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A method based on satellite imagery to identify spatial units for eutrophication management

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ABSTRACT

A procedure based on analysis of time series of MODIS-Aqua satellite chlorophyll *a* images was developed in order to spatially delimit areas of the Alboran Sea with distinguishable annual cycles of productivity. For this objective, daily images of satellite chlorophyll were obtained from 2002 to 2013. Monthly means were calculated for each pixel and then the pixels were grouped by means of the statistical technique of non-hierarchical clustering analysis according to the features of their annual cycle. The outcome of the clustering analysis was validated by comparing the pixel grouping patterns with the spatial distribution of *in situ* chlorophyll *a* and nutrients as determined from the available data (about 2900 registers obtained in the 20 m upper seawater layer in 70 sampling stations). Six grouping areas were identified which reproduced the expected zonation according to the distribution of the main mesoscale hydrological structures that modulate the productivity in the study area (oligotrophic gyres and coastal upwelling). The grouping areas presented contrasting chlorophyll *a* concentrations as well as annual minimum and maximum occurring at different seasonal cycle timing. Seasonal means of *in situ* chlorophyll *a* and nitrate and phosphate concentrations calculated for the six grouping areas were significantly correlated, supporting that dissolved inorganic nutrients were the main factor controlling the productivity in the Alboran Sea. Consequently, the grouping of pixels based on satellite data reflected reasonably the underlying mechanisms that control the phytoplankton biomass in the study area. The utility of this technique to define spatial units for eutrophication management is discussed. These units can be used for spatial aggregation of eutrophication indicator data collected from *in situ* samplings as well as for calculating robust reference values and time trends. Furthermore, the pixel grouping is useful for optimizing the existing monitoring programs as it facilitates the selection and location of sampling stations in order to avoid collection of redundant and/or pointless information.

1. Introduction

The Marine Strategy Framework Directive (European Commission, 2008; MSFD) that entered in force in 2008, includes eutrophication among the eleven descriptors of the marine environment which must be evaluated by the Member States for assessing the good state of the European Seas. The MSFD defines eutrophication as a process whose symptoms are progressive and its effects on the marine ecosystems are multiple (European Commission, 2010; Ferreira et al., 2011). In a first stage, nutrient pollution is manifested by increases in chlorophyll *a* concentration in the water column and/or opportunistic macroalgae abundance (the so called 'direct effect indicators'), afterwards secondary effects such as low dissolved oxygen concentration, changes in phytoplankton community composition and increased frequency of nuisance and toxic blooms are produced ('indirect effect indicators'; Ferreira et al., 2011). The MSFD impulses the implementation of common strategies for eutrophication monitoring among the Members States (MS) by 2016. Among other things, these joint strategies should include not only the collection of information regarding to mandatory indicators but also the adoption of shared criteria to define the spatial scales of assessment as well as for selecting the sampling areas and stations (Zampoukas et al., 2012). The national programs for eutrophication monitoring should be based on the principle of the sampling effort is optimized in terms cost/benefit (*i.e.* the effort is kept at a minimum although it must guarantee that all relevant information is collected) and the produced information should be comparable and embeddable for supporting assessments at regional scale (Zampoukas et al., 2014). However, the analysis of the eutrophication initial assessment reports carried out by the MS in the first implementation phase of the MSFD by 2013 reveals that the monitoring strategy as well as the evaluation areas or geographical units used by the different

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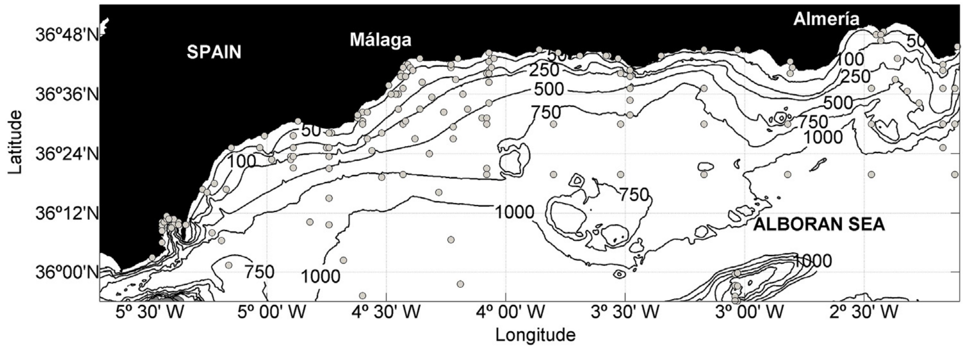

Fig. 1. Location of the sampling stations (grey points) where the *in situ* chlorophyll *a* concentrations used in this work have been obtained. Isolines of depth are shown.

countries in the implementation of the Directive were fairly dissimilar (Palialexis et al., 2014; Prins et al., 2013).

