh-water plume from the Haringvliet and Nieuwe Waterweg.

3.3 MATERIALS AND METHODS

In April-May 2003 a dedicated measurement campaign was carried out to collect samples for *Phaeocystis* cell counts up to 5 times a week at the Brouwersdam sluice, the entrance of Lake Grevelingen. The analysis was performed with a high-performance flow cytometer (Rutten et al., 2005). For stations Goeree 6, Walcheren 2 and Wissenkerke, *Phaeocystis* cell counts were determined microscopically (Baretta-Bekker et al., 2009). These stations are part of the national monitoring program (MWTL) and are visited once a month in winter and twice a month in spring and summer. For these stations Chl-a measurements with HPLC were made available via a public website (www.waterbase.nl).

Satellite-based measurements were collected from the MEdium Resolution Imaging Spectrometer (MERIS) instrument from the European Space Agency that has a mean local time of overpass at 10 AM UTC. In this study we used the reduced resolution data that have a spatial resolution of 1.2 by 1.2 km² for nadir view. Due to orbit restriction the MERIS instrument can observe the Voordelta only two out of three days. Due to additional restrictions, in particular clouds, sun glint and adjacency effects, the number of high-quality MERIS observations of the Dutch Voordelta numbered 32 in total in a time interval of 92 days in 2003 (March 1st – May 31st).

The MERIS observations were processed from MERIS reflectance (L2; MERIS data with processor version IPF 5.05) with the HYDROPT inverse algorithm (Van der Woerd and Pasterkamp, 2008). This algorithm derives the concentration of Chl-a, suspended particulate matter (SPM) and dissolved organic matter (CDOM) absorption by minimizing the difference between the observed and modelled reflectance spectra in 8 optical bands between 412 and 708 nm. The modelled reflectance is based on the Hydrolight radiation transfer code (Mobley, 1994) that simulates the observed remote sensing reflectance as

a function of absorption and scattering within the water, taking into account the angular distribution of the down-welling radiance and the transmission function through the air-water interface. HYDROPT was parameterised with a set of absorption and scattering properties for Chl-a, SPM and CDOM that resulted in the highest correlation between geometric mean Chl-a and SPM values for 14 monitoring stations in the Dutch coastal zone for the years 2003 – 2006 (Peters et al., 2009).

The Generic Ecological Model (GEM) ecosystem model was used to simulate effects of river discharges and biogeochemistry in the relatively shallow estuarine and coastal waters of the southern North Sea. The GEM model consists of a hydrodynamic module and an ecological module. The combination of the two modules has been used to calculate total algal biomass and *Phaeocystis* in equivalent carbon concentration and Chl-a. Nutrient cycles of nitrogen, phosphorus and silicate and phytoplankton dynamics are simulated in three forms: dissolved inorganic nutrients, algal biomass and detritus. Four phytoplankton species groups are simulated: diatoms, flagellates, dinoflagellates and *Phaeocystis*. The model assumes that fast-growing (less efficient) phytoplankton species dominate in a situation where resources (light, nutrients) are abundant, while slow growing, but efficient phytoplankton species gain dominance when resources become limited (Los and Wijsman, 2007).

Transport of substances within the model and temperature forcing are based on information from the hydrodynamic model. The model area extends from the English Channel in the South, up to Denmark in the North and covers the whole southern North Sea in between. The schematisation uses a curvilinear grid with a resolution varying from circa 2 km near the mouth of the Rhine river to circa 20 km in the most north westerly part of the model area. Boundary conditions are based on astronomic tides and long term averaged observations. These boundary conditions are sufficiently far away from the area of interest in this study to provide adequate nutrient concentrations and residual currents (Los and Blaas, 2010), while not overriding the simulated near-shore phytoplankton dynamics. River nutrients inputs are based on daily observations of discharges and circa 2-weekly observations of concentrations near the river mouths (www.waterbase.nl). The model runs started in January 2003 with initial conditions resulting from model simulations from 1996 – 2002. The model set-up and validation results for the GEM model for the southern North Sea are described in more detail by Los et al. (2008), Blauw et al. (2009) and Los and Blaas (2010).

Spring bloom formation is triggered by light availability that is, in these shallow waters, strongly related to sediment load (Tian et al., 2009; Blauw et al., 2010). Blauw et al. (2006) found a significant correlation between turbidity and averaged wind speed during the preceding week for monitoring stations near the Dutch coast. Assuming that most of the temporal variability is due to wind-induced re-suspension, this information

was used in combination with monthly averaged sediment maps from remote sensing data to construct a forcing function for suspended matter concentrations in the model. A similar approach has been followed by Huret et al. (2007), who used SeaWiFS suspended matter observations to force the phytoplankton production model for the Bay of Biscay, by Tian et al. (2009) in the German Bight and Li et al. (2010), for the southern North Sea. The overall extinction coefficient in the model is the sum of the extinction by suspended matter, phytoplankton, particulate organic matter, dissolved organic matter from rivers (approximated by salinity) and background extinction (Blauw et al., 2009). The underwater light climate experienced by phytoplankton in the model is also affected by vertical mixing. The light intensity per layer is the weighted average of the light intensity in each vertical layer and the part of the day that the phytoplankton spent in each layer (simulated by the hydrodynamic model).

