Potential Application of the New Sentinel Satellites for Monitoring of Harmful Algal Blooms in the Galician Aquaculture

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Received: 25 April 2019 / Revised: 30 September 2019 / Published online: 28 November 2019
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Abstract
Harmful Algae Blooms (HABs) in the Rias Baixas area (Galicia) cause a strong ecological and economic impact, since they can even force the closure of the rafts production areas for mollusc culture. In this work, we introduce a method for detection and monitoring of HABs in Galicia based on the analysis of map products derived from optical satellite images, including chlorophyll a concentration or species indicators. The approach is developed in the framework of CoastObs project, which started in 2017 and explores the potential of new Sentinel satellites for coastal water monitoring, suggesting different applications such as seagrass, phytoplankton size class or HABs detection. Preliminary results obtained using a set of images acquired on July 2018 suggest the great potential of this approach, which could complement the existing monitoring program based on direct observations.

Keywords Harmful Algae Blooms (HABs) · Rias Baixas · Monitoring program · Sentinel-3 · Chlorophyll a concentration

Introduction
Temporary increases of phytoplankton abundance, commonly known as blooms, are an increasingly frequent phenomenon on coastal regions around the world (Berdalet et al. 2016). Some phytoplankton species involved in these blooms produce toxins that are harmful to human health and other organisms, causing not only ecosystem damages but also strong impacts on human activities as fishing or aquaculture (Zohdi and Abbaspour 2019). Proliferations of toxic microalgae are usually referred as Harmful Algae Blooms or HABs.

The Rias Baixas are four large V-shaped coastal embayments located in the south-west coast of Galicia (NW Spain). As a consequence of its high productivity, the area is rich in fish and shellfish resources and supports an intensive mussel culture using floating rafts (or bateas) organized in farming polygons. In fact, Galicia is the most important producer of aquaculture mussel of Europa and one of the world leaders (Labarta and Fernández-Reiriz 2019).

HABs are a frequent and well-documented phenomenon in Galicia, and a great number of studies can be found in the literature since the 1950's. The sudden appearance and recurrence of bloom events may be linked to the presence of algal cysts particularly those of dinoflagellates in sediments, that constitute a seed bank for the region and provide the initial inoculums for harmful algal blooms once favorable conditions are created (Mohamed and Al-Shehri 2011). In addition to the ecological damage, HABs cause an important social and economic impact since they even force the closure of the mussel...
farming polygons (González-Vilas et al. 2014; Rodríguez et al. 2011).

Traditional HABs detection and monitoring systems are founded on direct observations, i.e., field samplings in fixed stations and subsequent cell count of toxic species using optical microscopy (Anderson 2009). Although direct observations are essential, different approaches based on indirect observations, such as satellite images, have also been proposed. Methods based on satellite images are cost-effective, produce map outputs providing a more synoptic view of the study area as compared to traditional methods using sampling stations (Blondeau-Patissier et al. 2014; Kudela et al. 2017).

After the successful results obtained using MERIS images between 2002 and 2012, European (EU H2020) funded project CoastObs (http://coastobs.eu) explores the potential use of the new Sentinel satellites to monitor coastal water environments. It started in 2007 and aims at providing low-cost validated products, including phytoplankton size classes, seagrass, primary production and also HABs. Specifically, two maps products derived from Sentinel images are expected to provide useful information for HABs detection and monitoring in the Galician rias: chlorophyll a (chl a) concentration and species indicators.

Chl a concentration is one of the most important products derived from optical satellites images, in fact, it has been processed in an operational way for open ocean areas since the 1980’s (Gregg and Rousseaux 2014). Since chl a concentration can be used as a phytoplankton biomass indicator and it is common to almost all taxonomic groups, chl a maps could be suitable for identifying and monitor blooms, although they do not provide information about the species or its toxicity (Zheng and DiGiacomo 2017). Chl a maps derived from ENVISAT MERIS have already proven to be useful in the Rias Baixas area (Spyrakos et al. 2011).