In this article, a procedure for identification of the spatial units that can be used as eutrophication management areas within a given region or sub-region is proposed. This method is mainly based on the use of satellite images and assumes the coastal eutrophication conceptual model proposed by Cloern (2001). The latter emphasized that the effects of nutrient pollution on phytoplankton productivity in a given system are conditioned by its physical and/or biological characteristics (*e.g.* optical properties of the water column and/or horizontal transport processes that depend on several factors like wind, bathymetry and basin geography and river flow). These attributes that vary among systems act as a filter that modulate (*i.e.* amplifies or mitigates) the impacts of nutrient enrichment on the marine system. Satellite images offer information at a high temporal and spatial resolution about the horizontal distribution patterns of hydrological properties and chlorophyll *a*. Several reports demonstrate that satellite chlorophyll images reflect adequately the impact of the hydrological structures on phytoplankton biomass distribution. Satellite imagery has been also proposed to detect changes in the distribution patterns of chlorophyll *a* that are attributable to anthropogenic impact (Gohin et al., 2008) as well as to detect algal blooms and shifts in dominance patterns of some phytoplankton taxonomic groups (Hu et al., 2005; Ahn and Shanmugam, 2006; Carvalho et al., 2011; Shanmugam et al., 2008; Jackson et al., 2011). If this satellite information is appropriately analyzed for a given marine region, it would permit spatial delimitation of the areas distinguishable according to the particular mechanisms that control the nutrient-driven chlorophyll dynamics (for instance, upwelling areas, anticyclonic gyres or zones affected by river discharge; Klemas, 2011).

The utility of the satellite images in dealing with the spatial scaling of the eutrophication assessment as required by the MSFD is researched in this work. To achieve this, a method for analysing satellite image time series (clustering analysis) is tested for the northern Alboran Sea basin (the most western basin in the Mediterranean Sea). This basin is a fairly adequate frame for this objective since this region features a remarkable hydrological singularity. In short, the Atlantic jet that penetrates through the Gibraltar Strait feeds two quasi permanent anticyclonic gyres which occupy the entire central part of the basin. Intensive fronts are located at the north part of the anticyclonic cores where nutrient concentrations are relatively high in comparison to the oceanic areas (Rodríguez et al., 1997; Mercado et al., 2007). Furthermore, the littoral fringe along the north-western coast of the Alboran Sea is densely populated (about 440 inhabitants km^{-2}). Therefore, the entry of domestic waste and urban drainage represent significant sources of nitrate and phosphate for the coastal waters (Mercado et al., 2012).

2. Materials and methods

2.1. Gathering and processing of satellite chlorophyll a images

Level-2 images of MODIS-Aqua for the northern Alboran Sea (Western Mediterranean Sea) acquired in the period 2002–2013 were downloaded from the NASA website (http://oceancolor.gsfc.nasa.gov/) in June 2014 (MODIS-Aqua reprocessing 2013.1). The supplier provides a daily scene of chlorophyll for the study area with a spatial resolution of 1.1 × 1.1 Km^2. Satellite chlorophyll *a* (C_{SAT}) was calculated from reflectance values by using the global algorithm OC3M v.6 based on NOMAD v.2 database (O'Reilly et al., 2000; Werdell and Bailey, 2005). Daily data of satellite surface temperature (SST) were also retrieved from the images of MODIS-Aqua. The temporal series of SST and C_{SAT} for each pixel was processed in order to compose climatological monthly maps.

The monthly means of C_{SAT} were used to identify contrasting areas with respect to their annual cycle. For this objective, all pixels were grouped by means of the statistical technique of non-hierarchical clustering analysis (*k-means* clustering analysis). In contrast to the hierarchical cluster analysis, *k-means* clustering analysis classifies objects (pixels) into a pre-defined number of clusters unrelated hierarchically. In our analysis, each pixel was assigned to a particular group according

Table 1
List of sampling stations and research projects used for gathering of nutrient and chlorophyll concentration data in this study. The location of the sampling stations according to the zonation obtained by the clustering analysis of the satellite images is indicated (column "Grouping areas").

Stations	Sampling year	Projects/cruises	Grouping areas
A1	2008	Nitroalboran	ALBP1
P2, F3	2002–2007	Ecomalaga/Radiales	"
MARB2, MARB3, MARB4	2003–2004	Noralboran	"
EJ1, EJ2, EJ3	2010	Eutrofizacion	ALBC2
F2, FU4, GU3, M2, M3, MA4, V1, V2, V3	1992–2010	Ecomalaga/Radiales	"
R1, R2, T1, T2	2002–2004	Ecomalaga/Radiales	"
CV1, CV2, CV3, CV4	2010–2012	Eutrofizacion	"
P1, M1, MA1, MA2, MA3	1992–2012	Ecomalaga/Radiales Trofoalboran	ALBC1
B1, MARB1	2008	Nitroalboran	"
F1, FU1, FU2,FU3	2002–2007	Ecomalaga/Radiales	"
GU1, GU2, GU3	2010	Eutrofizacion	"
ST1, ST2, ST3, AG3	2010–2012	Eutrofizacion	"
A3, A4, A5, B4, B5	2008	Nitroalboran	ALBO1
AL1 (VUL), AL2 (VUL), AL3 (VUL)	2009	Vulnerables	"
F4	2002–2007	Ecomalaga/Radiales	ALBP2
P3	1993–2010	Ecomalaga/Radiales	"
A2, B2, B3	2008	Nitroalboran	"
T4	2002–2004	Ecomalaga/Radiales	"
R3, R4	2002–2004	Ecomalaga/Radiales	ALBO2
T3	2002–2004	Ecomalaga/Radiales	"
M4, M5	2002–2010	Ecomalaga/Radiales	"
V4	2002–2010	Ecomalaga/Radiales	"
AL1, AL2, AL3	2010–2012	Trofoalboran, Eutrofizacion	"