

Definition of the Mediterranean eco-regions and maps

of potential pressures in these eco-regions

Deliverable Nr. 1.6





Project Full title		Policy-oriented marine Environmental Research in					
		the Southern EUropean Seas					
Project Acronym		PERSEUS					
Grant Agreement No).	287600					
Coordinator		Dr. E. Papathanassiou					
Project start date and	d duration	1 st January 2012, 48 months					
Project website		www.perseus-net.eu	www.perseus-net.eu				
Deliverable Nr.	1.6	Deliverable Date	31-10-2014				
Work Package No		1					
Work Package Title		Pressures and Impacts at Basir	Pressures and Impacts at Basin and Sub-basin Scale				
Responsible		Xavier Durrieu de Madron - C	Xavier Durrieu de Madron - CNRS				
Project Full title		Policy-oriented marine Environmental Research in the Southern EUropean Seas					
Project Acronym		PERSEUS	PERSEUS				
Grant Agreement No).	287600					
Coordinator		Dr. E. Papathanassiou					
Project start date and	d duration	1 st January 2012, 48 months					
Project website		www.perseus-net.eu					
Deliverable Nr.	1.6	Deliverable Date	31-10-2014				
Work Package No		1					
Work Package Title		Pressures and Impacts at Basin and Sub-basin Scale					
Responsible		Xavier Durrieu de Madron - CNRS					



	D1.6 Scientific team				
Authors & Institutes Acronyms	UPMC-LOV: G. Reygondeau, S.D. Ayata, S. Gasparini, C. Guieu, J-O. Irisson, P. Koubbi UMR-BOREA: (UPMC) P. Koubbi				
	UQ: C. Albouy				
	LEMAR: T. Hattab				
Status:	Final (F)	•			
	Draft (D)				
	Revised draft (RV)				
Dissemination level:	Public (PU)	•			
	Restricted to other program participants (PP)				
	Restricted to a group specified by the consortium (RE)				
	Confidential, only for members of the consortium (CO)				



Subtask 1.6: Definition of the Mediterranean ecoregions and maps of potential pressures in these ecoregions



Gabriel Reygondeau^{1,2*}, Jean-Olivier Irisson^{1,2}, Sakina-Dorothée Ayata^{1,2}, Stéphane Gasparini^{1,2}, Fabio Benedetti^{1,2}, Camille Albouy³, Tarek Hattab⁴, Cécile Guieu^{1,2}, and Philippe Koubbi^{1,2,5}.

- ¹ Sorbonne Universités, UPMC Univ Paris 06, UMR 7093, LOV, Observatoire Océanologique, F-06230, Villefranche-Sur-Mer, France.
- ² CNRS, UMR 7093, LOV, Observatoire Océanologique, F-06230, Villefranche-Sur-Mer, France.
- ³ Université du Québec à Rimouski, Département de biologie, 300, Allée des Ursulines, Rimouski, Qc, G5L 3A1.
- ⁴ Laboratoire des Sciences de l'Environnement Marin, UMR 6539 LEMAR (CNRS/UBO/IRD/IFREMER), Institut de Recherche pour le Developpement, Institut Universitaire Européen de la Mer, Technopôle Brest-Iroise, Rue Dumont d'Urville, 29280 Plouzané - FRANCE
- ⁵ Sorbonne Universités, BOREA UMR 7208 MNHN/CNRS/IRD/UPMC, F-75005 Paris, France.
- * Now at the Centre of Macroecology, Evolution and Climate in University of Copenhagen. Department of Biology, Universitetsparken 15, DK-2100 Copenhagen and DTU Aqua, Jægersborg Alle 1, 2920 Charlottenlund, Danemark.



