OBSERVING AND EXPLAINING THE TIMING OF SPRING/SUMMER ALGAL BLOOMS IN THE SOUTHERN NORTH SEA USING OCEAN COLOUR REMOTE SENSING

DIMITRY VAN DER ZANDE[1], GENEVIEVE LACROIX[1] AND KEVIN RUDDICK[1]

Royal Belgian Institute of Natural Sciences, MUMM, Brussels, Belgium

[1]Gulledelle 100, 1200 Brussel, Belgium (dimitry.vanderzande@mumm.ac.be)

INTRODUCTION

Phytoplankton or algal blooms (AB) are generally defined as a rapid increase in the biomass of algae in an aquatic system (e.g. Cloern, 1996). The naturally occurring spring algal blooms are an important source of organic food for the subsequent trophic levels in the marine food chain of the Southern Bight of the North Sea (SNS). The timing of the bloom may influence the secondary production (match-mismatch hypothesis) and the higher trophic levels and thus algal bloom information is useful for fish stock management (Platt et al., 2003). The magnitude and species composition of algal blooms in turn depends on human activities, particularly in coastal areas where nutrient discharges from rivers can cause eutrophication (Beman et al., 2005). In eutrophicated perturbed ecosystems the bloom timing is also important because it determines the period when undesirable effects can occur. Extensive blooms can disrupt the food chain or deposit thick layers of white odorous foam on the beach in case of *Phaeocystis globosa* (Lancelot, 1995). Sustainable management of these marine ecosystems requires detailed information of the algal bloom intensities and their dynamics.

The development of a bloom depends on the interplay of multiple factors, including light and nutrient availability as well as grazing pressure and species assemblages of both the grazing and grazed communities (Irigoien et al., 2005). In deeper pelagic systems, it is the onset of stratification combined with increased surface light in spring that usually triggers the bloom (e.g. Sverdrup, 1953; Pingree et al., 1976; Smetacek and Passow, 1990). In well-mixed coastal waters where stratification rarely plays a role, the light availability in the water column, determined by the ratio between the eupothic layer and the total depth, is the limiting factor at the end of the winter (e.g. Iriarte and Purdie, 2004; Wiltshire et al., 2008). Once a bloom is triggered, its magnitude and duration are controlled by the nutrient availability and the grazing. Bloom timing shows regional differences and interannual variability that could be attributed to different factors such as the effects of: increased nutrients and light-limiting suspended particles carried by freshwater runoff which vary greatly from year to year (e.g. Chesapeake Bay, Gallegos et al., 1997), the meteorological conditions which affect the ecosystem via temperature (e.g. North-western North Sea, Sharples et al., 2006), rainfall and wind (e.g. Southern North Sea, Breton et al., 2006; North Atlantic, Henson et al., 2006).

The main objective of this study is to evaluate the potential of satellite remote sensing methods to map and explain AB dynamics in the English Channel and the SNS. Satellite chlorophyll a (CHL) data are a suitable proxy for phytoplankton biomass and provide a unique means to monitor AB dynamics over a large area with a temporal and spatial resolution that is unmatched by traditional seaborne observations. Standard satellite-based CHL products from MERIS and MODIS were used to generate AB timing maps for the years 2003 to 2010. These yearly AB timing products are supplemented with maps and time series of parameters expected to affect timing such as total suspended matter (TSM) and total water depth. Results are presented for the spatial and interannual variability of AB timing in the Southern North Sea as detected by satellite data, and will be explained in terms of the relevant factors.

MATERIALS AND METHODS

STUDY AREA

The study area is the Southern Bight of the North Sea (SNS). The SNS is a system with strong tidal currents where waters of Atlantic origin are mixed with fresh water river inputs (Fig. 1). The total suspended matter (TSM) distribution in the area is the result of the hydrodynamics mainly driven by tides and the prevailing winds. The input of suspended matter originates mainly from the English Channel and the resuspension/erosion of fine-grained sediments (Fettweis et al., 2006). The area is characterized by significant spatial variability of TSM with highest concentrations close to the coast and less turbid waters offshore. TSM varies in time over the seasonal cycle and on smaller time scales due to tides, the spring neap cycle, storm events and other wind effects. In particular in the Belgian Coastal Zone (BCZ), TSM measurements indicate variation between a minimum of 20-70 mg/l and a maximum of 100-1000 mg/l while low values (<10mg/l) have been measured in the offshore area (Fettweis et al., 2007).

