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Analysis of the spatial evolution of the 2003 algal bloom in the Voordelta (North Sea)

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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.

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

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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., submitted for publication).

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., 2007). 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 undersampling 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).

2. Study area description

This study focuses on the southern part of the Dutch coastal zone, the Voordelta and adjacent (former) estuaries and inlets (Fig. 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 freshwaters in a relatively shallow shelf sea, enclosed between the United Kingdom and continental Europe.

The main freshwater (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 m, 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 freshwater plume from the Haringvliet and Nieuwe Waterweg.

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 km^2 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 downwelling 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.