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Water quality assessment using satellite-derived chlorophyll-*a* within the European directives, in the southeastern Bay of Biscay

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ABSTRACT

The implementation of water quality European Directives requires an intensification of water quality monitoring, within the limits of the Exclusive Economic Zone. Remote sensing technologies can provide a valuable tool for frequent, synoptic, water-quality observations, over large areas. The aim of this study is to assess the ecological status of Basque coastal water bodies using satellite imagery from MODIS sensor, together with optical and chlorophyll-*a* *in situ* measurements. Thus, sea surface satellite-derived chl-*a* algorithms, the OC3 M, OC5 and a Local empirical algorithm, were compared against *in situ* measurements using satellite *in situ* match-ups, 90th Percentile (P90) monthly values for the 2005–2010 period. The OC5 algorithm corresponded most accurately with *in situ* measurements performed in the area, hence, it was selected. A P90 chlorophyll-*a* map was created with this algorithm to apply the classification scheme required by the directives. The classification of water bodies, based upon satellite-derived chlorophyll-*a*, could improve considerably the assessment of water quality.

1. Introduction

The approval of the Water Framework Directive (WFD, 2000/60/EC) and the Marine Strategy Framework Directive (MSFD, 2008/56/EC) entailed a densification and an increase in the frequency of water quality monitoring in areas along the coast and within the limits of the Exclusive Economic Zone (EEZ) (200 nautical miles). According to the WFD, a "good" surface water status should be achieved for all European waters by 2015. To attain this objective, the ecological and chemical status of surface water bodies need to be assessed and the quality conditions reported using a classification scheme. Phytoplankton biomass has been selected by the WFD and MSFD (Borja et al., 2011; Ferreira et al., 2011) as one of the parameters for quality assessment because it can respond to nutrient enrichment that causes water eutrophication (Nixon, 1995; Halpern et al., 2008; Conley et al., 2009). Nutrient inputs caused by anthropogenic discharges can enhance phytoplankton growth, leading to disturbances in the balance of the water ecosystem, together with decreases in water quality (i.e., reduction of dissolved oxygen, increases in organic matter and turbidity) (Bricker et al., 2008). The concentration of the photosynthetic pigment chlorophyll-*a* (chl-*a*) in the water is widely used as a proxy of phytoplankton biomass (Cullen, 1982; Jeffrey and Vesk, 1997). It also represents a simple and integrative measure of the response of the phytoplankton community to nutrient enrichment, provided that the systems under assessment are not 'poor light' environments, and picophytoplankton are not the most important contributors (Domingues et al., 2008).

However, some authors (Domingues et al., 2008) have stressed the constraints on the use of this element within European Directives related to issues such as sampling frequency and overlooking blooms. In this regard, remote sensing technologies provide the most effective means for performing frequent synoptic water quality observations over large areas (Lee et al., 2005). Therefore, satellite imagery can be used to complement traditional monitoring techniques (Domingues et al., 2008; Gohin et al., 2008), offering a substantial improvement in terms of spatial and temporal coverage for the upper layers of the water column, especially when a densification of sampling efforts is necessary for monitoring purposes. In optically complex waters, such as coastal waters affected by river outflows (Morel and Prieur, 1977), the standard and global algorithms used in clear or "oceanic" waters present inaccuracies (e.g., Carder et al., 1999; Novoa et al., 2011). Inputs of suspended and dissolved substances through river discharges alter the optical properties of water, significantly affecting accurate chl-*a* estimation (IOCCG, 2000). As these substances are region and season specific, regionally parameterized empirical algorithms are required to accurately estimate chl-*a* at a local scale (IOCCG, 2000).

Along the Basque coast (southeastern Bay of Biscay), *in situ* coastal monitoring network surveys have been carried out since 1994 (Borja et al., 2009, 2011) to meet WFD and MSFD requirements.

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However, the researchers performing these studies have highlighted the need to obtain more extensive (spatial) and intensive (temporal) data coverage to produce more accurate assessments of phytoplankton status, as recommended by Ferreira et al. (2011).

Hence, the aim of the present study was to evaluate the potential use of satellite data estimations of chl-*a* as a tool for the assessment of both phytoplankton status within the WFD and anthropogenic eutrophication within the MSFD for Basque coastal and offshore water bodies. For this purpose (i) an algorithm to predict chl-*a* with a suitable accuracy in coastal areas had to be selected; and (ii) chl-*a* estimations predicted by three different algorithms developed for MODIS (Moderate Resolution Imaging Spectroradiometer) were compared to chl-*a* values measured *in situ* obtained from historical data (WFD monitoring surveys) and *ad hoc* oceanographic surveys using *in situ* satellite comparisons and 90th percentile (P90) monthly values for the 2005–2010 period. Furthermore, P90 chl-*a* maps were generated with the selected algorithm, and (iii) an ecological status assessment was then performed based on a phytoplankton biomass metric. Finally, the results were compared with the present assessment undertaken using only chl-*a in situ* measurements.

