DETECTING ALGAE BLOOMS IN EUROPEAN WATERS

Young-Je Park[(1)] & Kevin Ruddick[(2)]

Management Unit of the North Sea Mathematical Models (MUMM)
Royal Belgian Institute for Natural Sciences (RBINS)
100 Gulledelle, 1200 Brussels, Belgium
Email: [(1)] Y.Park@mumm.ac.be, [(2)] K.Ruddick@mumm.ac.be

ABSTRACT

A near real-time algal bloom detection service has been developed for European waters. Daily chlorophyll *a* data from Envisat/MERIS and Aqua/MODIS are compared to a predefined threshold map to determine whether an algal bloom has occurred. The design of the threshold map takes account of two factors. Firstly, over European waters regional differences in typical and extreme levels of chlorophyll *a* span two orders of magnitude. A concentration, e.g. 2 µg/l, that would be considered as a bloom concentration in one region could correspond to a relatively low concentration in another region. Secondly, the errors in satellite chlorophyll *a* can be significant in coastal waters effectively giving an artificial background level in satellite images. To account for these two factors a threshold map has been designed using satellite chlorophyll *a* data from a previous year, with separate threshold maps for each sensor to take account of sensor-specific bias. This threshold is defined here as the top 10% level of a previous year's chlorophyll *a* data. The results of algal bloom detection in various regions are analysed in terms of bloom timing, duration and strength. Differences between the performance for the MERIS and Aqua sensors are also discussed.

1. INTRODUCTION

Satellite chlorophyll *a* concentration (Chl) data provide a unique means to monitor an algal bloom (AB) synoptically over a large area. Past and current uses of ocean colour in harmful algal bloom studies are reviewed in [1] and [2].

An AB detection service in European waters is in operation in the framework of the Marine & Coastal Environmental Information Service (MARCOAST) project [3]. This service presents, as a basic product, a daily map of algae blooms detected in the European waters, which is delivered to users a day after satellite overpass by email interface.

The term "algae bloom" is generally defined as *rapid growth* of algae, which can be related to the temporal derivative of a suitable proxy for algal biomass, such as Chl. Such a definition can be translated into a satellite AB detection algorithm by comparing an instantaneous

Chl map with, for example, mean Chl over the preceding two months, excluding the previous two weeks [4]. However, this was found not suitable here for the detection of early spring blooms in February/March in the North Sea or higher latitudes since during the preceding winter months satellite Chl data is generally unavailable because of cloud cover and/or low sun angle. An approach has, therefore, been developed comparing an instantaneous Chl map with a threshold Chl map. This corresponds to defining an AB via *high biomass* rather than rapid growth, although in practice the two concepts are closely related.

The harmfulness of an AB cannot generally be detected by satellite [2] and further information is required to determine whether an AB is a HAB (Harmful Algae Bloom). Such information may come from in situ data for species composition, or from prior region-specific knowledge of the system. As an example, low backscattering relative to Chl has been correlated to blooms of the harmful *Karenia brevis* along the west coast of Florida [1] but general algorithms based on such optical correlations cannot be developed to determine harmfulness of ABs for other regions. The service described here detects only ABs and provides no information regarding harmfulness.

This paper describes the technical aspects of the AB detection service including AB detection procedure and its output, AB flag map in section 2, Chl threshold map in section 3, time-series at several locations in section 4, and MODIS and MERIS Chl comparison and quality control in section 5.

2. AB DETECTION PROCEDURE AND ITS OUTPUT-AB FLAG MAP

The AB detection procedure is illustrated in Fig. 1. Daily Chl data are compared to a predefined threshold map to determine areas where an AB has occurred. This comparison is made for each sensor using separate threshold maps to take account of possible sensor specific bias. Quality control is performed on MODIS Chl to remove turbidity dominated data as described later. The two AB flags are combined to give a single

daily merged AB flag map with priority given to MERIS. Information from the previous 7 days is used for pixels where near real-time data were unavailable. From this European AB flag image, a regional AB flag image and statistics are derived for local areas where users are interested.
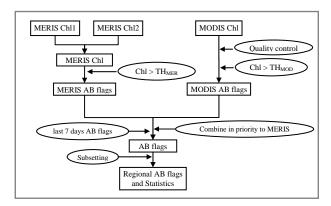