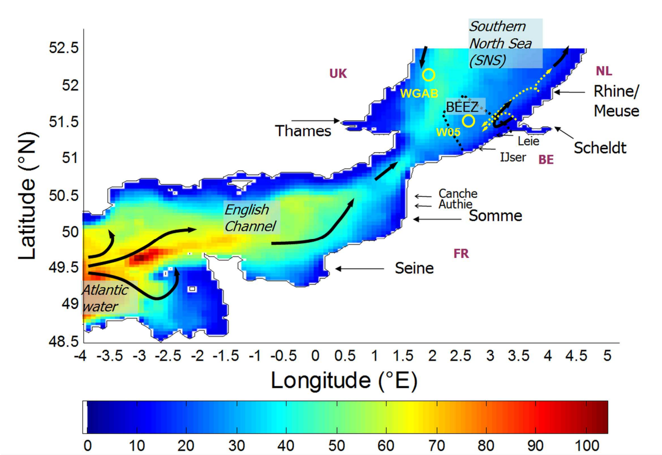

Fig. 1. Map of the English Channel and the Southern North Sea (SNS) with schematic representation of the circulation (solid arrows) and the dispersion (dotted arrows) redrawn from Lacroix et al. (2004). The Belgian Exclusive Economic Zone is delimited by the dashed line. The bathymetry is given by the color scale.

REMOTE SENSING DATA

The Medium Resolution Imaging Spectrometer (MERIS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) are multi-spectral sensors on board EOS-PM ('Aqua') and ENVISAT, both of which are polar orbiting satellites launched in 2002. Oceanographic parameters related to ocean colour can be derived from the spectral bands of these sensors, such as CHL and TSM concentrations. The imagery that has been collected by these sensors provides an extensive and unprecedented coverage for coastal and oceanic regions, both regarding temporal and spatial aspects.

In this study CHL products from both instruments were used, binned to a spatial resolution of 2 km and an approximately daily temporal resolution for the SNS during cloud-free periods. For MERIS-processing, a composite was generated based on both the algal 1 and algal 2 products (algorithm version used: MEGS7.5) which was then used for AB detection. A quality control has been applied according to the standard MERIS product confidence flags. In case of the MODIS data, a flagging procedure for turbid pixels is used to detect where the MODIS CHL is likely to be contaminated. This is done using a model relationship between normalized water radiance at 667nm (*nLw*667) and CHL for case 1 waters. Details on this flagging procedure can be found in Park et al. (2010).

Remotely sensed TSM data are estimated from water-leaving reflectance at 667 nm using the algorithm of Nechad et al. (2010). In the case of quality issues due to atmospheric correction error, straylight or sun-glint, the pixel is masked as unreliable and rejected. Multi-temporal composite maps for the months January to April (incl.) were used as a representation of the turbidity conditions during the winter and early spring. This was done for each year separately as well as for the years 2003 to 2010 combined.Next to the composite maps also CHL and TSM time series were extracted from the satellite datasets for specific stations: the Belgian W05 station (51.42°N, 2.80°E) and the UK WGAB station (51.98°N, 2.08°E). These stations are located in highly turbid waters (yellow circles in Fig 1.)