Table of Contents

Ex	ecutive summary / Abstract	6
1.	General Introduction	7
2.	Biogeochemical regions of the Mediterranean Sea 2.1. Scope of the study	9 9
:	2.2. Materials and methods	9
	2.2.1 Environmental data	9
	2.2.2 Quantification of the vertical boundaries	9
	2.2.3 Characterization of the environmental condition of each vertical layer	12
	2.2.4 Identification of the spatial distribution of the biogeochemical regions	12
2	2.3 Results	13
	2.3.1 Spatial and vertical environmental gradients of the Mediterranean Sea	13
	2.3.2 Biogeochemical regions of the Mediterranean Sea	17
2	2.4 Conclusions on the biogeochemical regions	19
3.	Ecoregionalisation of the Mediterranean Sea: characterisation of the marin	e
ec	osystems and their potential threats	20
	3.1 Scope of the study	20
5	3.2 Materials and Methods	20
	3.2.1 Biological data	20
	3.2.2 Anthropogenic pressures	22
	3.2.3 Environmental niche modelling	23
	3.2.4 Identification of the marine ecoregions	26
	3.3 Results and Discussion	27
	3.3.1 Mediterranean marine communities	27
	3.3.2 Distribution of the Mediterranean marine ecosystems	28
	3.3.3 Anthropogenic pressures on each marine ecosystem	28
:	3.4 Conclusions on marine ecoregions	30
4.	General conclusions on the ecoregionalisation of the of the Mediterranean 31	Sea
5.	References	40

. References	40
5.1. Cited references	40
5.2. Presentation to International conferences	42



Executive summary / Abstract

In recent decades, it has been found useful to partition the ocean using the concept of ecoregionalisation where within each region it is assumed that environmental conditions and species associations are distinguishable and unique. Indeed, all partitions of the ocean that has been proposed aimed to delineate the main oceanographical, ecological patterns and discontinuities in order to provide a geographical framework for ecological studies and management purposes. The aim of the present work is to integrate and process existing environmental data and biological observations (from phytoplankton to top predators) in order to define and characterize the Mediterranean Sea' ecosystems. The first step was to gather a comprehensive database informed on environmental conditions (22 parameters), biological observations (more than 1500 species from plankton to whales) and human pressure (Halpern et al., 2008) from online database, cruises and published articles. Based on a novel multi-clustering methodology and on environmental niche modelling, a two levels partition of the Mediterranean Sea the: biogeochemical regions (biotopes) and the ecoregions (associated biocenoses) are proposed. This work allows us to characterize the main environmental divisions of the basin as well as the biodiversity and mean organisms size gradient at each trophic level. Finally, an ecological characterization of each ecoregion is proposed along with a perturbation index based on 13 human pressures.

Keyword: biogeography, ecoregionalisation, macroecology, human pressure, biodiversity, biogeochemical regions, ecoregions.

Scope

The aim of the subtask 1.1.6 was to synthetize all the available data in the Mediterranean Sea (and also from the other subtasks of the task 1.1 of PERSEUS) in order to give a geographical framework for the work packages : WP3, WP4, and WP6.



1. General Introduction

Anthropogenic pressures strongly influence the physical and biological systems of the oceanic realm. Recent modifications of the natural range and dynamic of environmental factors that regulates the global marine ecosystems have introduced drastic modifications over the biogeochemical division of the ocean (Reygondeau et al. 2013) and hence on marine habitats with consequences on distributions and dynamics of species (Cheung et al., 2012). In recent years, the combined effects of increasing observations and growing demands of effective ecosystem based management have made possible to characterize the present state of marine ecosystems which is a prerequisite to predict their future changes.

In this context, a geographical framework based on environmental and biological discontinuities is required to characterize marine ecosystem at a basin-scale. Over the last decades, several types of oceanic partitions have been proposed such as Large Marine Ecosystems (LME, Sherman, 2005), Marine Ecoregions of the World (MEOWS) (Spalding et al., 2007) or Biogeochemical provinces (BGCP, Longhurst, 2007). Due to the growing availability of marine observations with a global or basin-scale coverage combined with the application of multidimensional or exploratory analyses in ecology, several novel approaches, based on statistical modelling? have been developed to partition in a more accurate way the global ocean.

