Remote sensing chlorophyll $a$ mapping of optically complex waters

(rias Baixas, NW Spain): Application of a regionally specific chlorophyll $a$ algorithm for MERIS full resolution data during an upwelling cycle

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Abstract

This study takes advantage of a regionally specific algorithm and the characteristics of Medium Resolution Imaging Spectrometer (MERIS) in order to deliver more accurate, detailed chlorophyll $a$ (chl$a$) maps of optically complex coastal waters during an upwelling cycle. MERIS full resolution chl$a$ concentrations and in situ data were obtained in three Galician rias (NW Spain) and the adjacent shelf, an area of extensive mussel cultures that experiences frequent harmful algal events. Regionally focused algorithms (NNRB) for the retrieval of chl$a$ in the Galician rias optically complex waters were tested in comparison to sea-truth data and the one that showed the best performance was applied in a series of six MERIS (FR) images during a summer upwelling cycle to test its performance. The best performance parameters were given for the NN trained with high-quality data using the most abundant cluster found in the rias after the application of fuzzy c-mean clustering techniques (FCM). July 2008 was characterized by three periods of different meteorological and oceanographic states. The main changes in chl$a$ concentration and distribution were clearly captured in the images. After a period of a strong upwelling favourable winds a high biomass algal event was recorded in an area of low SST. However, MERIS missed the high chlorophyll upwelled water that was detected below surface in the ria de Vigo by the chl$a$ profiles, proving the necessity of in situ observations. Relatively high biomass "patches" were mapped in detail inside the rias. There was a significant variation in the timing and the extent of the maximum chl$a$ areas. The maps confirmed that the spatial structure of the phytoplankton distribution in the study area can be complex. Surface currents and winds off the rias Baixas affected the distribution of chl$a$ in the rias Baixas. This study showed that a regionally specific algorithm for an ocean colour sensor with the characteristics of MERIS in combination with in situ data can be of great help in chl$a$
monitoring, detection and study of high biomass algal events in an area affected by coastal upwelling such as the *rias Baixas*.

**Keywords:** Chlorophyll $a$, MERIS, algorithms, upwelling, Galician *rias*

**Highlights**

* We apply regionally specific chlorophyll $a$ algorithms from MERIS data. * We study chlorophyll $a$ distribution coupled with *in-situ* data during upwelling. * We provide more accurate chlorophyll $a$ maps of optically complex coastal waters. * Images captured the main changes in chlorophyll $a$ concentration and distribution.*
1. Introduction

Among ocean-colour derived data, chlorophyll $a$ (chl\textsubscript{a}) concentration is the most used product since it provides a good estimation of phytoplankton biomass and is common to almost all taxonomic groups (Jeffrey et al., 1997). The phytoplankton community responds rapidly to environmental changes (EC, 2000), which can cause visible changes in chlorophyll in the surface waters.

The estimation of chl\textsubscript{a} concentration in the oceans from the first dedicated ocean colour scanner (CZCS) that launched in 1978 and operated until 1986 provided useful information on the global distribution of chl\textsubscript{a} but the quality of the data was limited (Robinson, 2004). The Sea-viewing Wide-Field-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS) and the most recent Medium Resolution Imaging Spectrometer (MERIS) that succeeded CZCS are using more and narrower spectral bands and finer spatial resolution. MERIS provides data with a 300 m on-ground resolution in nadir (Full Resolution) and has a spectral resolution of fifteen bands from visible to near infra red, supporting one of the mission objectives for delicate coastal zone monitoring (Doerffer et al., 1999).

Traditionally, chl\textsubscript{a} is estimated using empirical algorithms based on the ratio between the radiance of blue and green light reflected by the sea. For the retrieval of chl\textsubscript{a} from ocean colour sensors various empirical spectral-ratio algorithms (Evans and Gordons, 1994; Muller-Karger et al., 1990; Aiken et al., 1995; McClain et al., 2004; O’ Reilly et al., 2000; Brown et al., 2008) and semi-analytical models (Garder and Steward, 1985; Garder et al., 1999) were developed. In typical case II waters, where high concentrations of water constituents (CDOM, detritus) absorb strongly in the blue...
decoupling the phytoplankton absorbance, this ratio cannot be used for an accurate retrieval of chl$_a$ (Morel and Prieur 1977; Gons, 1999; Gitenlson et al., 2007).

In the effort for more accurate retrieval of water constituents in optically complex waters, neural network (NN) techniques can play an important role, since they seem ideal for multivariate, complex and non-linear data modelling (Thiria, 1993). In the last decades the application of neural network (NN) techniques for the estimation of selected water quality parameters from ocean-colour has increased (Atkinson and Tatnall, 1997; Keiner and Yan, 1998; Dzwonkowski and Yan, 2005; Zhang et al., 2003; Shahraiyni et al., 2009). Dransfeld et al., (2004) proposed that studies for development of ocean colour algorithms should be regionally specific and emphasised the role of NNs in the retrieval of water constituents especially in Case 2 waters. NN based algorithms are currently used as standard products for the estimation of chl$_a$, SPM and yellow substances by the European Space Agency (ESA) for MERIS data (Doerffer and Schiller, 2007, 2008).

Although remote sensing tools can be used with a relatively high precision at global scale for the calculation of chl$_a$, they are not always totally accurate in local areas (Ruddick et al., 2008). Validation methods and development or expansion of chl$_a$ algorithms for specific areas have been widely used to test and regionalize the satellite products (e.g. Gons et al., 2002; Cota et al., 2004; Witter et al., 2009).