AB DETECTION AND TIMING

Algal bloom detection is performed by comparison of the near real-time chlorophyll concentration with a reference (threshold) value that is defined a priori. The reference chlorophyll is defined by the top 10% level of the satellite chlorophyll concentrations during the growing season (March-November incl.) of the studied year (Park et al., 2010). This reference product is called the chlorophyll 90 percentile (P90) product. This threshold is sensor specific and variable with location and can thus cope with a large spatial variability of chlorophyll concentration, which is important especially when the target area is large as the SNS. Using a sensor specific threshold map for daily AB detection has the advantage of mitigating the effect of systematic errors in satellite CHL caused by, for example, sensor calibration or atmospheric correction errors or yellow substance or mineral particles. For example, using this approach, if one sensor systematically overestimates CHL by a factor, say 30%, or gives a systematic offset or minimal concentration of, say a few mg/m³, in turbid regions, this will make absolutely no difference to the AB detection. The daily AB map for both MERIS and MODIS are then combined to give a single daily merged AB map with priority given to MERIS. Information from the previous 7 days is used for pixels where near real-time data were unavailable. The AB detection maps are subsequently used to compose yearly AB timing maps providing pixel by pixel information of the date at which a first AB was detected. AB timing maps were generated for the years 2003 to 2010 and an average AB timing map for this period was created to obtain a general view of the AB timing in the SNS. The complete production process is presented in figure 2.

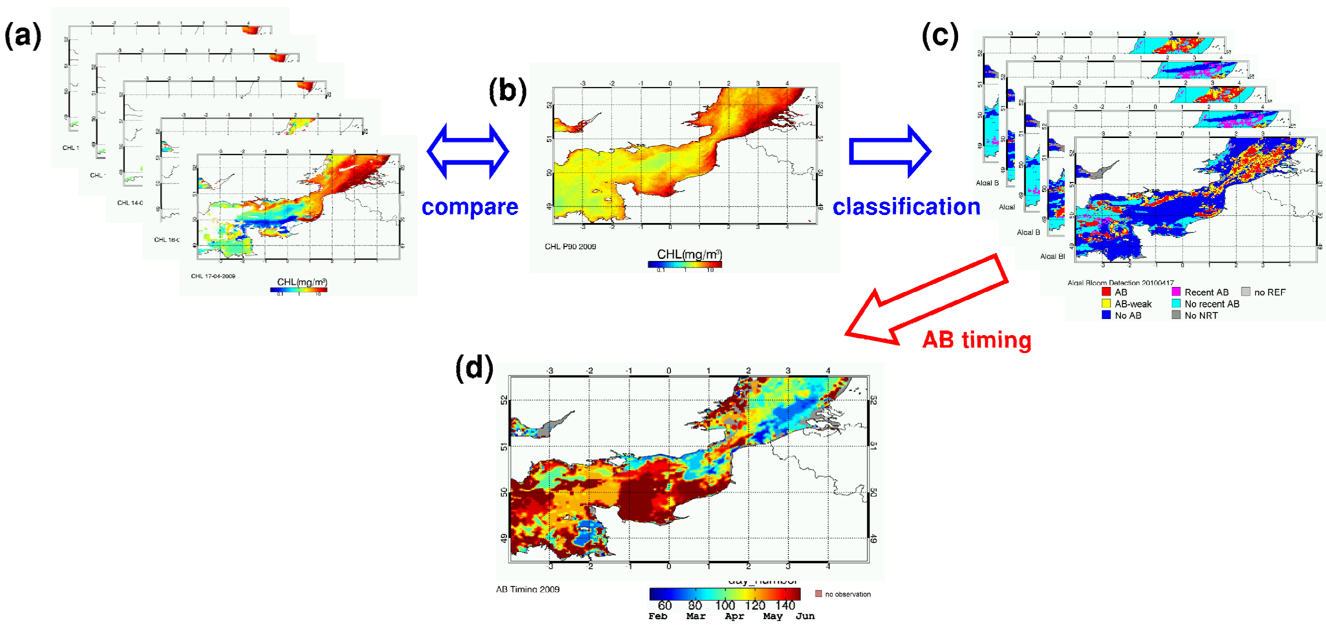

Fig. 2. Daily CHL maps from MERIS and MODIS (a) with a spatial resolution of 2 km are compared pixel by pixel to the sensor specific threshold maps (b) (CHL-P90 per growing season) and are classified to one of the six classes (c). Information of the last 7 days is taken into account in case of near real-time data unavailability. A yearly AB timing product (d) is generating by providing the first date at which an AB was detected.