Such approaches named ecoregionalisation can be defined by as "the process and output of identifying and mapping broad spatial patterns based on physical and/or biological attributes through classification methods used for planning and management purposes" (Vierros et al. 2008). Ecoregionalisation is provides marine ecological geography rests on significant changes in environmental forcing. Ecoregions are thus considered as unique macro-assemblages of flora, fauna and the supporting geophysical environment contained within distinct but dynamic spatial boundaries (Vierros et al., 2008). Such ecological partition clearly helps understanding biogeochemical or ecological processes at local, regional and macro-scale providing a framework for ecosystem management.

Historically, the Mediterranean Sea (MS) has been divided into 8 geographical zones (UNEP-MAP-RAC/SPA, 2010): Adriatic Sea, Aegean Sea, Alboran Sea, Levantine Sea, Ionian Sea, Tyrrhenian Sea, Algerian-provencal basin and Tunisian-Syrian gulf. Each division delineates specific parts of the basin topography and coastline morphology and are now mainly used for European marine strategy consortium or for economical and political. Nonetheless, this original partition does not take into account the biogeochemistry, oceanography and ecology features of the Mediterranean Sea. More recently, several studies have attempted to partition the basin either using abiotic parameters (Gabrié et al., 2012) or biotic parameters (D'Ortenzio & D'Alacala, 2009). These studies have confirmed a non-stationary picture of the dynamic of the basin, and significant biogeochemical differences between regions that have consequences on the local dynamic of the primary production for example.

In this subtask, a two-level ecoregionalisation of the Mediterranean Sea is proposed. Based on both open access and data gathered from the subtask 1 of the PERSEUS project for environmental and biological datasets, an ecological spatial reference is investigated. The ecoregionalisation will present two level partitions: (1) a first 3D partition based on the main environmental characteristics **named biogeochemical regions** following the concept



from Longhurst (2007; MEDI province) but here revisited using novel statistical approach (Reygondeau et al., in revision) and (2) a subdivision based on the identification of main biological assemblages **named ecoregions**. Finally, the **impact of anthropogenic pressures** will be including into the spatial analysis to identify the most endangered systems of the Mediterranean Sea.



2. Biogeochemical regions of the Mediterranean Sea

2.1. Scope of the study

Previous partitioning studies of the Mediterranean Sea have mainly based their methodology on a few descriptors and without consideration of the vertical dimension and thus they do not provide a full picture of the basin biogeochemical complexity.

In this section, we attempt to provide an objective division of the pelagic and seafloor compartments of the Mediterranean Sea into what we call **the biogeochemical regions**. This biogeochemical framework needs to be interpreted as the biogeochemical provinces described by Longhurst (2007) but forced by mesoscale environmental features. Therefore, our approach was to (1) identify the vertical limits of each pelagic layer; (2) quantify the environmental characteristics of each layer; (3) identify the all-significant types of environmental conditions in the I; and (4) identify the strength of the regions' boundaries.

2.2. Materials and methods

All the steps of the methodology are summarized in figure 1.

2.2.1 Environmental data

To capture the main environmental conditions and oceanographical features of the Mediterranean basin, several annual and seasonal climatologies have been downloaded from open access databases. Datasets are mainly composed by remote sensing observations and merged oceanographic campaign data. Each parameter has been selected to depict and/or characterize specific oceanographic features such as gyral system, frontal structure, continental shelf, river runoff, water masses, coastal upwelling and Low nutrient low chlorophyll (LNLC) areas. All relevant information of the dataset are summarized in table 1.

Temperature, salinity, nitrites, nitrates, orthophosphate, silicate, pH, Chlorophyll-a concentration, and dissolved oxygen concentration were gathered from the MEDAR/MEDATLAS datasets (Medar Group, 2002). These datasets were computed into seasonal and annual climatology. These parameters are gathered because of the full spatial coverage of the basin at a 0.2° resolution ranging from 9.3°W to 36.5°E of longitude and from 30°N to 46°N of latitude, and also the information on the vertical gradients of each parameters (26 depths with non linear width). Available dataset for particulate organic carbon fluxes, chlorophyll-a concentrations, euphotic depth (i.e., depth where only 1% of the surface photosynthetically active radiation is available), mixed layer depth, thermocline depth and intensity, wind speed, were gathered from publications. They were first interpolated using a spline interpolation on a similar grid than the MEDAR/MEDATLAS data. Seasonal and annual climatologies were computed from these data.