3.4 RESULTS

3.4.1 Field data

The information that is available from discrete water samples is given in Figure 3.2, that shows the *Phaeocystis* cell concentrations near the Brouwersdam (◇), starting from the last day of March and continuing to the end of May 2003. At April 11th (day 101 in 2003) the level of 10 million cells per litre was exceeded. No samples were taken during the weekend of 12, 13 April. The bloom intensity at this location increased to 90 million cells per litre at April 14th. This can be either due to transport of an existing bloom to the Brouwersdam, a local doubling of the number of cells per day in an exponential growth phase or a combination of the two mechanisms. Cell numbers remained high, between 10 to 30 million cells per litre, until the first week of May.

The coastal stations Goeree 6 and Walcheren 2 also showed elevated *Phaeocystis* levels at April 14th of 36 and 29 million cells per litre, respectively. The Chl-a concentrations measured at the same location were high (37.8 and 38.8 mg m⁻³ respectively). If we assume a carbon content of 14.15 pgC per *Phaeocystis* cell and a typical C/Chl ratio of 18 (Rousseau et al., 1990; Schoemann et al., 2005) we find that 10 million cells per litre correspond to 7.9 mg m⁻³ Chl-a. When this conversion factor is applied to the April 14th measurements at Goeree 6 and Walcheren 2, high equivalent *Phaeocystis* Chl-a concentrations (28.3 and 22.8 mg m⁻³ respectively) are calculated, indicating a dominance of *Phaeocystis* in the overall Chl-a signal. Unfortunately no information exists on the *Phaeocystis* bloom phases before this date. The two stations show lower *Phaeocystis* concentrations at May 6th with values of the order of the Brouwersdam measurements around that time.

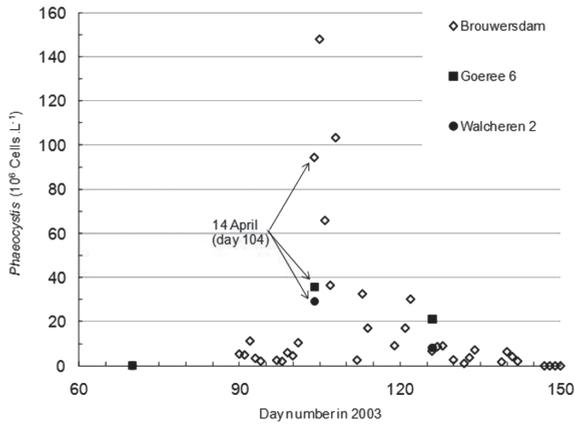


Figure 3.2: Time series of the cell counts of *Phaeocystis* at the inlet of Lake Grevelingen (Brouwersdam) and two stations in the Voordelta.

3.4.2 MERIS observations

The full set of MERIS images contains many clouded scenes and the Voordelta can only be observed one out of three days (on average) in the bloom period. The images with best coverage of the Voordelta are shown in 16 panels in Figure 3.3. On March 28th (day 87) Chl-a higher than 20 mg m⁻³ are detected in a narrow strip close to the coast. The next clear observation is on April 9th, when a bloom is already more prominent close to the coast near the mouth of the Westerschelde and the tidal inlets of Oosterschelde and Grevelingen. In the next week the bloom fully develops in the whole Voordelta. Chl-a levels above 20 mg m⁻³ are observed up till the image of May 4th (day 124). Note that the bloom has a tendency to be located close to the coast and large off-shore gradients can be seen, for example on April 23rd and May 4th. After May 11th the bloom intensity decreases, interestingly revealing a striped pattern with an interval between the lines of elevated algal density of typically 10 km. At May 15 and May 31 elevated Chl-a levels are only observed close to the coast and could be related to the nutrient-rich freshwater from Westerschelde and Haringvliet. Satellite measurements within the estuaries are mostly of low quality and are therefore not interpreted in this article.