RESULTS & DISCUSSION

AVERAGE AB TIMING MAP

In European waters at a large scale a general link between AB timing and latitude can be observed where the ABs occur later in the growing season from South to North due to light availability (data not shown). The situation in the North Sea is more complex since other factors such as total water depth, TSM, and human induced eutrophication play a more significant role. Although some significant inter-annual variability of the AB timing in the English Channel and the SNS is evident (data not shown), the general spatial variability is demonstrated in the mean AB timing map shown in figure 3. In the shallow and highly turbid waters of the SNS the temporal variability of light attenuation is linked to resuspension and advection of suspended particulate matter which directly impacts the variability in AB timing as can be seen in the mean winter TSM maps. Late winter blooms (green in figure 3) occur in eastern French coastal zone and Belgian off-shore waters as a result of the combination of shallow waters and low TSM values which results in high light penetration in the water column. Early spring blooms (yellow to orange in figure 3) can be observed in the nutrient-rich waters of the Belgian and Dutch coastal zones and north of the mouth of the Thames as a result of shallow waters with high TSM values in the winter which decrease in the spring. AB are delayed to the summer (red in figure 3) in the central and western part of the English channel where waters are clear but deeper.

These results support the assumption that the AB onset is linked to light availability which in turn is directly related to the TSM in the turbid shallow waters of the SNS. A more detailed assessment of this assumption can be made looking at the temporal variability of the AB timing and TSM through the years 2003-2010 in two stations located in shallow highly turbid waters. The time series of CHL and TSM are shown in figure 4 with a green vertical line indicating the AB onset per year. Both stations are generally characterized by spring blooms with a significant variability in AB intensity. In station W05, the years 2004 to 2007 are relatively moderate years in terms of AB intensity compared to the years 2003, 2008, 2009 and 2010. In station WGAB, the years 2005 and 2006 are relatively moderate years compared to the other years. Comparing the CHL and TSM time series show that ABs generally start when the local TSM concentrations start to decrease which results in an increase of available light in the water column.