Species indicators are intended to detect a specific species directly from satellite images. Product output could be a map showing the species abundance or a binary map identifying bloom/no bloom areas (Devred et al. 2018; Kurekin et al. 2014; Soto et al. 2015). Species indicators for some of the most common toxic species in Galicia, such as Pseudo-nitzschia spp. and Gymnodinium catenatum, have been initially proposed within CoastObs. Moreover, a product could be also developed for Alexandrium minutum taking advantage of the bloom detected in summer 2018 (Rodríguez 2018).

In this work, we introduce the methodology developed in the framework of CoastObs project for the detection and monitoring of HABs in Galicia using map products derived from Sentinel images and show some preliminary results obtained in 2018. This methodological approach could be useful for complementing the existing monitoring program based on direct observations.

### Material and Methods

#### Sentinel Images

The European Space Agency (ESA) Sentinel program (https://sentinel.esa.int) started in 2014 for fulfilling the operational needs of the Copernicus program, which provides information on a global scale in six domains: ocean, land and atmosphere monitoring, emergency response, security and climate change. It consists of a family of five satellite missions based on different technologies (e.g. SAR, multi-spectral imaging instruments) and focused on different targets (e.g. ocean, land or atmosphere).

Sentinel-3 mission is based on the heritage of ENVISAT MERIS, which has kept operational between 2002 and 2012 achieving excellent results in marine applications. Its Ocean and Land Colour Instrument (OLCI) covers a swath width of 1270 km providing the same spatial resolution (300 m) as MERIS, but with more spectral bands (21 instead of 15) ranging from 400 nm to 1020 nm. Since December 2018, with a two satellite configuration (Sentinel-3A and Sentinel-3B), revisit time in mid-latitudes (Galicia) is only 1 day (Donlon et al. 2012).

In this work, five Sentinel-3 images over the Rias Baixas area in July 2018 were available. Images were acquired on the same dates as field data were collected during a field campaign (Table 1).

#### Field Campaign

In July 2018, a field campaign consisting of five field trips on the same dates as Sentinel overpasses was conducted in the Ria of Vigo (i.e. the southern of the rias Baixas) using two research vessels. Data were collected from a total of 58 sampling stations (Table 1). At each point, water-leaving reflectance spectra were measured using two different sets of field radiometers: TrioOS and Water Insight Spectrometer (WISP-3). Water samples were also collected from surface to a depth of 4 m using a PCV hose and then filtered in the laboratory to determine several optical parameters in a later processing: chlorophyll-a concentration (chl a), coloured dissolved organic matter (CDOM), size-fractionated chlorophyll and total suspended matter (TSM). Finally, a set of parameters were measured in situ using different sensors: depth, temperature, pH, conductivity, turbidity, phycocyanin and apparent optical parameters (AOP), such as chl a or CDOM.

#### Image Processing and Modelling Procedure

Considering that OLCI instrument on-board Sentinel-3 is actually a continuity of ENVISAT MERIS, the approach for the development of reliable map products (i.e. chl a concentration or species indicators) from Sentinel-3 is mainly based on the
protocol previously designed by González Vilas et al. (2011) to estimate chl concentrations from MERIS images. The main steps of this methodological approach are summarized in Fig. 1. Note that in situ data collected on the same date as the satellite overpass are essential for the development and subsequent validation of the products.

The first step is the masking of land, cloud or invalid pixels using the pixel identification and classification tool Idepix, which is available in the SNAP v6.0 Sentinel processing toolbox (http://step.esa.int/main/toolboxes/snap).

The second step is the atmospheric correction (AC), i.e. the application of an algorithm that removes the effects from the atmosphere to derive the water signal (water-leaving reflectance spectra) from the signal that is directly measured by the satellite instrument (top-of-atmosphere radiance spectra). Atmospherically corrected images are comparable on different dates and hence they could be processed using the same algorithm to retrieve a specific parameter (e.g., chl concentration) (Mobley et al. 2016).

The third step is the application of a fuzzy c-means (FCM) clustering algorithm (Moore et al. 2009) based on the reflectance spectra extracted from pixels linked with the sampling stations. According to González Vilas et al. (2011), reflectance spectra obtained from atmospherically corrected images over the Galician complex case 2 waters are affected by different optically active constituents (i.e. chl, CDOM and TSM), and application of single estimation algorithms to data from different situations (e.g. clean and sediment-dominant waters) could lead to unreliable results. Although FCM clusters are only based on reflectance values, they are expected to be related to different optical water types and are hence useful for defining the scope of the estimation algorithms to be developed in the next step.