2.2.2 Quantification of the vertical boundaries

Three vertical boundaries have been defined to separate the epipelagic, mesopelagic, and bathypelagic vertical layers. The shallower boundary represents the depth where the epipelagic and the mesopelagic domains are separated. This boundary is approximated at the maximal depth where primary production is available. Based on previous work on vertical limitation of photosynthesis activity (Sverdrup, 1953; Behrenfeld,



	Space resolution	Period	Vertical resolution	units	Reference	Source
Temperature	0.2°	annual and montly climatology	medatlas depth	റ്	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
Salinity	0.2°	annual and montly climatology	medatlas depth	PSU	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
Chlorophyll-a	0.2	annual and montly climatology	NA	mg.ml-1	MODIS AQUA	http://oceancolor.gsfc.nasa.gov/cgi/l3
concentration	0.2°	annual and montly climatology	medatlas depth	mg.ml-2	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
NO2	0.2°	annual and montly climatology	medatlas depth	millimole/m3	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
NO3	0.2°	annual and montly climatology	medatlas depth	millimole/m3	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
P04	0.2°	annual and montly climatology	medatlas depth	millimole/m3	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
SiO4	0.2°	annual and montly climatology	medatlas depth	millimole/m3	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
Dissoved Oxygen	0.2°	annual and montly climatology	medatlas depth	тV	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
PH	0.2°	annual and montly climatology	medatlas depth	NA	MEDAR/MEDATLAS	http://www.ifremer.fr/sismer/
Bathymetry	0.2°	annual climatology	NA	Э	General Bathymetric Chart of the Oceans	http://www.gebco.net/
Particulate Organic Carbon flux	0.2"	annual climatology	5 m	mol/l	Henson et al. (2012)	NA
Euphotic depth	0.2°	annual and montly climatology	NA	э	Morel et al. (2007)	NA
Thermocline Intensity	0.2°	annual and montly climatology	NA	°C/5m	Reygondeau et al. (2011)	NA
Thermocline depth	0.2°	annual and montly climatology	NA	з	Reygondeau et al. (2011)	NA
Mixed layer depth	0.2°	annual and montly climatology	NA	Э	D'Ortenzio et al. (2005)	NA
Wind direction	0.2°	annual and montly climatology	NA	angle	QUICKSCAT	ftp://podaac-ftp.jpl.nasa.gov/allData/ccmp/L3.0/
Wind speed	0.2°	annual and montly climatology	NA	m/h	QUICKSCAT	ftp://podaac-ftp.jpl.nasa.gov/allData/ccmp/L3.0/

Table 1. Information on the Environmental variables taken into account in this study.





Figure 1. Sketch diagram of the methodology of the part 1 on Biogeochemical regions. All step are detailed in the 2.2 Materials and Methods



2010) the upper mesopelagic boundary is set at the shallowest depth between the euphotic depth and the mixed layer depth for each geographical cell of the global ocean. The annual climatology and latitudinal variation of the upper mesopelagic boundary were mapped for the MS following this concept for the global ocean (Figure 2a).

The bottom boundary separates the mesopelagic and the bathypelagic layers. In absence of any consensual definition, this boundary has been based on the shape of the flux of particular organic carbon (FPOC). Indeed, it has been shown that it reflects the main biogeochemical vertical gradients in the water column (see Reygondeau et al., in revision). The bottom boundary has been defined at the depth where FPOC tends to an asymptote (decrease of POC is not significant between two consecutive depth). First, each profile is interpolated every 5 meters between 0 and 5000m using a cubic spline interpolation. Second, to identify the depth of the boundary, two tests are performed on each FPOC profiles. The derivative function of FPOC against depth is computed and the depth of the boundary is set at the depth where the decrease of FPOC between 5 consecutive points is not significant. This resulting depth is compared to the one identified at the depth corresponding to 5% of the surface FPOC. The average depth resulting from the two methods is calculated and mapped on Figure 2b.