In the Galician rias (NW Spain) the interest in developing an accurate estimation of chl$_a$ is considerable, mainly because of the economic and social importance of the extensive culture of mussels, and the frequent occurrence of harmful algal events (GEOHAB, 2005).
In the present paper a neural network-based chla algorithm previously developed for the Galician rias waters (within the rias and for coastal waters on the continental shelf) was applied for the first time in a short series of MERIS (FR) images delivered during an upwelling cycle in order to obtain maps of chla. The performance of the neural network-based chla algorithm is compared to in situ measurements and other algorithms that are routinely used for MERIS data. The temporal and spatial distribution of the chla patterns that were captured in the MERIS images using the local adapted algorithm in relation to the meteorological and oceanographic conditions in the area are also discussed.

2. Methods and data

2.1 Description of the study area

The Galician rias are V-like coastal formations along the northwest part of the Iberian Peninsula (Fig. 1). The rias Baixas constitute the southern part of the Galician rias. They are formed by four large coastal embayments, from north to south: Muros y Noya, Arousa, Pontevedra and Vigo, all oriented in a SW-NE direction, and characterized by strong tides. Surface area covers approximately 600 km² and water depths range from 5-60 m. This study focuses on three rias (Arousa, Pontevedra and Vigo), each connected to the open sea through two entrances, to the north and south of the islands located at the external part of each ria. The ria de Vigo is the longest of the rias whereas the ria de Arousa is the widest one. Rias vary in width from 1-3 km in their inner part to 8-12 km in their external part (Vilas et al., 2005). The main freshwater inputs in the rias are by rivers that located in innermost part of the rias.

In these highly primary productive upwelling estuarine systems (Fraga, 1981; Torres & Barton, 2007) transient increases of phytoplankton abundance, referred to as blooms,
are a frequent phenomenon occurring mainly between early spring and late fall (Fraga, 1988; Varela, 1992; Figueiras & Ríos, 1993). Sporadically, some phytoplankton blooms in the Galician rías are perceived as harmful with direct and indirect impacts to the mussel production that constitute an important economic activity in the area. Harmful algal events in the Galician rías are a well documented phenomenon. Several studies since the 1950s referred to the harmful algal events and in general to phytoplankton ecology on the Galician rías particularizing favourable conditions to the development of HABs, their origin, dynamic, distribution and toxicity levels (Margalef, 1956; Tillstone et al., 1994; Figueiras et al., 1994; GEOHAB, 2005), seasonal taxonomic and chemical composition of phytoplankton and picophytoplankton, “patchiness” (Figueiras & Niell, 1987; Nogueira et al., 1997; Tillstone et al., 2003). Despite the fact that an ocean colour sensor with the characteristics of MERIS is considered adequate for chla monitoring and detection of HABs in coastal areas, to our knowledge the number of studies using MERIS data in the Galician rías is limited those of Torres Palenzuela et al. (2005a; 2005b) and González Vilas et al. (2011). The latter authors developed a chla algorithm based on NNs and classification techniques from MERIS full resolution data for rías Baixas coastal waters.

2.2 Sampling regime

Two samplings were conducted in 2008 in the ria de Vigo. Twelve fixed stations were visited on cloud-free days (July 9 and 22). The sampling transect extended from the open sea towards to the inner part of the ria. Satellite data from MERIS (FR) were available for the same days. The depth of the stations ranged from 5 m inside the ria to 100 m outside. Triplicate water samples from surface to 3 meters were collected at each station from a sampler (3524 cm$^3$) for the determination of HPLC pigments and SPM.
2.3 *In situ* measurements

*In situ* chl *a* fluorescence profile was monitored by a Turner designs CYCLOPS-7 submersible fluorometer. Profiles of water temperature were provided by a portable meter (HI 9829, Hanna instruments). The depth of the euphotic zone was established with a Secchi disk. For the High Performance Liquid Chromatography (HPLC) chl *a* determination, water samples (100-200mL) were filtered through 9mm diameter Whatman GF/F filters and stored at -80°C for two weeks, and 95% methanol was used as extraction solvent for the pigments. In this study only chl *a* concentration data are presented, calculated as the sum of chlorophyllide *a*, chlorophyll *a* epimer, chlorophyll *a* allomer and divinyl chlorophyll *a*. An HPLC method using a reversed phase C$_8$ was applied for the separation of the pigments. Details of pigment extraction and separation are provided in Zapata *et al.* (2000).

Suspended particulate material (SPM) was evaluated in terms of SPM concentration and percent weight of organic material (%OM). Pre-combusted (450 °C for 24 h), pre-washed in 500 mL of MilliQ, 47mm Whatman GF/F filters were used. These filters were then dried at 65 °C to a constant weight. Particles were collected by filtering a standard volume (1000mL) of seawater samples and then rinsed with 50mL MilliQ in order to remove salts and dissolved organic material. For the determination of SPM the filters were dried at 65°C till no weight changes were observed. The filters were then re-combusted at 450 °C for 5 h in order to obtain the inorganic suspended material (ISM). The percent weight of organic material (%OM) was determined by subtracting the ISM from the SPM. All the filters were weighted on a Precisa 262 SMA-FR microbalance (10$^{-5}$ g precision).