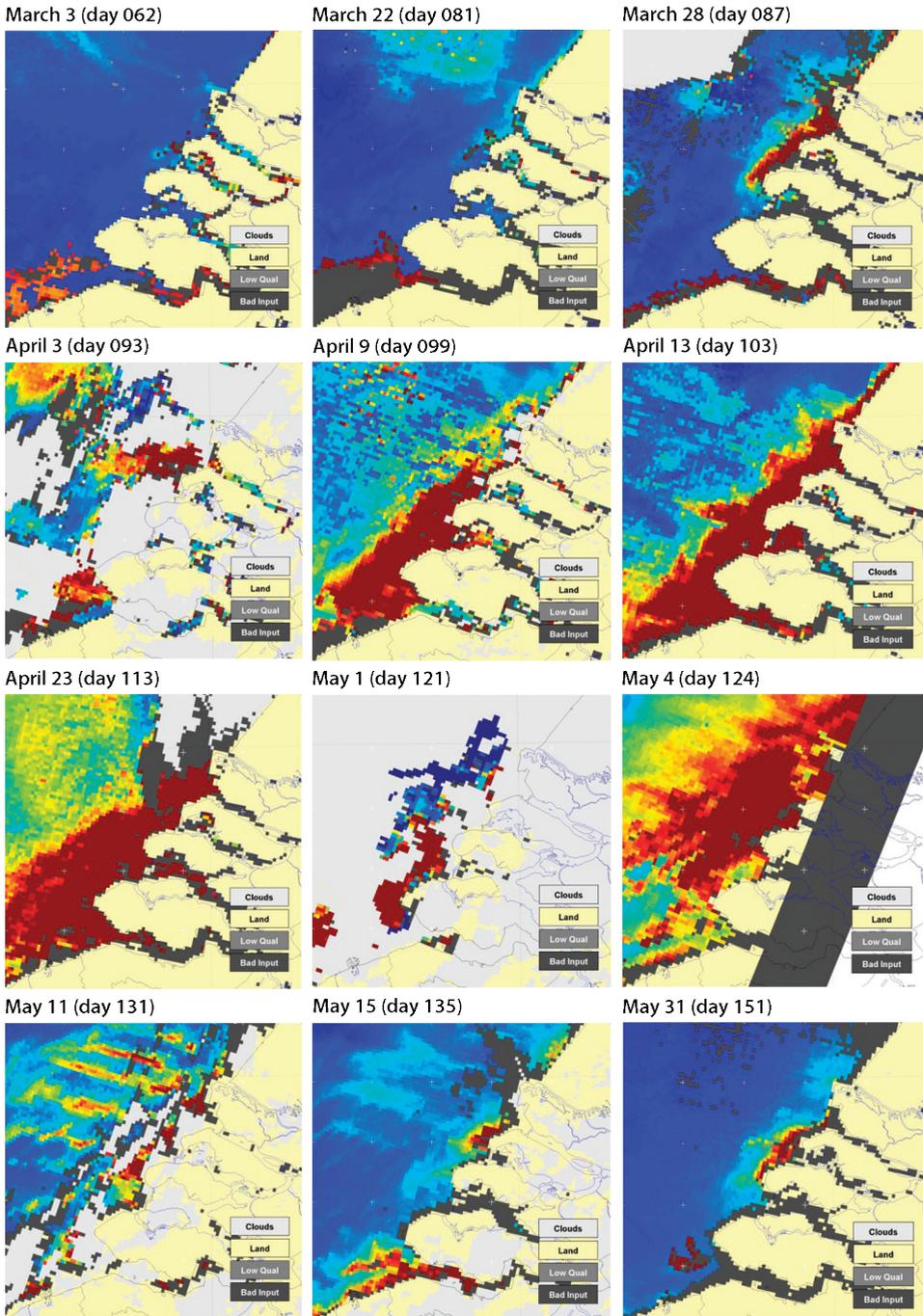
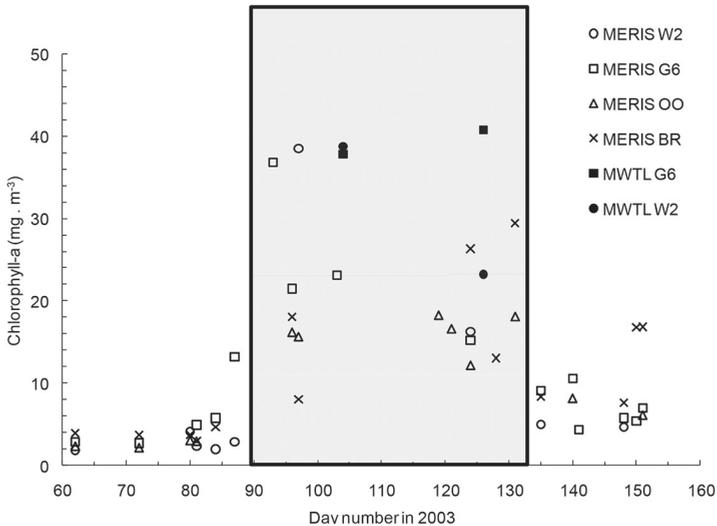


Figure 3.3: Development of the algal bloom in spring 2003 as observed by the MERIS sensor. The colour bar gives the Chl-a concentration in (mg m^{-3}). White indicates land, light grey pixels are contaminated by clouds and darker grey pixels indicate problems in the retrieval process.

In Figure 3.4 the development of the bloom is compared at four stations, two at the entrance of an estuary (Brouwersdam (BR) and Oosterschelde (OO)) and two off shore (Walcheren 2 (W2) and Goeree 6 (G6)). The information is extracted from the MERIS images, partly shown in Figure 3.3, supplemented with four in-situ Chl-a measurements. Before day 90 and after day 135 the levels are low, while in the bloom period (indicated by the grey box) 20 out of 21 observations have a level well above 10 mg m⁻³ Chl-a. This figure demonstrates that in this complex marine area the four stations show a high spatial and temporal variability and demonstrates the scarcity of in-situ measurements. In addition it demonstrates that a simple relation between Chl-a levels off shore (Goeree 6) and the Chl-a levels at the entrance of the Oosterschelde is hard to find.



