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Biogeochemical regions of the Mediterranean Sea: An objective multidimensional and multivariate environmental approach

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ABSTRACT

When dividing the ocean, the aim is generally to summarise a complex system into a representative number of units, each representing a specific environment, a biological community or a socio-economical specificity. Recently, several geographical partitions of the global ocean have been proposed using statistical approaches applied to remote sensing or observations gathered during oceanographic cruises. Such geographical frameworks defined at a macroscale appear hardly applicable to characterise the biogeochemical features of semi-enclosed seas that are driven by smaller-scale chemical and physical processes. Following the Longhurst's biogeochemical partitioning of the pelagic realm, this study investigates the environmental divisions of the Mediterranean Sea using a large set of environmental parameters. These parameters were informed in the horizontal and the vertical dimensions to provide a 3D spatial framework for environmental management (12 regions found for the epipelagic, 12 for the mesopelagic, 13 for the bathypelagic and 26 for the seafloor). We show that: (1) the contribution of the longitudinal environmental gradient to the biogeochemical partitions decreases with depth; (2) the partition of the surface layer cannot be extrapolated to other vertical layers as the partition is driven by a different set of environmental variables. This new partitioning of the Mediterranean Sea has strong implications for conservation as it highlights that management must account for the differences in zoning with depth at a regional scale.

1. Introduction

In recent decades, several divisions of the global ocean have been proposed. Each division aims at summarising environmental and/or biological global complexity into comprehensive atlases: the Large Marine Ecosystems (LME, Sherman, 2005), the Marine Ecoregions Of the World (MEOW, Spalding et al., 2007) or the BioGeoChemical Provinces (BGCP, Longhurst, 2007). Yet, such macro-ecological partitions are hardly applicable for regional seas since they do not intend to capture the full biogeochemical and physical complexity inherent to such scale (Reygondeau et al., 2013). However, marine ecosystem management policies are developed and implemented at Oceanic basin or semi-enclosed sea scales (e.g., OSPAR, CCAMLR, HELCOM, GFCM, etc.), thereby requiring regionally specific ecosystem information and spatial delineation. In order to provide optimal conservation management, appropriate downscaling approaches must be performed.

The Mediterranean Sea (MS) is a semi-enclosed regional sea surrounded by heavily populated areas of 23 different countries, and where the number of endemic species is considered one of the highest in the world ocean (Cuttelod et al., 2009). Historically, the MS has been divided into 8 zones by the International Hydrographic Organisation: Adriatic Sea, Aegean Sea, Alboran Sea, Levantine Sea, Ionian Sea, Tyrrhenian Sea, Algerian-Provencal basin and Tunisian-Syrian Gulf (see Supplementary Fig. 1). However, these divisions relied on the basin's topography and coastline morphology as well as sea governance delineation (e.g. Exclusive Economic Zone). Nevertheless, these partitions have been widely used for the

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European Marine Strategy, for fishing quotas quantification, and for other economic and political management strategies.

Recent ecological studies promoting ecosystems-based management have stressed the need for a more objective division based on environmental/ecological parameters, in order to provide an accurate representation of the ecological complexity. So far, only coarse partitions of the MS have been proposed in macro-ecological studies: 1 biogeochemical province according to Longhurst (2007) and 6 MEOWs mostly relying on the EEZ (i.e. Exclusive Economic Zone) definition according to Spalding et al. (2007). More recently, some studies have attempted to partition the MS either by using classical abiotic parameters (temperature, salinity or chlorophyll-*a*; Gabrié et al., 2012), hydrodynamics (Rossi et al., 2014; Berline et al., 2014), satellite-derived estimates of chlorophyll-*a* seasonality (D'Ortenzio and Ribera D'Alcalã, 2009), or meso-scale environmental parameters (Nieblas et al., 2014). Such approaches rely solely on surface and a few selected parameters, therefore failing to fully capture the environmental complexity of the MS.

In this study, we aim to identify all the various environmental/pelagic habitat conditions that could be encountered at the scale of the MS. We investigate whether the consideration of a larger number of environmental parameters and the vertical dimension would better capture the full hydrodynamic and biogeochemical complexity of the basin. Following the macro-ecological approach promoted by Longhurst, we provide a new regional delineation here named biogeochemical regions (BGCR) based on annual mean biogeochemical and hydrodynamic conditions. First, the depth of each vertical boundary of the water column (epipelagic, mesopelagic and bathypelagic) and seafloor is numerically quantified. Second, based on a comprehensive annual environmental climatology (16 physical, chemical and biophysical variables), the biogeochemical regions within each pelagic layer and seafloor are characterised by using several multivariate analyses (validated by independent measures for the shallow waters). For each vertical layer, the strength of the boundaries between each BGCR is quantified and the contribution of each environmental parameter to the partitioning is provided. Finally, after a validation process involving recent independent *in situ* observations, the first 3D biogeochemical partition of the MS is proposed.