2.4 Oceanographic and meteorological data
Oceanographic and meteorological data off the *rias Baixas* were provided by the Spanish Port System (www.puertos.es). More specifically, wind speed ($W$) and direction, current data and water temperature were observed at a Seawatch buoy station located off Cape Silleiro (42° 7.8′N, 9° 23.4′W). This meteorological station was selected as fairly representative of the study area (Herrera et al., 2005). Daily upwelling index ($I_W$) was estimated from wind by Bakun's (1973) method:

$$I_W = - \frac{\tau_y}{(\rho_W \cdot f)} = - \frac{1000 \cdot \rho_a \cdot C_D \cdot W \cdot W_y}{(\rho_W \cdot f)} \text{ m}^3/(s \cdot \text{km})$$

where $\rho_a$ is the density of air (1.2 kg·m$^{-3}$ at 15°C), $C_D$ is an empirical dimensionless drag coefficient (1.4·10$^{-3}$ according to Hidy, 1972), $f$ is the Coriolis parameter (9.9·10$^{-5}$ s$^{-1}$ at 42° latitude), $\rho_W$ is the density of seawater (1025 kg·m$^{-3}$), and $W$ and $W_y$ are the average daily module and northerly component of the wind.

Moderate Resolution Imaging Spectroradiometer (MODIS-Aqua) sea surface temperature (SST) daily level 2 data for July 2008 were downloaded from the website of the National Aeronautics and Space Administration Goddard Space Flight Center (NASA-GSFC) (http://oceancolor.gsfc.nasa.gov/). The 1 × 1 km resolution MODIS data were processed using MATLAB software to derive projected SST maps of the study area. The study area for the SST maps was expanded to 42-43° N and 9.3-8.3° W. The MODIS imagery contains 6 images for the dates that MERIS data were available.

2.5 MERIS data and MERIS chla algorithms for Case 2 waters

2.5.1 MERIS case II Regional Processor (C2R)

MERIS Case-2-Regional Processor (C2R) (Doerffer & Schiller, 2007, 2008) is the algorithm for chla that is currently used as a standard product by the European Space Agency (ESA) for Case 2 waters. The MERIS C2R processor takes advantage of the
combined NN technique to derive the optical properties of the water (absorption of pigments, yellow substance and scattering of all particles). It includes an atmospheric correction. An inverse NN is used to emulate the inverse model and a forward NN to emulate the forward model and to test if the measured spectrum is within the scope of the training set. MERIS reflectances of eight bands in the visible spectra, information about geometry and biooptical data of the water constituents are trained in the NNs. The bio-optical model used for the simulations is based on a large data set collected mainly in European waters. Among the final outputs of the algorithm is the absorption coefficient of phytoplankton pigment ($a_{\text{pigment}}$). Final concentration of chl$_a$ is calculated according to the empirical relationship between chl$_a$ (algal$_2$) and absorption coefficient ($a_{\text{pigment}}$) (Doerffer & Schiller, 2005):

$$\text{algal}_2 = 21 \ast a_{\text{pigment}}(443)^{1.04}$$

which permits the modification of the parameters in order to be suitable for the each study area.

2.5.2 Regional neural network for rias Baixas (NNRB)

Developed by González Vilas et al., (2011), this set of algorithms represents feed-forward NNs trained by supervised learning using iterative back-propagation of error for the retrieval of chl$_a$ from MERIS FR data. These algorithms approximate sets of different classes of water-leaving radiance reflectances data, determined after the application of Fuzzy c-means clustering techniques (FCM), to a set of appropriate chl$_a$ concentrations. Input variables are 11 MERIS water leaving radiance reflectance and 3 geometry values. It was found that MERIS data can be classified in 3 clusters (#1, #2 and #3) but only one could be used for the 3 different NNs that were developed for the retrieval.
The method performs well in the estimation of chla from MERIS (FR) data in the optically complex waters of the *rias Baixas* and detects perfectly the peaks of chla.

NNRB is based on *in situ* chla data collected from the *rias Baixas* during a long period survey (2002-2008), covering the temporal variability of chla in all the part of the *rias*. In contrast with the Schiller and Doerffer algorithm, this algorithm does not use simulated data. The result is a narrower range (0.03-7.73 mg m\(^{-3}\)), but this is considered as sufficient for the study area.

2.5.3 Application of chla algorithms to MERIS imagery

The MERIS satellite imagery used in this study contains 6 full-resolution level-1b images derived from the area in July 2008. MERIS overpasses were within 2 hours of the time that samples and data were collected *in situ*. Beam 4.2 (Brockmann Consult and contributors, Germany) software was used for the analysis of the imagery.

The BEAM-4.6’s smile correction was applied to the original level-1b data. For the atmospheric correction the ocean colour data were processed with a NN-based algorithm which was developed by Doerffler and Schiller (2008). The level-2 products of the chla concentrations calculated by the NNRB and the MERIS Case 2 Regional Processor (C2R) were processed with the same atmospheric correction. This NN algorithm for dedicated atmospheric correction over turbid case 2 waters is based on radiative transfer simulations. The performance test of the atmospheric correction showed increasing uncertainty with decreasing values of water leaving radiance reflectances (Doerffer & Schiller, 2008).

The flags for coastline, land, clouds and invalid reflectance were raised using the Beam software. Ocean colour data derived from areas significantly affected by sun glint
(beyond a solar zenith angle limit of 60°) were characterized invalid and removed from the analysis.