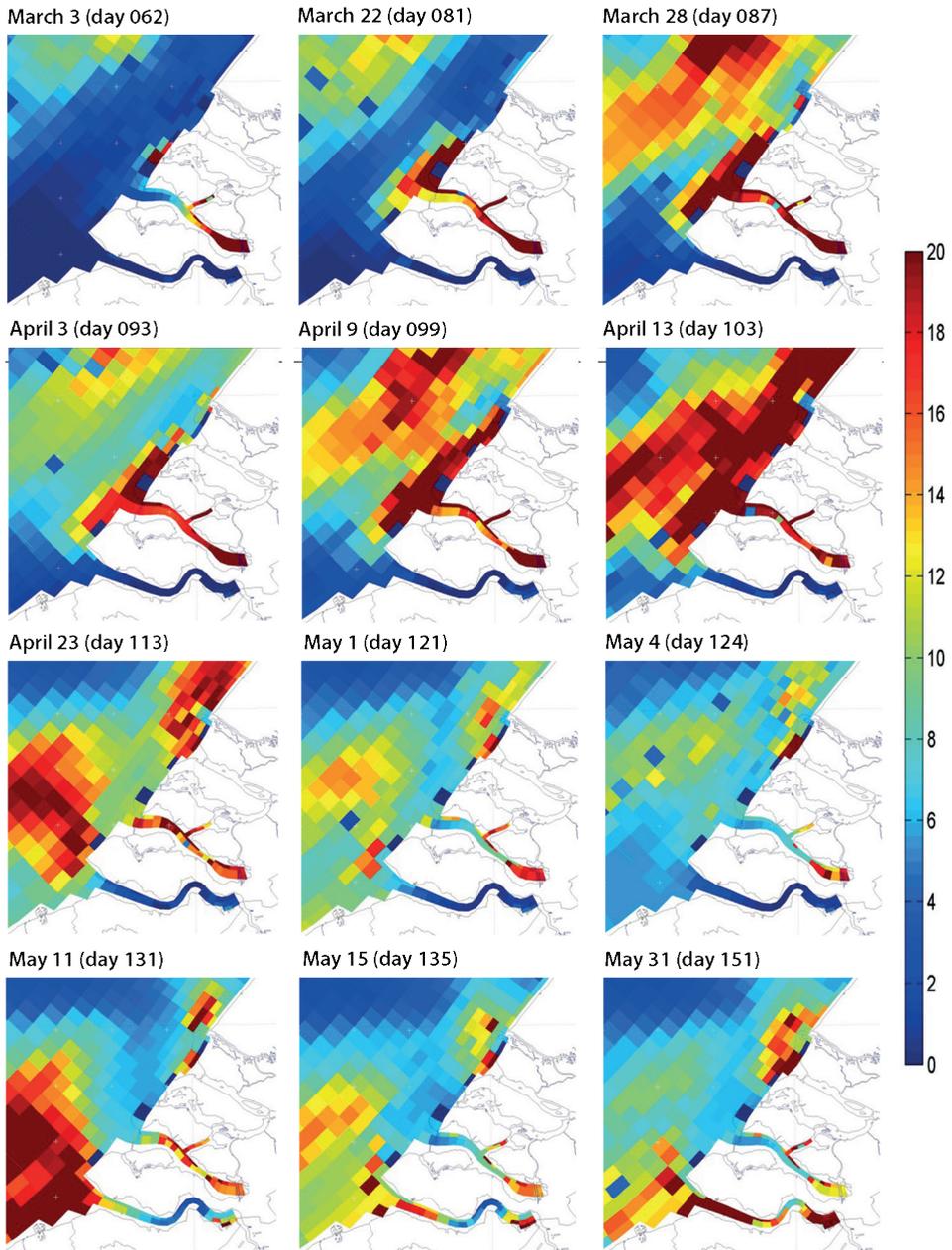


Figure 3.5: Bloom development, expressed as total Chl-a concentrations, simulated by the GEM phytoplankton model. The colour bar gives the Chl-a concentration in (mg m^{-3}). The model output is provided at the same days as the MERIS satellite images, shown in Figure 3.3.

matter concentrations, compared to the coastal zone, relieving the energy-limitation on growth. In the three weeks between March 26th and April 16th the GEM model describes the evolution of apparently two bloom phenomena: Within the Oosterschelde the chlorophyll-a levels remain high (more than 20 mg m⁻³) till about April 16th. At the same time a bloom develops off shore and some areas at sea reach chlorophyll-a levels above 20 mg m⁻³ on April 9th. On April 16th (day 106) an extended algal bloom is formed within the first kilometres from the coast, covering the Brouwersdam and Oosterschelde entrance. The last two panels show that the model predicts that the bloom is transported to the South to the mouth of the Western Scheldt. Chlorophyll-a levels start to drop below 20 mg m⁻³ in the major part of the Oosterschelde at April 23rd and below 10 mg m⁻³ at the end of April.