Figure 1. Data flow for algae bloom detection

An example of an AB flag image is shown in Fig. 2. From the previous day's data, a pixel is classified as one of three: 'Algal Bloom (AB)', 'weak Algal Bloom (AB-weak)', 'no Algal Bloom (no AB)', which are indicated in red, yellow and blue in the figure. There are pixels where input Chl may not be available for many reasons such as no satellite observation, cloud cover or bad quality data. For those pixels, the most recent classification from the previous seven days is presented as 'recent Algal Bloom (recent AB)' or 'no recent Algal Bloom (no recent AB)'. In the case that no input data were available within the previous seven days, the pixel is classified as 'no NRT'. The pixels for 'recent AB', 'no recent AB' and 'no NRT' are indicated as pink, cyan and dark grey in Fig. 2. This addition of recent AB information gives better visual representation of the spatial extent of on-going algal blooms.

For sub-areas defined for users, statistical numbers including the percentage of AB pixels and recent-AB pixels are also provided as a quantitative measure for bloom extent.
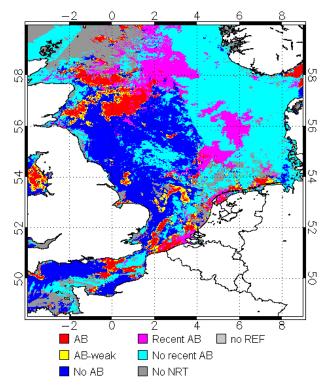

Figure 2. An example of AB flag image of 18-Apr-2007 for the North Sea, showing classification of pixels based on previous day's imagery and previous seven days' classification. See text for colours.

3. CHL THRESHOLD MAP

The threshold Chl used to trigger AB detection for such a large and biologically and optically diverse region must clearly take account of spatial heterogeneity. For example, a Chl concentration of 2 µg/l might be considered as a strong bloom in an oligotrophic region such as the central Western Mediterranean but would be a relatively low concentration, certainly not a bloom, for the eutrophic Belgian coastal waters.

In this study, the threshold was derived from a previous year's satellite Chl data. The threshold for AB and weak AB were defined as the 90 percentile and 80 percentile respectively. This threshold level is defined pixel by pixel, and can thus cope with the large variability across the European waters. For example, the threshold is 0.3~0.5 µg/l in off-shore Mediterranean waters while it can be 5~10 µg/l in Belgian coastal waters. This satellite based threshold might also mitigate the effect of systematic errors in satellite Chl caused by yellow substance or mineral particles. Separate threshold maps are prepared for each sensor to take account of possible sensor-specific bias. A MERIS threshold map derived from 2006 MERIS chlorophyll is shown in Fig. 3. The 90 percentile is also used for water quality assessment

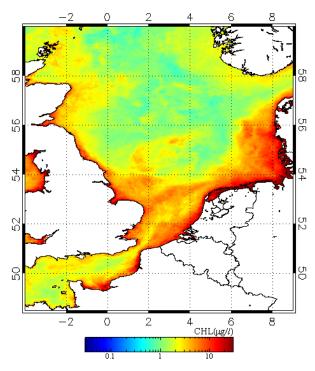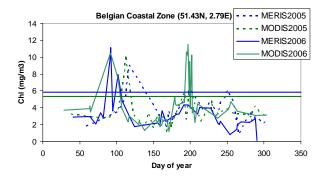in the context of the European Water Framework directive.

Figure 3. MERIS reference chlorophyll map (90 percentile) for the North Sea derived from 2006 MERIS chlorophyll data

4. TIME SERIES ANALYSIS

Time series for selected locations are given for verification of the AB detection algorithm. Fig. 4 shows Chl time series for three stations for 2005 and 2006 in the Belgian coastal waters, the Western Channel and the Baltic Sea. These three locations have different bio-optical properties related to very different ranges of Chl and TSM, but do not necessarily represent typical conditions for the whole of these sea areas which each have highly internal variability .
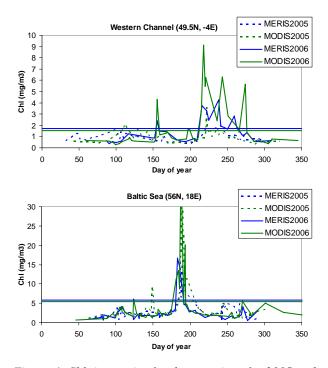

Figure 4. Chl time series for three stations for 2005 and 2006 – in the Belgian coastal waters, the Western Channel and the Baltic Sea – derived from the MARCOAST MERIS and MODIS data. The straight lines show the thresholds used for each sensor for determining algae bloom detection.