2. Materials and methods

2.1. Environmental data

To identify the different types of environmental conditions and hence the marine habitats that could be encountered in the MS, the annual climatologies of 16 environmental parameters were gathered. The set of environmental parameters used for this study (Table 1), was established according to the literature on macro-ecological partitioning (Longhurst, 2007; Sherman, 2005; Spalding et al., 2007; Reygondeau et al., 2013). It has been gathered to depict and/or characterise specific oceanographic features according to geography (shelf break, river runoff, etc.), hydrodynamics (gyral system, frontal structure, coastal upwelling) or Low Nutrient Low Chlorophyll (LNLC) areas. All the information about the dataset are summarised in Table 1.

Most of the environmental parameters were collected from a single source (MEDAR/MEDATLAS datasets; MEDAR Group, 2002): temperature, salinity, nitrates, nitrites, orthophosphates, silicates, pH, chlorophyll-*a* concentration, and dissolved oxygen concentration (see Table 1). These datasets were obtained from oceanographic campaigns and remote sensing observations. Each environmental variable is spatially resolved over the whole basin at a 0.2° resolution from 9.3°W to 36.5°E of longitude, and from 30°N to 46°N of latitude, and vertically informed for 26 depths layer (see MEDAR Group, 2002) on a non-linear scale between 0 and the seafloor (maximum depth of 5267 m). Each annual climatology used in the present study was calculated using the same methodologies (MEDAR Group, 2002). Additional environmental parameters were also added to the dataset from the literature (D'Ortenzio et al., 2005; Henson et al., 2012; Morel et al., 2007; Reygondeau and Beaugrand, 2011). This addition of environmental parameters aimed at describing the vertical physical composition of the water column using: Mixed Layer Depth, thermocline, euphotic depth or transport of organic matter. Each environmental parameter represented an annual average and was spatially resolved on the same horizontal and vertical resolution as the MEDAR/MEDATLAS parameters (see Table 1).

In addition, raw values were standardized to reduce the effects of environmental parameters amplitude of variation (i.e. variance) on the clustering methodologies (Legendre and Legendre, 1998). Nonetheless, it is important to keep in mind that there are under-sampled areas in the MS, especially in the southern parts of the basin. Therefore, the results could be biased by the low quality of the observation in these regions. Also, since the temporal fluctuations of each environmental parameter gathered was not available, no time series analysis was performed.

2.2. Statistical methodologies

We aimed at identifying biogeochemical regions in the MS (*sensu* Longhurst, 2007), relying on an exhaustive set of environmental parameters resolved in both horizontal and vertical dimensions, using a procedure based on the methodology developed by

Table 1
Spatial resolution, units and references of the environmental variables used in the study.

Environmental parameters	Spatial resolution	Unit	Reference	Source
Temperature	0.2° × 0.2°	°C	MEDAR Group, 2002. MEDATLAS/2002 database	http://www.ifremer.fr/sismer/program/seasearch/htql/prj_edmerp.htql?CPRJ=MAS3M
Salinity	0.2° × 0.2°	PSU		
Chlorophyll-*a* concentration	0.2° × 0.2°	millimole·m^{-3}		
NO$_2$ concentration	0.2° × 0.2°	millimole·m^{-3}		
NO$_3$ concentration	0.2° × 0.2°	millimole·m^{-3}		
PO$_4$ concentration	0.2° × 0.2°	millimole·m^{-3}		
SiO$_4$ concentration	0.2° × 0.2°	millimole·m^{-3}		
Dissolved oxygen concentration	0.2° × 0.2°	ml·l^{-1}		
pH	0.2° × 0.2°			
Bathymetry	0.2° × 0.2°	m	Smith and Sandwell (1997)	www.gebco.net
Particular organic flux	0.5° × 0.5°	mol·l^{-1}	Henson et al. (2012)	NA
Euphotic depth	0.2° × 0.2°	m	Morel et al. (2007)	NA
Thermocline intensity	0.5° × 0.5°	m	Reygondeau and Beaugrand (2011)	NA
Thermocline depth	0.5° × 0.5°	m	Reygondeau and Beaugrand (2011)	NA
Mixed layer depth	0.5° × 0.5°	m	D'ortenzio et al. (2005)	NA
Wind speed	0.2° × 0.2°	m·h^{-1}	Vujcich and Scharton (1999)	ftp://podaac-ftp.jpl.nasa.gov/allData/ccmp/L3.0/