3.4.4 Comparison of information

When we compare the spatial distribution of Chl-a concentrations in the model data (Figure 3.5) and the MERIS data (Figure 3.3) it is clear that the model data have a much higher resolution in time, covering every detail of the bloom development phase. The remote sensing data have a higher resolution in space, yet show little information on concentrations in the estuaries. In the remote sensing data the bloom patches seem to be very concentrated, with maxima almost touching the coastline. The blooms show almost a front (at approximately 10 km) with off-shore waters that have a lower Chl-a concentration (see e.g. the image of April 13). The model shows local maxima concentrations off the coast (until April 9) and a more gradual transition off shore. The bloom in the remote sensing data seems to extend further south and longer in time than the simulated bloom.

Despite these differences, it is of more interest whether information from these sources, combined at multiple locations off shore in the Voordelta, gives improved insight in the timing of the *Phaeocystis* bloom near the mouth of the Grevelingen and Oosterschelde estuaries. For this purpose we investigate the time series of the bulk optical indicator of bloom formation, the Chl-a pigment concentration, and the mass concentration of *Phaeocystis* cells.

Figure 3.6 shows a comparison of Chl-a concentrations from the three different data sources included in this study at the monitoring location Goeree 6 in the Voordelta area. Note that the satellite data that cover the GEM grid cell that includes the Goeree 6 location have been averaged. In this figure the model results are plotted every hour in order to visualize the large effect of the tides on the Chl-a at a specific geographical location. For example, the model describes a rise in the Chl-a concentration at Goeree 6 from 5 to 25 mg m⁻³ in the second week of April. Superposed on this average rise the Chl-a level show a significant tidal variation caused by the combined effect of tidal flow and the gradients in Chl-a field (Figures 3 and 5). Although this effect is not able to explain

all differences between model, MWTL data and MERIS data, it does complicate a direct validation. For example, if during the bloom formation two measurements are made a few hours apart, the concentrations can potentially differ by as much as 10 mg m⁻³. At occasions when the spatial gradients are much smaller, the influence of the tides is also smaller, like in the decay phase of the bloom.

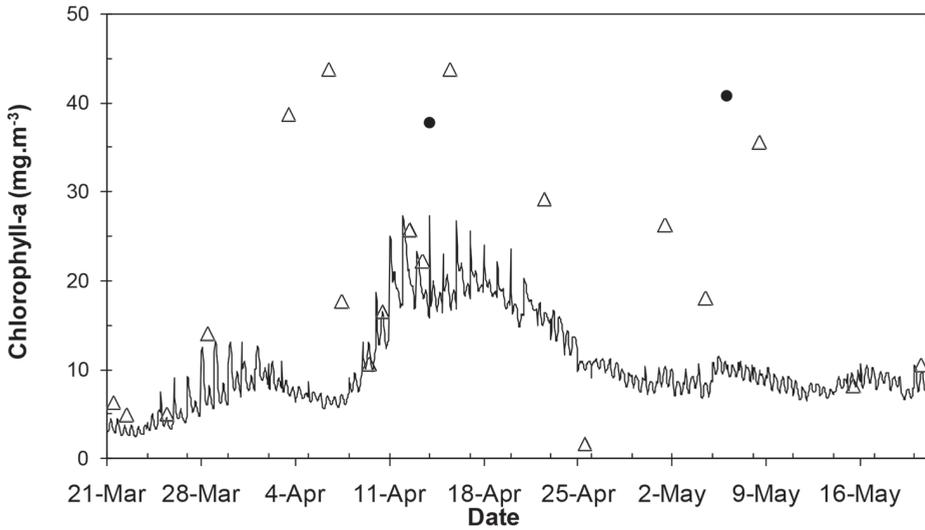


Figure 3.6: Time series of the Chl-a levels at station Goeree 6 in the Voordelta. The line presents the GEM model results. The open triangles are concentrations derived from remote sensing (MERIS), while the solid circles are based on laboratory HPLC measurements from in-situ water samples (MWTL).

The simulated Chl-a concentration shows a double peak structure, with a first concentration increase around April 1st (day 91) and another around April 10th (day 101). The first bloom period coincides with a period of enhanced light availability, due to a combination of solar irradiance and low wind speed and water turbidity (data not shown here). The MERIS images taken at days 87 and 93 confirm this first bloom period (see Figure 3.3). The satellite data and model results show a consistent start of the second bloom period (April 9-14). However, at maximum the model results (26 mg m⁻³) lay below the MERIS observations (43 mg m⁻³) and the HPLC measurements (day 104.6, 37.8 mg m⁻³). The measurements taken between May 1st and May 8th demonstrate that the decline of the bloom is not well reproduced by the model, although there is better convergence at day 135 (May 15th).