The FCM algorithm that was proposed by González et al., (2011) was applied to the data in order to identify the different clusters. Classification images were then obtained for the available MERIS images using the same FCM algorithm. The pixels in these images were assigned to the cluster with the highest value in its corresponding membership function and the percentage of pixels belonging to each cluster was computed. The performance of the available algorithms was then tested and the NN with the best performance measures was applied to the MERIS leaving radiance reflectance values in order to deliver the chl\textsubscript{a} maps for the study area.

\textit{In situ} chl\textsubscript{a} data points delivered from cloud-free scenes and areas that were not flagged for coastline and invalid reflectance were considered to be valid match-up data and were used for the performance testing of the chl\textsubscript{a} algorithms. Water-leaving radiance reflectances and chl\textsubscript{a} concentrations were computed as mean values of the pixel corresponding to the sampling station location and the 8 surrounding pixels. These 9 pixels cover approximately 0.8 km\textsuperscript{2} of surface area and it was considered that this averaging was able to reduce MERIS instrument noise. For each sampling point, the number of pixels included in the median computation was also extracted as a quality flag, ranging from 9 (highest quality) to 1 (lowest quality). Low quality values indicate that the sampling station is located in the proximity of the coast or cloudy or foggy areas, so that the reflectance values could be affected.

The imagery was then remapped using the standard Mercator projection with a fixed grid of 890 by 890 pixels. Each chl\textsubscript{a} image ranges from 42° 04' N to 42° 40' N latitude and from 8° 32'W to 9° 32'W longitude, which covers approximately 3.1 x 10\textsuperscript{3} km\textsuperscript{2}. 

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2.6 Performance measures

The following statistical measurements were used to evaluate the performance of the chla models. For the measured chla concentration (Chlx) and the modelled chla (Chlₓ) the difference

\[ PE_i = Chlx_i - Chlₓ_i \]  

(2)

was noted and was used to obtain the root mean square error (RMS error) and the relative RMS error, which are defined as:

\[ RMS \text{ error} = \sqrt{\frac{\sum_{i=1}^{N} PE_i^2}{N}} \]  

(3)

\[ Rel. RMS \text{ error} = \frac{\text{RMSE}}{\sqrt{\frac{1}{N} \sum_{i=1}^{N} Chlx_i}} \times 100 \]  

(4)

In addition, the coefficient of determination (R²) was computed as a measurement of the correlation between the Chlx and the Chlₓ. RMSE and relative RMSE were used in this work as measurements of absolute error (in mg m⁻³) and relative error respectively.

3. Results and discussion

3.1 In situ data

Sea-truthing ranges of HPLC chla, SPM, percentage of inorganic matter and Secchi disk depth for the two samplings are given in Table 1, which also summarizes information about the available MERIS imagery. Water temperatures near surface ranged from 16.90 to 19.54 °C and from 16.58 to 18.91 °C, respectively, for the two samplings. Temperature at 10 m depth during the first sampling was between 15.33 and 17.70 °C, whereas temperatures dropped to 13.50-14.47 °C at the sampling stations on July 22.
Water temperature decreased from the outer part towards the inner part of the *ria*. Values of Secchi disk depth between 2 to 12 m were measured in the *ria de Vigo*, generally less than half the water column depth.

Chla concentration in the surface water samples did not show a wide variation. Chla levels were relatively low in comparison with the temporal pattern proposed for the *rias Baixas* by Nogueira et al. (1997) where chla concentrations close to 5 mg m$^{-3}$ are described as typical during the summer period. Mean chla determined by HPLC varied from 0.03 at station 12 to 2.65 mg m$^{-3}$ in the inner part during the first sampling. On July 22 the highest chla concentration (2.72 mg m$^{-3}$) was recorded in the innermost *ria* station. Although the range in the surface chla concentration was similar in both samplings, differences were observed in the chla profiles. In the sampling conducted on July 9, small differences were observed in the chla concentration profiles in the first 10 m of the water column in all stations except the three at the inner part of the *ria* where a chla maximum was recorded at 4 m depth (Fig. 2A). On the other hand, a vertical gradient of chla was detected in almost all sampling stations during the second sampling (Fig. 2B), with the highest values of chla (up to 16 mg L$^{-1}$) found close to 10 m. The same vertical distribution pattern during the month of July in *ria de Pontevedra* is described in Varela et al. (2008) and is imputed to the presence of upwelled waters.

SPM concentrations varied from 1.17 to 3.15 mg L$^{-1}$ in the *ria de Vigo* and showed decreasing values with distance from st. 1, which is located in the inner, narrow part of the *ria* and closer to the main freshwater inputs. In this part of the *ria* sediment resuspension and continental runoff is probably higher having as a result high concentrations of SPM.
The results of the Chla and SPM analyses of this study combined with available unpublished data from the same sampling stations using the same methodology showed that these two variables vary independently (Fig. 3, determination coefficient of linear relationship $R^2=0.1$). This confirms the initial assumption that rias Baixas waters can be categorized as Case 2 (Morel & Prieur, 1977). This classification is not always a simple distinction of coastal and oceanic waters as Morel and Maritonema (2001) describe in a later study using a new dataset of optical properties, indicating the need for models more restricted in geographical and seasonal terms.