Unlike other non-fuzzy or hard algorithms, FCM generates a membership function for each cluster, so that a membership degree (between 0 and 1) to each cluster could be assigned to a given data point (reflectance spectrum). FCM only requires two input parameters: the number of clusters and the weighting exponent (any real number greater than 1).

A trial and error approach is first applied to determine the optimal input parameters, which are unknown a priori. The best FCM is selected according to the results of two validation functions (partition coefficient and compactness and separation index) computed for each input configuration (i.e. combination of number of clusters and weighting exponent), and hence it provides a maximum degree of separability among the clusters (see González Vilas et al. 2014 for more details about this procedure).

Table 1 Dates of the available Sentinel-3 images over the study area and number of sampling stations for each date

| Date       | #Sampling stations | # Valid Pixels | % Cluster#1 | % Cluster#2 |
|------------|--------------------|----------------|-------------|-------------|
| 04 July 2018 | 3                  | 14,631         | 1.13%       | 98.87%      |
| 09 July 2018 | 7                  | 3407           | 3.32%       | 96.68%      |
| 12 July 2018 | 18                 | 14,774         | 13.79%      | 86.21%      |
| 13 July 2018 | 6                  | 1616           | 6.81%       | 93.19%      |
| 17 July 2008 | 24                 | 9608           | 2.57%       | 97.43%      |

For each subset image (latitude from 41.9°N to 42.6°N, longitude from −9.2°W to −8.3°W), number of valid (water and cloud-free) pixels and percentage of valid pixels belonged to each cluster is also shown.

Fig. 1 Chain processing for generating a chla or species indicator map starting from a Sentinel-3 image
The best FCM is then applied to each image to obtain a classification map showing the cluster value (i.e. the cluster with the highest value in its corresponding membership function) for each non-masked pixel.

The last step is hence the development of cluster-specific algorithms for the retrieval of a given parameter, i.e., chl$\alpha$ concentration or species indicator. These algorithms are then applied to non-masked pixels with the corresponding cluster value in the classification image to build the final map. If a different algorithm is available for each cluster, membership grades for each cluster would also allow blending their results to create maps with soft transitions.

Different kinds of estimation algorithms could be applied, including regression models and machine learning methods, such as support vector machines (SVM) or AdaBoost. In this work, we used multilayer perceptron (MLP) artificial neural networks (NN), which approximate a set of input data (reflectance spectra) to the corresponding output (chl$\alpha$ concentration or species indicator). Once the NN architecture is designed, it requires a priori information about the real output, i.e. in situ data, in order to train the network and achieve the best possible approximation.

In this work, we developed a cluster-specific chl$\alpha$ NN consisting of an input layer with 14 nodes (reflectance spectra extracted from atmospherically corrected images), two hidden layers with 4 nodes and an output layer with only one node associated with the desired output (chl$\alpha$ concentration). Due to the small size of the input dataset, we applied a leave-one-out cross-validation to train the neural network (see González Vilas et al. 2011 for more details).

**Results**

Figure 2 shows the study area and the location of the sampling stations, while the dates and the number of sampling stations are summarized in Table 1. Although Sentinel-3 images were available each day, weather conditions were variable resulting in different percentages of cloud cover over the study area (Table 1). This percentage was computed as the number of pixels flagged as cloud using Idepix tool divided by the total number of water pixels.

Four different AC algorithms were tested: Case–2 Regional processor (C2RCC), Case 2 Regional Coast Colour (aug-C2RCC), OLCI Level-2 Water Full Resolution (WFR) and Polymer. Reflectance data from each atmospherically corrected image were first extracted from non-masked pixels containing the exact geographic location of the sampling stations on the corresponding day. Then, image reflectance data for each AC were compared to water-leaving spectra measured in situ using both TriOS and WISP-3 field radiometers using regression analysis. Results show that Polymer ($R^2 = 0.63$) outperforms the other algorithms ($R^2 = 0.56$ for C2RCC; $R^2 = 0.44$ for aug-C2RCC and $R^2 = 0.17$ for WFR).