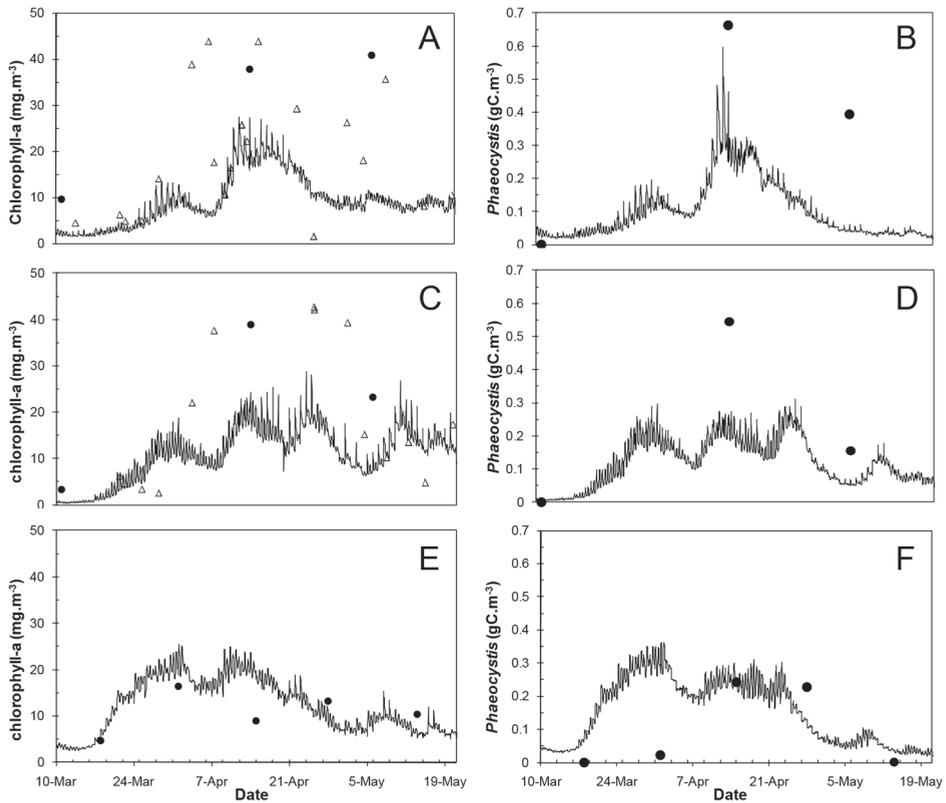


Figure 3.7: Time series of Chl-a levels (left panels) and *Phaeocystis* concentration (right panels) at two stations in the Voordelta (Goeree 6 (A, B); Walcheren 2 (C, D)) and one station in the Oosterschelde (Wissenkerke (E, F)). The drawn line presents the GEM model result. The open triangles are concentrations derived from remote sensing (MERIS), while the solid circles are based on laboratory HPLC measurements from in-situ water samples (MWTL).

Figure 3.7 shows a comparison of the time series of Chl-a concentration and *Phaeocystis* concentrations at three different locations. The drawn line is based on the GEM model output, while the black dots are MWTL bi-weekly or monthly measurements. In Figure 3.7E it is demonstrated that the model gives a rather accurate reproduction of the measured Chl-a levels within the Oosterschelde at station Wissenkerke. However, the *Phaeocystis* bloom in the model is two weeks earlier than in the observations (Figure 3.7F). Nevertheless, it is important that the timing of the model for the spring bloom at the end of March in the Voordelta can be confirmed by in-situ measurements at three locations and satellite images. This spatiotemporal information can be used for the strategic collection of in-situ samples. For example, based on the information available

from model results and satellite images at March 28th it is possible to schedule water sampling in the Voordelta, well before the emergence of the *Phaeocystis* bloom at the entrance of Lake Grevelingen or Oosterschelde. Fast analysis on the composition by flowcytometer measurement can be used to confirm or deny the harmfulness of the biomass accumulation that is about to start.

3.5 DISCUSSION

One thing that was exceptional for the harmful 2001 *Phaeocystis* bloom in the Voordelta was that it was transported with relatively low-salinity water (circa 27) into the Oosterschelde. Peperzak and Poelman (2008) present evidence that the bloom was about to decline when it entered the relatively clear, calm and shallow Oosterschelde estuary, inducing massive *Phaeocystis* sedimentation that most-likely resulted in anoxia and a loss of the mussel harvest (equivalent of 20 million Euro). An early detection of the harmful *Phaeocystis* bloom would have allowed shellfish growers to take appropriate measures. The purpose of this discussion is to explore how the synergetic use of in situ data, satellite data and modelling can effectively contribute to an early warning system for harmful effects of *Phaeocystis* blooms.