3.2 Classification results and comparison of MERIS chla algorithms with in situ data

Classification images, showing the cluster value for each sea pixel, were obtained for the MERIS images involved in the analysis (Fig. 4). In theory, the membership grades for each cluster would allow us to blend the chla concentration, obtained from the different neural networks developed for each cluster, into a given pixel, so that chla maps with soft transitions would be created (Moore et al., 2009). In practice, the NNRB model was only developed for Cluster#1 (González Vilas et al., 2011), so that these classification images presented here were only useful for detecting the zones where Cluster#1 is the dominant cluster and therefore the areas where NNRB can be best applied to obtain more reliable results. Figure 4 shows that Cluster#1 is dominant in almost all the images in the rias Baixas and the adjacent area. Table 2 shows the percentage of pixels belonging to each cluster for each image over the rias Baixas. Cluster#1 includes the majority of the pixels in ria de Vigo, with more than 72% of pixels in the six images. On average, 71% and 65% of the pixels over ria de Pontevedra and ria de Arousa belong to this cluster. Cluster#2 is the predominant one in in the ria de Pontevedra and ria de Arousa in the image delivered on July 29. Cluster#3 is the least abundant in most of the images, with less than 3.25% of pixels in all of them.
However, the presence of Cluster#2 and Cluster#3 does not prevent the continuous chlorophyll mapping over large areas in the *rias*, because of the predominance of Cluster#1. The image delivered on the July 29 is more problematic (referring to the high percentage of pixels belonging to Cluster#2), although the mapping of a large part of *ría de Vigo* and small parts of *ría de Pontevedra* and *ría de Arousa* was possible.

Insofar as the two cloud-free field campaigns were designed specifically to collect samples within a time period of 2 hours from the MERIS overpasses time, 24 valid data were available to test performance of the MERIS chla algorithms. The performance parameters for the match-up data of MERIS chla retrieved by the C2R processor and the three NNRB algorithms (NNRB#1, NNRB#2 and NNRB#3) are shown in Table 3. The available dataset did not show a wide range of environmental variation, with chla ranging from 0.03 to 2.72 mg m$^{-3}$. The three NNRB algorithms outperformed the C2R showing higher $R^2$ and lower RMSE values. However, the NNRB for the Cluster#1, high quality data produced well correlated results ($R^2=0.70$) which are much higher than the CR2 results. Bottom effects on the reflectance or the presence of macroalgae and adjacency effects might be the factors responsible for the difference in the performance parameters that was observed between NNRB#1(2) and NNRB#3. The C2R has shown good results for chla retrieval in coastal areas and inland waters (Peters, 2006; Odermatt et al., 2010) but the correlation with the *in situ* data in this study was poor. The poor correlation shown by C2R may be the result of the low chla concentrations that were recorded in the *ría de Vigo*. C2R is more likely to be inaccurate in low chla concentrations with moderate values (>2 mg m$^{-3}$) of SPM (Doerffer and Schiller, 2007).

Further error may arise from sea bottom reflection especially in the innermost part of the *ría*. The good performance of NNRB#3 is not surprising considering that NNRB#3 can clearly follow the cycle of chlorophyll recorded in the *rias Baixas*: concentrations
lower than 1 mg m$^{-3}$ during the winter months, up to 8 mg m$^{-3}$ during the spring and autumn maxima and close to 5 mg m$^{-3}$ during the summer. Moreover, the NNRB algorithm is trained with MERIS and in situ chla data during upwelling events. NNRB#3 seems to be robust and ideal for the rias Baixas coastal waters where it can be used for a more accurate mapping of chla in order to improve the understanding of the spatial and temporal distributions.

3.3 Upwelling cycle

Different meteorological and oceanographic periods were identified and categorized as three different states in the area during July of 2008 (Table 4, Fig. 5). The states lasted from nine to eleven days which is typical in an upwelling cycle in the area (Nogueira et al., 1997).

State 1 (July 1-11)

This 10 d period state comes after a strong upwelling that occurred in the area at the end of June (Fig. 5A) and it is characterized mainly by weak winds of variable direction which are typical of upwelling relaxation in the area (deCastro et al., 2004). An exception of strong downwelling-favourable wind from the south was recorded on July 4.

Surface flow off the rias had a northward direction with a speed ranging between 0.5 and 7.5 cm s$^{-1}$ (Fig. 5B). On July 3, SST ranged between 16-17 °C inside the rias, but an area with temperature higher than 17 °C was observed outside the rias. In the next SST image (July 9) an increase in temperature was recorded in the rias Baixas and the adjacent area (Fig. 6). The temperature increase was confirmed by the Seawatch data (Fig. 5C). The daily mean water temperature off the rias Baixas increased from 16.4 °C, in the first days of July up to 18 °C in a period of 10 days after the upwelling.
Two MERIS (FR) images (Fig. 7) from the study area were available during state 1, one on July 3 and the other on July 9. In both, several high chla "patches" were mapped inside and in the outer parts of the rias. In the area off the external coast of the rias the chla concentration in the images remained at levels close to 0 mg m$^{-3}$. This pattern of the phytoplankton biomass principally confined in the rias while in neighbouring shelf area the chla levels remained very low, seems to be generated by the northward flow of surface waters outside the ria. The development of northward currents in the relaxation following intense north winds, responsible for the upwelling recorded at the end of June, may introduce water of high chla to the three rias from the ocean area outside them in the first days of July. The continuing mainly north-westward directed transport over several days may have been responsible for the chla distribution observed on July 9, where chla concentration was significantly higher in the ria de Arousa than in the other two rias in the south.