The best FCM algorithm based on Polymer reflectance spectra linked to sampling stations was achieved with two...
clusters and a weighting exponent of 1.5. The cluster to each reflectance spectra in the input dataset and classification maps for each Sentinel-3 image were obtained assigning the cluster with a highest value in its corresponding membership function. 90.9% of the spectra in the input dataset were classified as Cluster#2, and as is seen in Table 1, more than 85% of the valid pixels (non-masked water pixels) in each classification image were also assigned to Cluster#2.

The chl\(\alpha\) NN was developed using reflectance spectra extracted from non-masked pixels belonged to the predominant Cluster#2 as input, and the corresponding chl\(\alpha\) concentrations measured in situ as output. Specifically, chl\(\alpha\) concentrations were retrieved from WISP-3 field spectra using the algorithm provided by the own instrument (based on the work by Gons et al. 2005). In total, 20 chl\(\alpha\) concentrations ranging from 3.1 mg m\(^{-3}\) to 9.8 mg m\(^{-3}\) were obtained. Figure 3 shows the relationship between the chl\(\alpha\) concentrations measured in situ and the chl\(\alpha\) concentrations predicted by the NN in the leave-one-out cross validation process. A good fitting, with a clear linear trend and a positive correlation (\(R^2 = 0.95\); RMSE = 0.44), was obtained.

Starting from the classification image (Fig. 4a), the chl\(\alpha\) NN was applied to non-masked pixels belonging to Cluster#2 of each Sentinel-3 image to build chl\(\alpha\) maps (Fig. 4b). Finally, as in shown in Fig. 5, chl\(\alpha\) values derived from maps were spatially averaged using the mollusc production areas defined by the Spanish government (Spanish Ministerial Order APM/392/2017 of 21 April).

**Discussion**

The Rias Baixas waters are optically very complex because of regional characteristics such as upwelling or freshwater inputs from numerous small rivers. As a consequence, standard chl\(\alpha\) algorithms provided by ESA are not expected to produce accurate results and development of regional specific algorithms is thus required for obtaining more reliable maps (González Vilas et al. 2011).

The chl\(\alpha\) NN developed in this work is is specific to Cluster#2 and limited to the ranges defined by the training dataset, i.e. chl\(\alpha\) concentrations between 3.1 mg m\(^{-3}\) and 9.8 mg m\(^{-3}\). Therefore, the algorithm does not cover the complete range recorded in the Rias Baixas, which varies typically from 0.03 mg m\(^{-3}\) to 8 mg m\(^{-3}\) (González Vilas et al. 2011; Nogueira et al. 1997). In fact, anomalous high concentrations have been measured during the field campaign, which can be explained by the bloom of *Alexandrium minutum* detected during July 2018 in the area (Rodríguez 2018). This bloom could also explain the higher chl\(\alpha\) concentrations inside the Rias Baixas as compared to the adjacent platform that are also observed in Fig. 5.

![Fig. 3](image-url) Relationship between the chl\(\alpha\) concentrations measured in situ and the chl\(\alpha\) concentrations predicted by the NN in the leave-one-out cross validation process
With the aim of being applied operationally, the chl NN would need to be adapted using new data to cover the complete range of variation of chlorophyll concentrations over the Rias Baixas. However, it is able to produce reliable

Fig. 4  Map products derived from Sentinel-3 OLCI image acquired on 4 July 2018: a classification image obtained using the 2 clusters FCM classifier; b chlα map obtained by applying the NN chlα algorithm
chl\text{a} maps from images acquired in July 2018, providing useful information about the spatial distribution of phytoplankton biomass (Fig. 4).

As it was also shown in previous studies using its predecessor MERIS (Sýrakos et al. 2011), chl\text{a} maps derived from Sentinel-3 images could complement phytoplankton data from monitoring programs based on direct observation in order to know the distribution and evolution of a bloom. Despite the fact that chl\text{a} maps can only be obtained under cloud-free conditions, Sentinel-3 images not only provide a good spatial resolution (300 m) for studying the Galician area but also an excellent temporal resolution with images available on a daily basis since December 2018 (Donlon et al. 2012).