A key problem that is identified in the interpretation of the data of 2003 is the considerable variability in the relationship between total community chlorophyll concentration and *Phaeocystis* abundance, and the resulting difficulty in reconstructing *Phaeocystis* abundance from field chlorophyll measurements. Historic data already show that in the spring bloom period variation of *Phaeocystis* colony abundance does not at all resemble the variation in phytoplankton biomass or Phytoplankton Colour index (Gieskes et al., 2007). Based on community composition monitoring in the Belgian coastal zone, Muylaert et al. (2006) demonstrated that in 2003 the *Phaeocystis* bloom showed a significant spatial variation in timing and magnitude. Equally important is that diatoms and other algae always contribute to the Chl-a budget at each station (Figure 3 in Muylaert et al., 2006).

Note also that before the GEM model output is compared to the Chl-a concentrations measured in the laboratory or by satellite, the carbon present in phytoplankton groups is multiplied with a Chl-a to C ratio. This ratio is specific for each group (diatoms, flagellates, dinoflagellates and *Phaeocystis*) and for the growing conditions, in particular a function of N-, P- or light-limitation (Blauw et al., 2009). In the Voordelta, spring bloom growth conditions are highly variable under the influence of tidal mixing, wind stress and turbidity, freshwater inflow with nutrients, nutrient limitation after the initial exponential growth phase and so on. Under these rapidly changing environmental conditions it can

be assumed that the algae adopt changing physiological responses, for example in their Chl-a to C ratio. Despite the large uncertainty on Chl-a to C ratios, the overall matching between model and observation is rather satisfactory.

The in-situ data, satellite data and model results differ widely in their information on offshore development of a threatening algal bloom: the field data at most monitoring stations had a temporal resolution of at most twice per month during the bloom period. This is too limited to monitor bloom development and transport, which can occur within one week. The flowcytometer data at the Brouwersdam with almost daily coverage gave a much better impression of bloom timing. The rise and maximum peak of the *Phaeocystis* bloom occurred between 10 and 16 April. It is unclear how representative the observations at station Brouwersdam are for other areas and estuaries in the Voordelta. Ideally one would like to have this type of measurement at stations offshore and at the mouth of the Oosterschelde where *Phaeocystis* blooms are potentially harmful.

From the 2003 hind-cast exercise it is clear that the remote sensing information has been severely restricted by clouds. Nevertheless, the data cover the onset of a bloom formation close to the shoreline and estuaries. Elevated levels of chlorophyll-a can first be reported on Thursday April 10th, the first processing day after a non-obscured MERIS observation of the area on April 9th. The next good image is at April 13th, showing an extensive bloom in the whole Voordelta. Reliable observations in the estuaries such as the Oosterschelde were scarce. Some improvement can be made if Chl-a maps, derived from other instruments like MODIS on Terra and Aqua satellites, are used to increase the observation frequency and enhance the chance to collect additional non-clouded observation from the coast. The model results support the idea that validation of satellite data in bloom conditions require that remote sensing and in-situ measurements must be sampled within a small time window (few hours). Unfortunately this is rarely realized in the absence of high-frequency automated monitoring stations.

The relevance of satellite information would be much higher if *Phaeocystis* detection in the optical reflection signal can be achieved. However, the pigment composition of *Phaeocystis* is not very different from that of other fucoxanthin- and fucoxanthin-derivative-containing phytoplankton groups (Antajan et al., 2004). Astoreca et al. (2009) found in laboratory experiments that potentially stronger absorption at 467 nm by the pigment chlorophyll c3 might enable discrimination between *Phaeocystis* and diatoms. In the field, the positive detection of this relatively weak absorption feature would require a *Phaeocystis* cell density in the order of 10 million cells per litre (Astoreca et al., 2009). In the near future this new monitoring capability for specifically detecting *Phaeocystis* biomass might be successful.

In this study it was observed that the GEM model simulates rather well the moment when conditions were favourable for phytoplankton growth. However, the *Phaeocystis*

bloom development in the model occurred simultaneous with the bloom development expressed in Chl-a. In the field data the *Phaeocystis* bloom developed circa 2 weeks later and was preceded by a diatom bloom. This is consistent with earlier reported observations (Figure 9 in Reid et al., 1990; Peperzak, 2002) that *Phaeocystis* blooms can be preceded by a diatom bloom. However, for the Dutch coastal zone this is certainly not always the case (Peperzak et al., 1998; Blauw et al., 2010). Also in the Belgian North Sea a clear distinction between a diatom and *Phaeocystis* dominated bloom is not always clear (Muylaert et al., 2006). Observed peak bloom abundances of *Phaeocystis* (See Figures 2, 7B,D) generally exceed those in the model. The use of constant carbon content per *Phaeocystis* cell in the conversion from cells per litre to gC/m^3 may play a role in this. During the fast bloom development when cell numbers double every day, total *Phaeocystis* biomass may increase at a smaller rate than the cell number density.