Different patterns of the higher chla areas in the rias were mapped during state 1. On July 3, areas of high chla concentrations were mapped in the ria de Arousa (3-4.5 mg m$^{-3}$) and close to the mouths of the three rias (higher than 2 mg m$^{-3}$). On July 9, chla concentrations greater than 2 mg m$^{-3}$ were mapped mainly in the middle and inner parts of the ria de Vigo and in the outer part of the ria de Arousa.

In the image obtained on July 3, areas of high chla concentrations were observed in the outer part of the three rias, whereas chla decreased towards the inner part of the rias. Varela et al. (2008) reported that this gradient is common in the ria de Pontevedra during the upwelling period when the meteorological forcing is the main factor responsible for the circulation of the ria.
Six days after the first available image, the gradient of chla in the rias described above was observed only in the ria de Arousa. On the contrary, Vigo and Pontevedra were characterized by a chla gradient where concentration increased toward inshore. In the ria de Pontevedra areas of higher chla were recorded at the innermost part and close to the northern mouth of the ria. In the rest of the ria de Pontevedra chla concentration was close to 0 mg m$^{-3}$. In the inner part of ria de Vigo, MERIS chla varied between 2 and 3 mg m$^{-3}$. MERIS data delivered from areas like the most interior, shallow part of the rias normally considered as suspicious because the high abundance of macroalgae increases the chla signal (Gons et al., 1999) were here characterized as reliable, since they were confirmed by in situ data. Moreover, water transparency in the 20 m station (St. 1) as determined by the Secchi disk measurements during the first campaign was 2 meters, decreasing the effect of the bathymetry. This part of the rias can be firmly considered as estuary and during nutrient enrichment from river flows, high concentrations of chla have been recorded (Evans and Prego, 2003). In this case the observed relatively high concentrations of chla at the inner part of the two southern rias may be the result of the mixture of estuarine water with Eastern North Atlantic Central Water (ENACW) combined with high residence times. The different offshore-inshore gradient of ria de Arousa seems to be formed by material transferred to the north from the rias de Vigo and Arousa due to the northward surface currents. Differences in topography and local winds should also be considered as possible factors for the observed differences. Ria de Arousa is considered to be the most productive of the rias Baixas (Bode and Varela, 1998). In the classification of Vidal-Romaní (1984) ria de Arousa is categorized as open bay, while ria de Pontevedra and ria de Vigo as fjord-like. Though fjords have deep quiescent interiors, only intermittently renewed, and a
shallow sill at the entrance, while the rias are shallow and have a 2 layer circulation that
reverses between up and downwelling.

*State 2 (July 12-21)*

State 2 was characterized by 9 d of sustained upwelling favourable winds (Fig. 5A) and
southwest currents of up to 6 cm s\(^{-1}\) (Fig. 5B). SST maps showed that temperature
ranged between 16-17 °C in the coastal area outside the *rias* (Fig. 6). Temperature
recorded by the Seawatch buoy decreased more than 1 °C during the upwelling (Fig.
5C).

The two chla maps (Fig. 7) for this state trace the primary results of the upwelling
favourable winds. On July 16 map areas with the highest chla concentrations were
recorded in the middle part of *ria de Pontevedra*, at the mouth of *ria de Arousa* and
through the entire *ria de Vigo*. The distributions were similar in form in the *ria de Vigo*
and *ria de Pontevedra* but higher chla (>2.5 mg m\(^{-3}\)) was found in the former.
Unpublished data showed the outflow of *ria* water towards offshore in speeds that
reached 4 cm s\(^{-1}\). This situation of the surface water being advected offshore in the *rias*,
when upwelling favourable wind started to blowing off the *rias Baixas* is typical of the
positive estuarine circulation that has been described in the area (Fraga and Margalef,
1979; Figueiras and Pazos, 1991). In this two-layer circulation, the offshore surface
Ekman-transport advects the low salinity water out of the *ria*, while the denser upwelled
water flows into the *ria* along the sea bed. The zone of enhanced surface chla
concentration that in the MERIS images extends throughout the *ria de Pontevedra* and
*ria de Vigo* is probably surface water that is flowing out of the *rias* due to the positive
estuarine circulation generated during the upwelling favourable conditions.
The July 19 chla image shows a noticeable increase in chla with concentrations higher than 1 mg m\(^{-3}\) over the entire continental shelf zone, although chla decreased slightly within the rias. In the study of Ospina-Álvarez et al. (2010) it was found out that during the upwelling favourable conditions that characterized the Northern Galician rias during the period July 13-22 2008 the ENACW did not enter in the rias. While in that period chla in the Northern Galician rias did not exceed the value of 1 mg m\(^{-3}\) (Ospina-Álvarez et al. 2010), in the rias Baixas it was generally higher than 1 mg m\(^{-3}\), confirming the suggestion that there is a difference between Northern and Western (rias Baixas) Galician rias with respect to their eutrophication status under the same meteorological conditions.

