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Remote sensing chlorophyll *a* 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 on the Galician (NW Spain) shelf and in three adjacent *rias* (embayments), sites of extensive mussel culture that experience frequent harmful algal events. Regionally focused algorithms (Regional neural network for *rias Baixas* or NNRB) for the retrieval of chl*a* in the Galician *rias* optically complex waters were tested in comparison to sea-truth data. The one that showed the best performance was applied to 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 strong upwelling favorable winds a high biomass algal event was recorded in the study area. 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 complex spatial structure of the phytoplankton distribution in the *rias Baixas* is affected by the surface currents and winds on the adjacent continental shelf. This study showed that a regionally specific algorithm for an ocean color 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*.

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1. Introduction

Although remote sensing tools can be used with a relatively high precision at global scale for the calculation of chlorophyll *a* (chl*a*), they are not always totally accurate in local areas (Cota et al., 2004; Ruddick et al., 2008) and highly dynamic systems such upwelling regimes. Eastern boundary upwelling systems cover a small percentage of the ocean surface, but account more than 20% of the global fish catch.

In these high productive systems harmful algal events due to toxic phytoplankton species and/or high-biomass blooms pose an increasing threat for aquaculture and fishing industries, ecosystem health and diversity and have possible implications for human health and activities (Trainer et al., 2010). Harmful algal events in eastern boundary upwelling systems have been closely associated with the wind properties (Bates et al., 1998; Pitcher et al., 1998) and have become a focal point of numerous studies (e.g. Fawcett et al., 2007; Kudela et al., 2005; Pitcher & Nelson, 2006). For example, in their review on harmful algal events in upwelling systems, Pitcher et al. (2010) noticed that variations in wind-stress fluctuations and buoyancy inputs in upwelling systems are controlling factors of the bloom timing and pointed out the role of inner-shelf dynamics on the spatial distribution of the bloom.

Upwelling waters are characterized by considerable variability in the vertical distribution of phytoplankton (Brown & Hutchings, 1987) and in their optical properties (Morel & Prieur, 1977). Optically active water constituents such as SPM which are brought into the surface because of the strong mixing and vertical advection that takes place during upwelling events may vary independently of the surface chl*a*, as they do in typically shallow estuarine case II waters.

In typical case II waters the traditional satellite-derived chl*a* models (empirical: Aiken et al., 1995; Brown et al., 2008; Evans & Gordon, 1994;

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McClain et al., 2004; Muller-Karger et al., 1990; O'Reily et al., 2000 and semi-analytical: Carder & Steward, 1985; Carder et al., 1999) based on the ratio between the radiance of blue and green light reflected by the surface waters cannot be used for an accurate retrieval of chl*a* (Gitelson et al., 2007; Gons, 1999; Morel & Prieur, 1977). However, chl*a* algorithms that use green to red and near infrared band ratios have shown good performance in inland and coastal waters (Gilerson et al., 2010). 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 modeling (Thiria et al., 1993). Dransfeld et al. (2004) emphasized the role of NNs in the retrieval of water constituents especially in Case 2 waters. In recent decades the application of neural network (NN) techniques for the estimation of selected water quality parameters from ocean-color has increased (Atkinson & Tatnall, 1997; Dzwonkowski & Yan, 2005; Keiner & Yan, 1998; Shahraiyni et al., 2009; Zhang et al., 2003). NN based algorithms are currently used as standard products for the estimation of chl*a*, suspended particulate matter (SPM) and yellow substances by the European Space Agency (ESA) for Medium Resolution Imaging Spectrometer (MERIS) data (Doerffer & Schiller, 2007, 2008).

The Galician *rias* are V-like embayments along the northwest part of the Iberian Peninsula formed by sunken river valleys flooded by the sea, whose ecosystems are strongly influenced by oceanic conditions on the adjacent continental shelf. Interest in developing an accurate estimation of chl*a* in these *rias* is considerable, mainly because of the economic and social importance of the extensive culture of mussels (Rodríguez Rodríguez et al., 2011), and the frequent occurrence of harmful algal events (GEOHAB, 2005).