2.2.3 Characterization of the environmental condition of each vertical layer

In the global ocean, environmental gradients over the vertical dimension are usually more pronounced comparatively to the horizontal dimension. Consequently, the partitioning of the variance in a three-dimensional analysis is biased for any ordinary statistics methodology, as the vertical gradient will be detected over the horizontal gradient. The biogeochemical division of the mesopelagic layer with consideration of both horizontal and vertical environmental gradients was performed on the basis of previous methodologies (Oliver et al., 2004; Beaugrand et al. 2011; Reygondeau et al. 2013). This allowed obtaining distinct environmental matrices for each of the four vertical layers (epipelagic, mesopelagic, bathypelagic, and seafloor).

To identify the main environmental parameters driving the spatial variance of each layer, a principal component analysis (PCA) was performed on the environmental matrix of each layer. The first and second components of each PCA are mapped on Figure 3 as well as the result of the PCA. The environmental factors that contribute the most to the first two principal components (i.e. that explain most of the total variance of the environmental matrix of each layer) were identified (table 2).

2.2.4 Identification of the spatial distribution of the biogeochemical regions

To propose an objective environmental spatial division, we applied the methodology proposed by Oliver et al. (2004). This numerical procedure uses four types of clustering methodologies, here applied on the normalized environmental matrices of each vertical layer: K-means (Hartigan and Wong, 1979), C-means (Quackenbush, 2001), agglomerative with ward linkage (Ward, 1963) and with complete linkage (Legendre & Legendre, 1998) (step 2.2; Fig. 1). These four types of clustering algorithm were selected for their ability to synoptically group similar environmental data and for their differences to handle low dissimilarity clusters (i.e. sensible cluster). Each clustering algorithm was run to retrieve from 2 to 50 clusters using a Euclidian distance. The C-means and K-means were repeated 999 times per iterations and the division the most retrieved was selected. The next step of the methodology consisted in the identification of the optimal number of cluster to consider (following the analysis called the figure of merit (FOM) in Yeung et al., 2001) in the next



steps of the procedure. The strength of the boundaries between the identified regions obtained from different clustering was estimated in order to provide an objective definition of the biogeochemical regions.

2.3 Results

The objectives of the study were to depict a synoptical view of the environmental condition for the whole basin by taking into account and summarizing the main environmental features of the Mediterranean Sea. The use of exploratory statistic allowed to objectively detangling the links between variables for each layer, to identify and describe the main 3D biotopes (*i.e.* multivariate environmental intervals) and quantify the strength of the vertical and horizontal boundaries between BGCRs. In this study, a set of methodologies is selected for these purposes because they decompose the vertical and horizontal variance of the whole Mediterranean Sea environmental gradients. Interestingly, even if result are logically link to database used, any biases on the absolute values of a given parameters does not affect the methodology if the spatial gradient are close to reality. Consequently, each result needs to be taken as a general biogeochemical trend and not as a fine scale resolution study that investigate on a given process.



Figure 2. Depth of the vertical boundaries of the water column: (a) between the epipelagic layer and the mesopelagic layer, (b) between the mesopelagic layer and the bathypelagic layer.

Using the shallowest depth between the mixed layer depth and the euphotic depth, we found that the epipelagic/mesopelagic boundary varies over a 65 m range between 10 m and 75 m (Fig. 2a). The deepest upper mesopelagic boundaries are found in open ocean areas and particularly in the oriental basin and Tyrrhenian Sea. These areas are typically oligotrophic with low primary productivity and low detritus concentration implying a high light penetration. In contrast, more productive areas located in the occidental basin and continental shelves exhibit shallower depth of epipelagic/mesopelagic boundary (down to 40 m). In those regions, the first 200 m are more turbulent waters resulting in shallower epipelagic layer than in tropical areas (Fig. 2a).