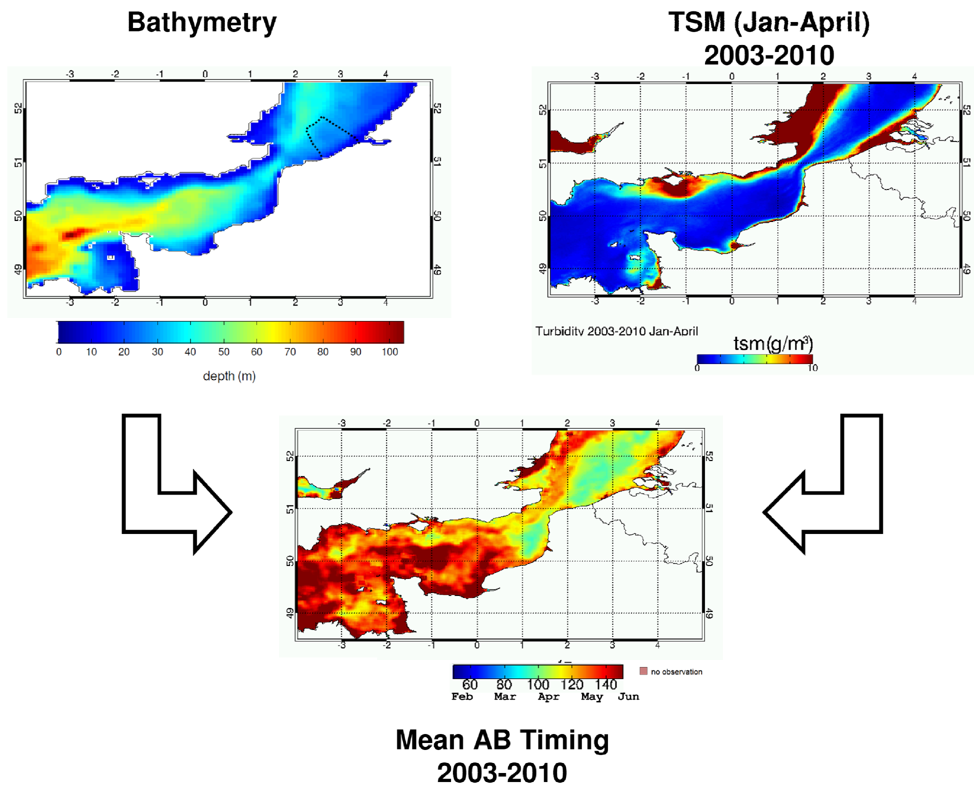

Fig. 3. The spatial distribution of the AB timing (bottom) computed as the first day that the daily CHL concentration exceeds the threshold value (i.e. CHL-P90). In the shallow and highly turbid waters of the SNS the AB timing shows similar spatial patterns as the mean TSM concentrations in the months January to April (top right). Later blooms occur in the western English Channel in the clear but deeper waters (top left).

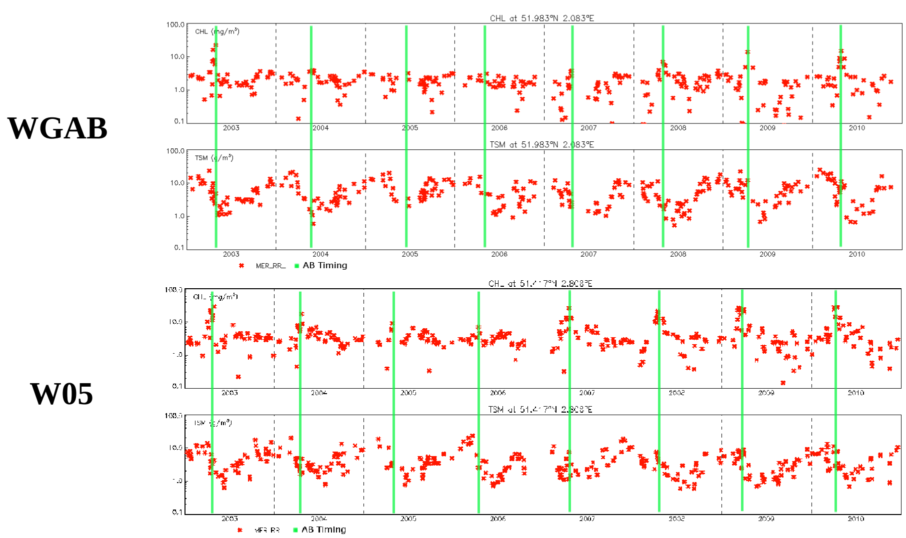

Fig. 4. Multi-temporal time series of CHL and TSM for stations WGAB (top) and W05 (bottom) in highly turbid shallow waters as measured by MERIS showing the temporal variability in AB timing (green vertical line) which is triggered by a decrease of the TSM concentrations in spring.

CONCLUSIONS

MERIS and MODIS ocean colour products were used to illustrate the strengths of satellite remote sensing to study the AB dynamics in the English Channel and SNS. ABs were detected by comparing the daily CHL maps pixel by pixel with a threshold value. This threshold value was the CHL-P90 value for the considered growing season (March-November incl.) providing a sensor and location specific threshold value. The daily AB detection maps were compiled into a mean AB timing map providing a spatial overview of AB timing patterns in the studied area. Comparing this AB timing product with TSM data both spatially and temporally has confirmed the major role played by light in the bloom triggering for the considered region. This finding is supported by Peperzak et al. (1998) who found that *Phaeocystis* blooms were triggered after a daily irradiance threshold was passed in Dutch coastal waters. In the SNS and English Channel earlier blooms are observed in shallow clear waters and later blooms are present in turbid waters. Future research will focus on taking other relevant factors such as euphotic depth, water column stratification and nutrient availability into account to improve the understanding of AB dynamics in the studied region.

ACKOWLEDGEMENTS

This work has been carried out in the scope of the AquaMar project (7th Framework program) and was supported by the MarCoast 2 project (www.marcoast.eu). Satellite data was provided by NASA and ESA and preprocessed by ACRI-ST.

REFERENCES

Beman, J.M., Arrigo, K.R., Matson, P.A., 2005. Agricultural runoff fuels large phytoplankton blooms in vulnerable areas of the ocean. Nature 434, 211-214.