State 3 (July 22-31)

As a result of the strong upwelling event a peak of chla with concentrations up to 5 mg m\(^{-3}\) was mapped on July 22 in the coastal area off Galicia. The high chla concentration was extended from the northern offshore area to the interior of the rias (Fig. 7). A coincident area of relatively low temperature was mapped in the north part of the study area, whereas an area of warmer water was detected at the south. Differences up to 2 °C were obtained between the rias (Fig. 6). This alongshore difference probably reflects the persistence of stronger coastal upwelling in the north after the event of 10-21 July and an earlier onset of relaxation in the south. It is often the case that upwelling is more persistent in the north of the area (Torres and Barton, 2007). Figure 8 shows the development of the upwelling on the Galician coast. With the abrupt decrease of upwelling-favourable to zero wind on July 22, currents at the Seawatch buoy became briefly northward as expected, but subsequently returned to southward despite the onset of intermittent northward winds. The last MERIS image (July 29) is consistent with strong relaxation: the offshore region has near-zero chlorophyll and a region of
moderately high chla is bound to the coast. Within the rias values tend to be low, reflecting downwelling conditions. It seems probable that flow more inshore of the Seawatch buoy was northward and convergent to shore. At the end of July chla in the ria de Vigo showed the lowest concentration of all the images of previous days.

The high chla concentrations along the Galician shelf coupled with low SST. MERIS and MODIS images at the start of this state on July 22 show clearly the presence of a cold, chlorophyll-rich area resulting from the previous 10 d of upwelling. Although high chla water was recorded below the surface in the in situ profiles (Fig.2B) during the second sampling in the ria de Vigo, MERIS data recorded the low surface values present. Figueiras and Pazos (1991) noted the presence of nutrient-rich water during a summer upwelling event in the rias Baixas that did not reach the surface. As soon as upwelling ceases, the 2-layer circulation reverses and surface waters flow inwards and sink to the lower layer carrying with them the higher surface concentrations of Chla. The possible non uniformity of the Inherent Optical Properties (IOP) in the water profiles (Stramska and Stramski, 2005) and the development and validation of the water constituent algorithms based on water samples from certain depths (e.g. O'Reily et al., 2000; González Vilas et al., 2011) affirms the necessity of the in situ data.

Although this high biomass area was not sampled directly, in situ data from the ria de Vigo revealed relatively high concentrations of diatoms (mainly Chaetoceros spp.), small flagellates (personal observation). The ASP producer Pseudo-nitzschia was also present in the ria de Vigo but in relatively low concentrations. This phytoplankton composition seems to be typical in the rias Baixas during the summer according to the annual cycle of phytoplankton abundance proposed in 1987 by Figueiras and Niel. Moreover, Frangopulos et al., (in press) mentioned the presence of the red-tide
dinoflagellate *Noctiluca scintillans* in high abundances in *ria de Vigo* during summer 2008.

### 4. Summary and conclusions

Three different states of meteorological and oceanographic periods were identified in the area during the July of 2008. Surface currents and winds off the *rias Baixas* affected the distribution of chla in the *rias Baixas*. At the beginning of July (State 1) the variable and weak wind and the resulting northward surface currents limited the high chla concentrations to the *rias* so that only low chla values were found in the offshore area. Differences in the topography of the *rias*, effects of local winds and transport by currents between the *rias* seem to be the main factors for the observed differences in the gradients of chla along the *rias* between *ria de Arousa* and the two southern *rias* (*Vigo, and Pontevedra*). MERIS images obtained during State 2 showed the first response of chla distribution due to the strong favourable winds that were blowing in the area. With the development of strong upwelling the circulation in the *rias* is reinforced in the estuarine sense so that chla increases rapidly there. After a period of six days of continued upwelling, chla concentrations higher than 1mg m\(^{-3}\) were observed in all the area mapped according to MERIS data. State 3 commences with the appearance of a high biomass algal event coincident with the area of low SST as the culmination of the preceding, extended upwelling. The weak northward winds that characterized this state permitted downwelling that transferred chla rich water toward the *rias*. The upwelled water was recorded in the chla profiles in the *ria de Vigo* but was missed by the MERIS. The continuing downwelling circulation resulted in decay of the bloom and subduction of surface waters in the *rias* compatible with the decrease of chla observed in the last MERIS image. Although MERIS has a repeat interval of three days, cloud cover prevented acquisition of all possible images. Nevertheless the 6 images obtained
in July 2008 captured the main changes in chla concentration and distribution during the three periods of different meteorological and oceanographic states.

Previous ocean colour studies by satellite sensors (CZCS, SeaWiFS, MODIS) in the Western Iberian Peninsula (WIB) during an upwelling event (McClain et al., 1986; Peliz and Fiuza, 1999; Joint et al., 2001; Bode et al., 2003; Ribeiro et al., 2005; Oliveira et al., 2009a, Oliveira et al., 2009b) played an important role in the identification of chla patterns and study of harmful algal blooms and primary production but were restricted to the ocean shelf because of insufficient spatial resolution. Another problem that affected many of the previous satellite remote sensing application studies in the study area was the failure of the algorithms used to provide reliable chla data during upwelling favourable conditions especially in the areas closest to the coast. Upwelling waters are characterized by considerable variability in the vertical distribution of phytoplankton (Brown and Hutchings, 1987) and in the optical properties (Morel and Prieur, 1977). Optically active water constituents such as SPM which are brought into the surface because of the strong mixing that takes place during upwelling events may vary independently of the surface chla as in the typically shallow estuarine Case 2 waters. On the other hand, the present study allows more detailed examination of the chla distribution in the Galician rias and the adjacent area during a summer upwelling cycle due to the finer spatial resolution and precise atmospheric correction offered by MERIS. The application of an algorithm specially developed for the study area provides more accurate mapping of chla, which has, for the first time to our knowledge, provided surface chla mapping of the interior of the rias Baixas. Moreover, the fine resolution of MERIS in combination with the local-based algorithm permitted the detailed detection of relative high biomass "patches" in the rias and the coastal area. There was a significant variation in the timing and the extent of the chla peak areas. The maps show
that the spatial structure of the phytoplankton distribution in the study area can be complex. Some of these areas of high chla that are apparent in satellite images can be missed by in situ monitoring programmes. High chla levels in the rias due to the increase in the concentration of harmful phytoplankton species have been recorded in the past especially in summer (GEOHAB, 2005). An example of a localized feature is that constantly high surface chla was observed in the Bay of Baiona, located in the southern mouth of ria de Vigo in all the images (Figure 9). The Bay of Baiona is characterized as the zone of ria de Vigo where harmful algal events due to species like Alexandrium minutum are a frequent and recurrent phenomenon (Bravo et al., 2010). It is worth noting that for the area seaward of the rias all the algorithms used in this study came up with very similar values and patterns for chla. Moreover, this study showed that the synergy of two space borne sensors (MERIS, MODIS) in combination with in situ data can be of great help in the monitoring, detection and study of high biomass algal events in an coastal upwelling areas.