3.6 IMPLEMENTATION OF AN EARLY WARNING SYSTEM

So far, we have mainly focussed on how the four data sources can be used in combination to reconstruct the development of the spring bloom of Chl-a and *Phaeocystis* in the Voordelta area. In this section we address the question in what way the information should be combined to provide an early warning system. Although scale differences and timing differences between satellite Chl-a results and model predictions have been shown to exist, it is also evident that both contain relevant information on near-coastal algal blooms that is impossible to obtain by other means. Satellite data contain information extracted from instantaneous colour observations which show good comparison with in-situ observations (Van der Woerd and Pasterkamp, 2008; Peters et al., 2009). Model results contain the compound information of nutrients inputs, winds and currents, translated into biomass and Chl-a development, which also show good comparison with in-situ observations (e.g. Los and Blaas, 2010). In the ideal case these essentially different realizations of the same parameter should produce approximately the same spatial patterns and temporal development.

In the future, assimilation of satellite observed Chl-a observations into ecological models will improve the spatial correctness of the models and enhance the relevance of satellite information. When we focus at the case of *Phaeocystis* blooms threatening the Oosterschelde, it is evident that we need information on the presence (amount or concentration), composition, horizontal extent, growth/decline and movement of the bloom. Interesting would also be the vertical extent of the bloom and its physiological state. In 2001 the *Phaeocystis* bloom and mussel mortality in the Oosterschelde coincided with exceptionally low salinities (Peperzak and Poelman, 2008). Although the relation

between the fresh water inflow and the mussel mortality is unclear, it seems wise to be extra alert when similar conditions as in 2001 occur. To complete the picture, one would also like to know what the fate (path) of the algal biomass is (after the bloom) to assess the risk on oxygen depletion.

At present we concede to the common understanding that satellite data and models are two almost separated sources of information. Satellite data is the best source of actual pattern information and models provide information any time (also on cloudy days) and facilitate interpretation and prediction. In-situ measurements of the *Phaeocystis* abundance remain indispensable. It is suggested to combine the information in a three-step warning procedure:

- Detect the spatial distribution of a bloom in near-real time with satellites and make a model prediction (3-5 days in advance) of the potential biomass evolution and transport based on the weather forecast and the present bloom distribution as estimated from the remote sensing information and / or model results.
- Detect the abundance of algal species in the coastal algal bloom with flowcytometer measurements to check if the bloom is dominated by *Phaeocystis* and make a model prediction of the cell concentration and timing of the decay.
- Detect the presence of *Phaeocystis* with flowcytometer measurements at the entrance of the Oosterschelde and combine this information with automated salinity, nutrient and oxygen measurements.

Based on the 2003 reconstruction it is expected that despite clouds interference, satellite imagery is sufficient to see different manifestations of the bloom development. The rapid (within 24 hours) availability of satellite products is feasible (Van der Woerd et al., 2005) and crucial for an early warning procedure. These images serve well to timely warn for the presence of a bloom and direct the sampling for *Phaeocystis* abundance. Also the model seems to accurately simulate the timing of the phytoplankton spring bloom. Model predictions over a period of approximately 5 days, would provide information about probable changes in horizontal extent, direction of movement, growth/decline and probably also of the physiological state of the bloom. It is recommended for operational use to combine the separate information sources into an on-line information bulletin.

3.7 CONCLUSIONS AND RECOMMENDATIONS

In this study we have investigated the potential for an algal bloom early warning system in the Voordelta, based on integrated use of in-situ and satellite data and results from biogeochemical modelling. We assessed the quality of the information provided, defined as the accuracy of the information on the bloom characteristics at the mouth of the Oosterschelde. Our aim was to establish the skill of the combined data sources to detect *Phaeocystis* blooms developing offshore in the Voordelta, allowing early warning to shellfish growers of this threat, who can then decide to take measures, like the relocation of the mussels to less vulnerable waters. MERIS observations can produce high-quality near-real-time chlorophyll maps, showing the patterns and evolution of potential harmful bloom events. Flowcytometry is a powerful tool to make actual in-situ measurements of the *Phaeocystis* concentration at a limited number of stations. Prediction about biomass growth or movement of blooms for any time of day can only be made by a model, based on biogeochemical and hydrodynamic principles. The results presented in this paper are encouraging, but do also show that the three building blocks of an early warning system (field data, satellite data and model data) still have some shortcomings and do not yet fit smoothly together.

This study has made it clear that a more comprehensive tool for monitoring and prediction of the spatial evolution of algal blooms in the Voordelta should be based on a better integration of data and the GEM model. In particular, since bloom formation is triggered by light conditions, it is recommended to feed actually observed light parameterisations in the model. This light parameterisation can be based on geostationary meteorological satellites (cloud conditions) and ocean colour satellites (turbidity information). In this study we have already made a first step in integrating remote sensing information with the GEM model for the southern North Sea, by using turbidity fields from remote sensing as model forcing. Secondly, in order to provide a tighter integration between Chl-a data from satellites and the GEM model, it is recommended to develop better C to Chl-a parameterizations of algal species groups in a broad range of environmental conditions and couple these to the spectral absorption properties that are used in the satellite retrieval of Chl-a concentrations. Finally, the comparison between field data, remote sensing data and model data should be done for more years to get a useful statistical representation of the reliability of the different data sources and their combined use.

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