Figure 3.Results of the PCA on the environmental conditions of each considered layer and map of the PC1 and PC2



The lower boundary separating the mesopelagic and the bathypelagic layers are presented Fig. 2b.The annual climatology (Fig. 2b) shows that this limit has strong variation between 140 m and 1500 m. The deepest boundaries are localized in open ocean areas with low biological activity. These area are also the deepest of the basin and the more stable in term of mesoscale activity. Thus, regions near rift show a lowest mesopelagic bottom boundary than oceanic basin.

The map of the first principal component (PC1) reveals a clear longitudinal gradient from the occidental to the oriental basin retrieved for epi- and mesopelagic layer and to a lesser extend for bathypelagic layer (Fig. 3). This gradient is mainly supported by the important contribution of the temperature to each layer environmental variance. Therefore, this environmental can be directly attributed to the principal atmospherical (i.e. climate) and ocean circulation (main current) forcing. Regional features such as influence of the Atlantic Ocean (impacting strongly on T and S) on the occidental basin or influence of river run-off or high primary productive regions are also retrieved on PC1 of pelagic layers. These regions are carried by the high contribution of several parameters to the total variance that varies between pelagic layer (table. 2): *epipelagic*: temperature, chlorophyll-a concentration, oxygen concentration, *mesopelagic*: temperature, euphotic depth, nutrients, salinity, *bathypelagic*: bathymetry, nutrients.

Logically, the regions with the higher primary production like in the Ligurian sea is retrieved because of the importance of chlorophyll-a concentration in the epipelagic layer, high nutrients concentration and stratification variation in deeper layers. The second component of the principal component analysis (PC2) mainly detects areas with strong wind stress and seasonal variability in water column stability that influence the deeper layers nutrient concentration. PCA performs on the seafloor layer reveal a strong opposition in the environmental conditions between continental shelf (warmer with higher nutrient concentration) and open sea areas.

	Epipe	elagic	Meso	pelagic	Bathy	pelagic	Sea	floor
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Temperature	71,4	1,0	68,1	0,3	84,7	3,8	55,8	1,8
Salinity	46,5	0,5	56,2	0,1	90,9	1,2	0,0	47,2
[Chla]	68,1	8,0	14,1	34,9				
Oxygen	59,9	0,2	8,7	39,5	0,7	55,4	35,3	41,7
pН	55,5	7,0	15,5	39,9	1,1	71,2	29,9	16,3
NO3	27,0	22,0	70,2	14,0	73,9	5,7	77,9	4,5
NO2	27,8	8,5	13,8	0,9	47,0	5,5	0,5	44,5
PO4	18,1	39,6	63,5	20,9	85,4	1,0	75,8	14,8
SiO2	15,0	18,5	52,7	23,2	68,8	1,1	75,8	14,8
Zeu	79,3	0,1	63,7	0,5				
Wind speed	7,5	5,1	7,9	0,0				
IT	0,6	22,3	0,0	12,8				
ZT	37,4	39,9	26,6	51,2				
std IT	6,9	0,4	3,9	2,1				
std ZT	37,4	39,9	26,6	51,2				
MLD	28,2	0,2	22,6	0,8				
std MLD	5,1	12,5	9,0	0,7				
Bathymetry							68,2	13,7

Table 2.Contribution of each parameter in the first two principal components PC1 and PC2 for each vertical layer (in %).





Figure 4.Biogeochemical regions of the Mediterranean Sea defined for each vertical layer.



2.3.2 Biogeochemical regions of the Mediterranean Sea

The previous analysis highlighted clear environmental gradients and regional features for the whole basin. This resulted in the identification of 63 biogeochemical regions: 12 for the epipelagic, 12 for the mesopelagic, 13 for the bathypelagic and 26 for the seafloor (Fig. 4). The strength of the spatial boundaries of each layer is represented on supplementary Figure 5 and the environmental intervals of each biogeochemical regions are shown on supplementary Figures 6 to 9.