Belgian coastal waters (51.43°N, 2.79°E) are relatively turbid and experience algal blooms of relatively high concentration. The MERIS AB threshold derived from 2005 data was 5.86μg/l. In 2006, spring blooms are clearly identified on days 91-92 and 102 by both MERIS and MODIS. The concurrence of the two sensors as regards the AB parameter defined here gives confidence in both the method and in the capability of both sensors to detect AB in this location. The spring bloom timing difference is noticeable between 2005 and 2006. Another bloom on days 195-202 was detected only by MODIS with Chl level similar to the spring bloom. It is not clear whether this is a real bloom or not, because the Chl difference between the two sensors is significant.

The Western Channel (49.5°N, -4°E) has much clearer oligotrophic water with a lower AB threshold of 1.71μg/l calculated from 2005 MERIS Chl data. Blooms were detected on day 155, 216-259 by MERIS, and 155-158, 197-199, 215-274 by MODIS in 2006. Since the bloom detected on 197-199 by MODIS is just above the threshold and MERIS Chl is well below the threshold, this detection seems doubtful. The other two blooms are detected by both sensors, which gives confidence in the algorithm. Bloom strength difference between 2005 and 2006 is noticeable.

The Baltic Sea is characterised by high coloured dissolved organic matter concentration and very high

concentrations of algae during certain summer periods. The MERIS AB threshold calculated for this location was 5.81μg/l. A single AB was detected on days 183-186 by MERIS. Two more blooms on days 124 and 270 were detected by MODIS alone, with Chl level just above the threshold. MERIS Chl remained low on day 124 while it was 4.1μg/l on day 271, which is significantly higher than average, though below the threshold.

5. MODIS-MERIS COMPARISON AND THE QUALITY CONTROL OF MODIS CHL

5.1. Chlorophyll data from MERIS and MODIS

The daily Chl data (MERIS Chl1, Chl2 and MODIS Chl) are generated from standard level 2 products by ACRI-ST within the MARCOAST project. Unreliable data were excluded using the product confidence flag for MERIS Chl. Pixels with low sun and less than 2 pixels from cloud pixels (for Chl2 data) are also excluded. For MODIS, the pixels where high viewing angle or sun zenith or straylight or high-glint contaminated are excluded using level-2 flags [5].

The MERIS Chl1 [6] product is derived from a blue-green band ratio algorithm which is appropriate for oceanic case 1 waters, while the MERIS Chl2 [7] product is derived by a neural network algorithm designed for case 2 waters. Either Chl1 or Chl2 is used according to the case2 water flag.

The MODIS Chl product is computed by another blue-green ratio algorithm, OC3M [8], regardless of water types. Since the blue-green ratio is affected not only by phytoplankton but also by CDOM and mineral particles, MODIS Chl is used with care, as discussed in the next sub-sections.

5.2. Comparison of MERIS and MODIS Chl

The MODIS 2005 Chl annual mean was compared to MERIS for the European waters defined by latitude 35°N-72°N, longitude 15°W-30°E. Linear regression analysis shows that MODIS and MERIS 2005 mean chlorophyll is highly correlated (r^2=94%) and shows good agreement within ~20% difference for the intermediate range (0.3-μg/l). However, MODIS chlorophyll is in general higher than MERIS for high concentration, and vice versa.