Although chl\text{a} concentration is a good estimator of phytoplankton biomass, it does not provide information about the species or its toxicity. So, some authors have proposed species indicators, i.e., direct detection of a specific species to build abundance or bloom/no bloom maps from satellite images. These indicators are based on the fact that high concentrations of some species cause a distinctive water colour, and thus a characteristic spectral signature that could be detected in the images. Unfortunately, results are limited by two factors: 1)
distinctive spectral features of the species could be out of the spectral range of the images, which is limited to a number of discrete bands; and 2) coastal waters are usually very complex and the spectral signature is the result of the interaction of different species, not only the target species, and other organic and inorganic components (Kudela et al. 2017).

A wide variety of methods have been applied to detect phytoplankton blooms in ocean and coastal regions from satellite ocean colour sensors. Although simple band ratios algorithms have proven to be adequate for open ocean waters, biophysical models and regression techniques are preferred in coastal complex waters as Galicia (Blondeau-Patissier et al. 2014). HABs detection can also be improved by integrating additional datasets derived from ecosystem models or other satellite sensors. For instance, Anderson et al. (2009) developed regression models for *Pseudo-nitzschia* spp. abundance in Santa Barbara channel incorporating ocean colour (MODIS-Aqua and SeaWiFS) and sea surface temperature (AVHRR) data.

At this moment, we are developing species indicators for three of the toxic taxonomic groups causing HABs in Galicia: *Pseudo-nitzschia* spp., *Gyrodinium catenatum* and *Alexandrium minutum*. Note that *Pseudo-nitzschia* spp. is a genre including both non-toxic and toxic species, making still more difficult to define distinctive spectral features, but data about toxic species are not available. In any case, we are adapting the same methodology as we have applied on the chla algorithm, but exploring other methods in addition to neural networks, such as regression models, SVM or AdaBoost.

With the aim of obtaining more reliable results in terms of bloom detection, we are developing a higher level product combining species indicator maps derived from Sentinel-3 images with auxiliary data defining the environmental conditions in previous days. In fact, in case of *Pseudo-nitzschia* spp., numerical models including variables as upwelling index, temperature and salinity have already been proven to be useful for detecting blooms (González Vilas et al. 2014).

In addition to Sentinel-3, Sentinel-2 could also be useful for generating maps products that could be applied to HABs detection and monitoring on coastal areas. Sentinel-2 mission consists of two satellites (Sentinel-2A and Sentinel-2B), each one carrying a single multispectral imager (MSI) instrument on-board. MSI provides high-resolution images (10 m, 20 m or 60 m depending on the band) with a swath width of 290 km and 13 spectral bands (443 nm - 2190 nm). Revisit time in mid-latitudes (Galicia) is about 5 days (Drusch et al. 2012).

As compared to Sentinel-3, Sentinel-2 shows poorer spectral and temporal resolution but a significantly better spatial resolution. Preliminary analysis of Sentinel-2 images over the Galician area during the bloom of *Alexandrium minutum* detected in July 2018 shows the potential of these high-resolution images. However, images have also proven to be difficult to interpret because of the noise and the presence of artefacts related to floating structures such as boats or culture rafts. Nevertheless, ongoing efforts are being made to develop an appropriate methodology to build map products based on these images.

CoastObs innovative products are being developed in accordance with final users. In Galicia, the main users are the Cooperative of Fishing Ship owners of Vigo (ARVI) and the Regulatory Council of Mussel from Galicia. Due to their lack of experience in managing raster maps products, simplified output format are preferred, e.g. spatial averaged data for mollusc production areas (Fig. 5) or rafts polygons.

The Quality Control Technology Institute of the Marine Environment (INTECMAR), monitors HABs and marine biotoxins in Galicia, regulating the closure of mussel rafts polygons if required to comply with the application of administrative regulations and sanitary requirements. Although its monitoring programme is essential and irreplaceable, it is only based on weekly samplings at a limited number of stations and thus important information could be missed considering that the Rias Baixas is a highly dynamic environment.

Therefore, the method proposed in this work could complement the existing monitoring program by providing information on a daily basis about the detection and spatial distribution of HABs with a higher spatial resolution.

Acknowledgments This work was partially funded by the European Union’s Horizon 2020 research and innovation program project CostObs (grant agreement n° 776348). Authors want to thank INTECMAR, ARVI and the Regulatory Council of Mussel from Galicia for their support.

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