Although MERIS is an ocean color sensor with characteristics considered suitable for chl*a* monitoring and detection of HABs in coastal areas (Doerffer et al., 1999), to our knowledge the studies using MERIS data in the Galician *rias* are limited to those of Torres-Palenzuela et al. (2005a, b), Spyrakos et al. (2010) and González Vilas et al. (2011). The latter authors developed a chl*a* algorithm based on NNs and classification techniques from MERIS full resolution data for *rias Baixas* coastal waters. Previous ocean color studies by satellite sensors (CZCS, SeaWiFS, MODIS) during active upwelling in the Iberian system (Bode et al., 2003; Joint et al., 2002; McClain et al., 1986; Oliveira et al., 2009a, 2009b; Peliz & Fiuza, 1999; Ribeiro et al., 2005) played an important role in the identification of chl*a* 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 these previous satellite remote sensing studies in the area was the failure of the algorithms used to provide reliable chl*a* data during upwelling favorable conditions especially in the areas closest to the coast.

In the present paper a set of neural network-based chl*a* algorithms previously developed for the Galician *rias* waters (within the *rias* and for coastal waters on the continental shelf) are applied for the first time in a short series of MERIS (FR) images delivered during an upwelling cycle in order to obtain maps of chl*a*. This study tests the potential of the algorithms to map the spatial extent of possible algal blooms caused by coastal upwelling. Also, the temporal and spatial distributions of the chl*a* patterns, captured in the MERIS images using the local adapted algorithm, are discussed in relation to the meteorological and oceanographic conditions in the area. Finally, the performance of the neural network-based chl*a* algorithm is compared to *in situ* measurements.

2. Methods and data

2.1. Description of the study area

The *rias Baixas* constitute the southern part of the Galician *rias* (Fig. 1). 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 km^2 and water depths range from 5 to 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. *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; Spyrakos et al., in press; Torres & Barton, 2007) transient increases of phytoplankton abundance, referred to as blooms, are a frequent phenomenon occurring mainly between early spring and late fall (Figueiras & Ríos, 1993; Fraga et al., 1988; Varela, 1992). Sporadically, some phytoplankton blooms in the Galician *rias* 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 *rias* 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 *rias* particularizing favorable conditions to the development of HABs, their origin, dynamic, distribution and toxicity levels (Figueiras et al., 1994; GEOHAB, 2005; Margalef, 1956; Tilstone et al., 1994), seasonal taxonomic and chemical composition of phytoplankton and picophytoplankton "patchiness" (Figueiras & Niell, 1987; Nogueira et al., 1997; Tilstone et al., 2003). More specifically, spring and summer upwelling events in the area have been associated with the dominance of diatoms including the potentially toxic, chain-forming diatom *Pseudo-nitzschia* spp. (Figueiras & Ríos, 1993). Harmful events due to the Paralytic shellfish toxin (PST) producer *Gymnodinium catenatum* have been occasionally (1976: Estrada et al., 1984; 1985: Laiño, 1991; 2005: Bravo et al., 2010b) or/and annually (1985–1995: Pazos et al., 2006) recorded in the Galician *rias*. It is generally considered (Fraga et al., 1990; Figueiras et al., 1996) that advection of warmer waters from the shelf into the rias at the end of the upwelling season coincides with the highest abundances of *G. catenatum*. Pazos et al. (2006) observed a northward progression of *G. catenatum* along the Iberian Peninsula starting on the Portuguese coast, suggesting this could provide an early notice of *G. catenatum* events in the Galician *rias*.

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 was extended from the open sea towards the inner part of the *ria*. Satellite data from MERIS (FR) were available for the same days. The depth of the sites, where samples were collected, ranged from 5 m inside the *ria* to 100 m outside. Triplicate water samples from surface to 3 m were collected at each station (Fig. 1B) from a sampler (3524 cm^3) for the determination of chl*a* 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 (100–200 mL) were filtered through a 9 mm diameter Whatman GF/F filters and stored at −80 °C for 2 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).