Breton, E., Rousseau, V., Parent, J.-Y., Ozer, J., Lancelot, C., 2006. Hydroclimatic modulation of the diatom/*Phaeocystis* blooms in the nutrient-enriched Belgian coastal waters (North Sea). Limnology and Oceanography 51, 1-14.

Cloern, J.E., 1996. Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Fransisco Bay, California. Reviews of Geophysics 34, 127-168.

Fettweis, M., Francken, F., Pison, V., Van den Eynde, D., 2006. Suspended particulate matter dynamics and aggregate sizes in a high turbidity area. Marine Geology 235, 63-74.

Fettweis, M., Nechad, B., Van den Eynde, D., 2007. An estimate of the suspended particulate matter (SPM) transport in the southern North Sea using SeaWiFS images, in situ measurements and numerical model results. Continental Shelf Research 27, 1568-1583.

Gallegos, C.L., Jordan, T.E., Correll, D.L., 1997. Interannual variability in spring bloom timing and magnitude in the Rhode River, Maryland, USA: observations and modelling. MEPS 154, 27-40.

Henson, S.A., Robinson, I., Allen, J.T., Waniek, J.J., 2006. Effect of meteorological conditions on interannual variability in timing and magnitude of the spring bloom in the Irminger Basin, North Atlantic. Deep Sea Research I 53, 1601-1615.

Iriarte, A., Purdie, A.D., 2004. Factors controllong the timing of major spring bloom events in an UK south coast estuary. Estuarine, Coastal and Shelf Science 61, 679-690.

Irigoien, X., Flynn, K.J., Harris, R.P., 2005. Phytoplankton blooms: A 'loophole' in microzooplankton grazing impact? Journal of Plankton Research 27, 313-321.

Lacroix, G., Lancelot, C., Ruddick, K., Spitz, Y., Gypens, N., 2004. Modelling the relative impact of the rivers Scheldt, Rhine, Meuse and Seine on the availability of nutrients in Belgian waters (Southern North Sea) using the 3D coupled physical-biological model MIRO&CO-3D, ICES Annual Sciences Conference, Vigo.

Lancelot, C., 1995. The mucilage phenomenon in the continental coastal waters of the North sea. Science of the total Environment 165, 83-102.

Nechad B., Ruddick K. & Park Y., 2010. Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. Remote Sensing of Environment, Vol. 114, pp. 854–866

Park, Y., Ruddick, K., Lacroix, G., 2010. Detection of algal blooms in European waters based on satellite chlorophyll data from MERIS and MODIS. International Journal of Remote Sensing 31, 6567-6583.

Peperzak, L., Colijn, F., Gieskes, W. W. C., and Peeters, J. C. H., 1998. Development of the diatom-Phaeocystis spring bloom in the Dutch coastal zone of the North Sea: the silicon depletion versus the daily irradiance threshold hypothesis. Journal of Plankton Research 20(3): 517-537

Pingree, R.D., Holligan, P.M., Mardell, G.T., Head, R.N., 1976. The influence of physical stability on spring, summer and autumn phytoplankton blooms in the Celtic Sea. Journal of the Marine Biological Association of the United Kingdom 56, 845-873.

Platt, T., Fuentes-Yaco, C., Franck, K.T., 2003. Spring algal bloom and larval fish survival. Nature 423, 398-399.

Sharples, J., Ross, O.N., Scott, B.E., Greenstreet, S.P.R., Fraser, H., 2006. Inter-annual variability in the timing of stratification and the spring bloom in the North-western North Sea. Continental Shelf Research 26, 733-751.

Smetacek, V., Passow, U., 1990. Spring bloom initiation and Sverdrup's critical-depth model. Limnology and Oceanography 35, 228-234.

Sverdrup, H.U., 1953. On conditions for the vernal blooming of phytoplankton. J. Cons. Int. Explor. Mer 18, 287-295.

Wiltshire, K.H., Malzahn, A.M., Wirtz, K., Greve, W., Janisch, S., Mangelsdorf, P., Manly, B.F.J., Boersma, M., 2008. Resilience of North Sea phytoplankton spring bloom dynamics: an analysis of long-term data at Helgoland Roads. Limnology and Oceanography 53, 1294-1302.