The spatial distribution of the relative difference of MODIS Chl from MERIS Chl is shown for European waters in Fig. 5. Significant parts of the map are green, which indicates a difference of less than 20%. Cyan and blue colours show MODIS Chl lower than MERIS by more than 20 or 50 %, respectively. Such waters include most of the Mediterranean Sea and some offshore waters, where Chl is generally low. Higher MODIS Chl by more than 50%, as shown in red and pink pixels, is

seen in the southern North Sea, the Irish sea, nearshore waters in the Baltic Sea and some off-shore waters. The distinct pattern of higher MODIS than MERIS in the southern North Sea suggests that the difference is related to the East Anglian suspended matter "plume" [9]. However, it is not clear whether the difference in the Baltic Sea is caused by mineral particles or yellow substance absorption or other reasons such as atmospheric correction. The differences seen in clear open seas might be caused by a small number of observations or mismatch in observation days.
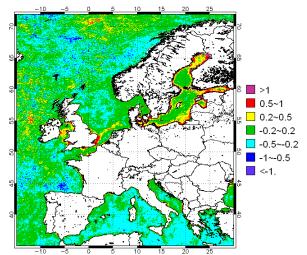

Figure 5 Map of the relative difference between MODIS and MERIS annual mean for 2005 - (MODIS-MERIS)/[(MODIS+MERIS)/2].

5.3. Quality control of MODIS Chl using normalised water-leaving radiance at 667nm

When the difference between MODIS and MERIS Chl is significant, at least one of the two data is wrong. In particular, the MODIS Chl which is strongly and erroneously correlated with turbidity in the southern North Sea should not be used for AB detection in certain situations.

Fig. 6 shows an example of the time series of MERIS and MODIS Chl and MODIS nLw(667) (normalized water radiance at 667nm) for 2005 at a location 52.5°N and 2.5°E. The 2005 annual mean Chl for MODIS is 30% higher than MERIS at this location. The graph indicates that high MODIS Chl (green) for days earlier than day number 135 and days around 300 is strongly influenced by the corresponding high nLw667, while MERIS Chl does not show such correlation with nLw667. The graph also illustrates that MODIS Chl should be removed when nLw667 is high, otherwise a AB would be detected in winter, which is not probable.

Fig. 7 shows a relationship between MODIS nLw667 and Chl for 2005 data. The regression line is indicated by the lower red dotted line, which shows that nLw667

increases as Chl increases as is well known in case 1 waters [10].

In the present study, the MODIS Chl is excluded if the measured nLw667 exceeds a limit set as 1.5 times higher than the regression line, as shown by the upper line in Fig. 7. Red symbols in Fig. 6 show the MODIS Chl data remaining after quality control with this nLw667 limit.
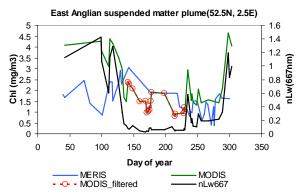

East Anglian suspended matter plume(52.5N, 2.5E)

Figure 6. An example of a time series of MERIS Chl, MODIS Chl, filtered MODIS Chl, nLw(667nm) for 2005 data .
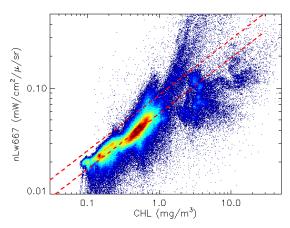

Figure 7 Relationship between MODIS nLw667 and Chl for 2005. The regression line (lower dotted line) is expressed by log(nLw667)=0.52*log(Chl)-1.24. The upper line, corresponding to 1.5 times higher nLw667, is used for quality control of MODIS Chl. The colour changes from blue to red as pixel density increases.

6. CONCLUSIONS

Algal bloom detection for European waters has been described, including the algorithm flow, algal bloom classification map and threshold determination.

With the threshold calculated as the 90 percentile Chl of the previous year's data, algal blooms were reasonably detected in three optically distinct waters: the Belgian coastal zone, western Channel and the Baltic Sea.

Significant inter annual variability in bloom timing or strength was observed in some locations. Further improvement on the threshold could be made by using multi year historical data and by spatial averaging.

The combination of MERIS and MODIS imagery is appropriate and provides much better temporal coverage than use of a single sensor. Comparison shows that MODIS and MERIS Chl are generally in good agreement, although the standard MODIS Chl should be used with caution in turbid or coastal waters. Quality control of MODIS Chl using nLw667 effectively removes data contaminated by turbidity-related errors. Further study is needed to explain the MERIS-MODIS difference in the coastal waters of the Baltic Sea.

7. ACKNOWLEDGEMENTS

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