Acknowledgements

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References


Tables and graphs
Table 1. MERIS imagery showing the acquisition time (UTC) and mean view zenith angle from west. Sea-truthing ranges of chlorophyll a (chl$_a$), suspended particulate matter (SPM), percentage of inorganic contribution to SPM and Secchi disk depth (Zsd) for ria de Vigo (12 stations) during the two samplings.

<table>
<thead>
<tr>
<th>Date</th>
<th>ria</th>
<th>Cluster#1</th>
<th>Cluster#2</th>
<th>Cluster#3</th>
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<tbody>
<tr>
<td>July 03 2008</td>
<td>Vigo</td>
<td>74.22</td>
<td>23.95</td>
<td>1.83</td>
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<td>Pontevedra</td>
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<td>27.57</td>
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<td></td>
<td>Pontevedra</td>
<td>24.17</td>
<td>75.40</td>
<td>0.43</td>
</tr>
</tbody>
</table>
|             | Arousa   | 11.67     | 86.60     | 1.73      

Table 2. Percentage of pixels belonging to each cluster over the study area (rias Baixas), obtained from classification images derived from the MERIS images used in this study.

Table 3. Performance parameters for the Chla neural networks tested in this study.
Table 4. Dominant atmospheric and oceanographic conditions off the *rias Baixas* categorized as three different states during the upwelling cycle in summer 2008.

<table>
<thead>
<tr>
<th>Period</th>
<th>Date</th>
<th>Dominant atmospheric and oceanographic conditions off <em>rias Baixas</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>July 1-10</td>
<td>winds blowing mainly in south direction (Iw=-108) after a period of favourable upwelling winds, mostly northward surface flow</td>
</tr>
<tr>
<td>2</td>
<td>July 11-21</td>
<td>strong north winds (Iw=900), surface flow towards southwest</td>
</tr>
<tr>
<td>3</td>
<td>July 22-31</td>
<td>mainly south blowing winds (Iw=-230), southward surface flow</td>
</tr>
</tbody>
</table>
Fig. 1. A) Galician coast and bathymetry of the area. From north to south the *rias* *Baixas: Muros y Noya, Arousa, Pontevedra* and *Vigo*. The location of the Seawatch buoy station off Cabo Silleiro is shown by a black rectangle. B) Map of *ria de Vigo* showing the locations of the sampling stations. The MERIS FR pixel size is presented in relation to the size of the *ria*.

Fig. 2. Plots of chlorophyll *a* fluorescence (mg m$^{-3}$) vertical profiles for the upper 10 m of the water column in *ria de Vigo* on A) July 09 2008 and B) July 22 2008. Also I would put the date actually in each panel for clarity.

Fig. 3. Regression analysis between Total Suspended Material (TSM, also termed Suspended Particulate Matter) and *chl a* concentrations. ($y=1.76+0.13x$, $R^2=0.1$ and sample size N=41).

Fig. 4. Classification of MERIS images derived from the study area. The 3 classes identified using the FCM are shown.

Fig. 5. A) Daily upwelling index off the *rias Baixas*. The Iw in m$^{-3}$ s$^{-1}$ 100m$^{-1}$ represents the offshore Ekman flux in the surface layer. Arrows indicating the days where MERIS FR images were available and numbers the different states identified during the studied period and cycles the days of sampling. B) Surface currents (cm s$^{-1}$) recorded by the Seawatch buoy station located off Cape Silleiro (42° 7.8’N, 9° 23.4’W). Data were daily averaged from 0 a.m. on July 1 2008 to 12 p.m. on July 31 2008. Symbols as in Fig. 2.
C) Daily average of sea temperature for the month of July 2008 off the rias Baixas. All data are means ± 1 S.D.

Fig. 6. MODIS-derived Sea Surface Temperature maps for rias Baixas and adjusted coastal waters during the upwelling cycle of July 2008. White patches represent clouds.

Fig. 7. Chla maps for MERIS FR data derived during the upwelling cycle of July 2008 in the study area. Land and clouds were masked and they appear with white colour.

Fig. 8. RGB MERIS (12) FR composite image acquired on July 22 2008 over the study area. Land was masked with black colour.