2. Materials and methods

2.1. Basque littoral monitoring network

The Littoral Water Quality Monitoring and Control Network (LQM) of the Basque Country (southeastern corner of the Bay of Biscay) was initially implemented in 1994 (Borja et al., 2004). In coastal waters, the LQM is currently composed of 16 *in situ* sampling stations (Borja et al., 2009); 3 additional stations are surveyed in offshore waters for the implementation of the MSFD (Borja et al., 2011). The monitored coastal water bodies lie within the northeast Atlantic eco-region and belong to the NEA-1 (northeast Atlantic) type following the WFD typology system. This type is characterized by euhaline fully mixed waters in exposed and shallow (30 m) coastal areas subject to a mesotidal regime (Borja et al., 2007). The offshore stations are considered to be reference stations for coastal waters because they are not impacted *a priori* by anthropogenic influences due to their distance from the main pollution sources on land (8–15 km). The coastal stations were selected based on the following criteria: (i) the depth of the water bodies had to be appropriate to reduce the variability caused by coastal features, such as bathymetry, waves or currents, so all of the coastal stations are located within the 1 nautical mile limit established by the WFD over waters of 25–35 meters in depth; and (ii) they needed to be situated at a suitable distance from land to be influenced by anthropogenic discharges, and most stations were therefore located near the most important river mouths in the area; whereas (iii) the offshore stations are considered to be reference stations because they are not impacted *a priori* by anthropogenic influences due to their distance from the main land-based pollution sources (10–15 km) over water depths of approx. 100 m. The stations are allocated in 5 different water bodies, which are classified based on the geographical characteristics of the area, such as the orientation of the coast, the presence of a submarine outfall, and the geographical limits established by the European Water Framework (from the coastline to 1 nautical mile offshore of the baseline) and Marine Strategy Directives (from the baseline to 200 nautical miles) (Borja et al., 2009, 2011); see Fig. 1. The 1 nautical mile distance is measured from the 3 main capes of the Spanish Basque Country (Matxitxako, Getaria, Higer), and the water bodies are delimited by linking nautical points off the capes. Four water bodies are considered as coastal (See Fig. 1), while one corresponds to 'oceanic waters', located beyond coastal waters (MSFD area).

Development of the methods used to evaluate the quality of coastal waters in relation to the WFD began in early in 2000. The first method used to assess the quality status of the WFD phytoplankton element in the Basque marine environment (Borja et al., 2004) was based upon a method developed at Ifremer (Vincent et al., 2002). This method utilized phytoplankton biomass (derived from chl-*a* concentrations) and phytoplankton abundance and composition to calculate an integrated index that classified quality status into five distinct categories (from "High" to "Poor") matching the WFD typology classification. However, this method did not provide any information regarding reference conditions or ecological quality ratios, which is a requisite of the WFD. Therefore, a new method for phytoplankton quality assessment was developed for the eastern Cantabrian coast, which includes the Basque coastal waters (Revilla et al., 2009). This new method involves integrating the results of two metrics for the water body that are calculated on the basis of a 6-year period: (i) the biomass metric (calculated as the P90 of chl-*a* concentrations) and (ii) the bloom metric (calculated as the frequency of cell counts above a threshold for any individual taxa). The values for the high/good and good/moderate boundaries were established during the first phase of the WFD intercalibration exercises (Carletti and Heiskanen, 2009). The boundary values of the chl-*a* metric for the moderate, poor and bad status classes along the Basque coast were proposed by Revilla et al. (2009). Thus, at present, in the Basque offshore and coastal waters, the ranges of P90 concentrations corresponding to the high, good, moderate, poor and bad classes are <3.5, 3.5–7.0, 7.0–10.5, 10.5–14.5, and $\geqslant$14.5 mg m^{-3}, respectively.

2.2. In situ dataset

The main dataset used for this study was obtained from the Basque LQM for the period between 2005 and 2010. Measurements were performed every three months from February to November to collect data representative of winter, spring, summer and autumn conditions. At each station, chl-*a* was estimated based on CTD fluorescence in continuous vertical profiles obtained with a SeaBird 25 CTD. Fluorescence units were calibrated regularly against spectrophotometer measurements of chl-*a* in natural water samples. The spectrophotometric analyses involved filtration of water samples through Whatman GF/C filters, pigment extraction in acetone, and employing the equations developed by Jeffrey and Humphrey (1975), without correction for phaeopigments. The chl-*a* data used for this study corresponded to CTD measurements that were carried out 1 m below the water surface in natural water samples.

In addition, simultaneous chl-*a* concentration measurements were performed using both methods (CTD fluorescence and spectrophotometric analysis) during two *ad hoc* oceanographic surveys ($n = 64$) undertaken in June 2007 and April and June 2009 over the study area. The collected water samples were filtered in the field, and spectrophotometric measurements were performed in the laboratory 72 h after their collection (Fig. 1). Simultaneous measurements with both methods were also carried out monthly at a coastal station near the Mompás submarine Outfall (Station L-UR20; Fig. 1) for an entire year (2009–2010). Comparison between the measurements obtained using both methods was performed to test their correlation and to account for possible inaccuracies related to *in situ* measurements.

2.3. MODIS imagery

The images selected for this study were provided by MODIS. The high frequency of synoptic images (daily) obtained by MODIS as well as their ready availability, number of spectral bands, and resolution (1 km × 1 km) make these images suitable for the estimation of chl-*a* and water quality monitoring. MODIS is type of a