The longitudinal pattern identified by the previous analysis (Fig. 2) is retrieved on Fig. 4, but here significant changes in environmental conditions are quantified allowing to cluster the sea into 3D biotopes. Strongest frontiers of all pelagic layers are distributed nearby the Gibraltar strait, the Sicilian strait, and between the Ionian Sea and the Levantine Sea. Also, marginal seas such as the Adriatic Sea, Aegean Sea and Ligurian Sea are systematically delineated from the occidental and oriental basin in each layer. We can than assume that the environmental pattern observed on Fig. 2 geographically vary by regional /stepwise shift over the basin (strength of shifts being quantified on Fig. S5). These significant geographical changes highlight well-known local/regional specificities driven by the continental morphology, the atmospheric forcing and the hydrological/oceanographical dynamics. For instance the strength of the environmental shift being the contour of each resulting division show a high similarity with the main circulation (Mermex group, 2011) from the bottom to the surface. These spatial modifications of environmental conditions can thus be linked to the surface climate forcing combined with time of water retention's. Therefore, each biogeochemical region is characterized by homogenous environmental conditions that are significantly different from surrounding regions. Each biogeochemical region represents a characteristic biotope (pelagic / benthic habitat) for marine species.

2.3.3 Caveat and validation of the spatial clustering

The present study is an attempt to provide a robust and objective environmental partition of the Mediterranean Sea by the implementation of a novel and objective statistical methodology. To decrease the potential bias of merging several types of dataset, only parameters coming from sources of comparable quality have been retained. Main datasets originated from the MEDAR/MEDATLAS or from published datasets because these data (1) presented a similar spatial and vertical grid, (2) have been computed from same sampling methodology and (3) have been interpolated using similar methodologies.

However, the spatial heterogeneity of the *in situ* sampling used as well as the variety of measuring techniques lead to some uncertainty on the resulting outputs. These different types of biases need to be kept in mind for the interpretation of the result, especially in under sampled areas that are mainly located in the southern regions of the basin. To decrease the potential effects of these biases, the methodology selected was performed after a normalization of the raw values. Therefore, the spatial partition of each methodology is based on changes in the distributions of each parameter rather than the raw amplitude value.





Figure 5. **Upper panel**: BOUM cruise track superimposed to the map of the epipelagic biogeochemical regions of the MS. Lower panel: Variation of the habitat suitability index (HSI: Habitat Suitability index which is the probability to retrieve a given regions according to the local environmental conditions) associated with in situ measurement of Sea Surface Temperature (SST), Salinity, Chlorophyll-a concentration [Chla] and dissolved oxygen. Dash line represent change in epipelagic biogeochemical region.





To test the effectiveness of the boundaries detected (Figure 4), the environmental partition obtained has been confronted to an independent set of data. Owing to the difficulty to retrieve deep environmental sampling originating from the same cruise and covering both occidental and oriental basins, only the epipelagic layer has been tested using data (SST, SSS, Chlorophyll-a and oxygen concentration) collected during the BOUM cruise (Moutin et al., 2012) in the epipelagic layer (Figure 5). Probabilities of each biogeochemical region (Habitat Suitability Index, HIS) crossed by the cruise track were confronted to actual surface parameters measured during the cruise. Each boundary between biogeochemical regions (dash line, figure 5) coincides indeed with significant change (defined as a variation of more than 5% of the mean of the 5 previous sampling site) of at least one of the parameters. However, significant changes of the in situ data are also detected within the same biogeochemical regions. Significant variations within biogeochemical regions can be either attributed to: (1) sub-mesoscale biogeochemical structures that are not detected by our methodology owing to the resolution of the used parameters; (2) temporal variations of the environmental parameters during the one-month summer cruise that are not considered in the environmental envelopes defined in our study that consider annual means.

2.4 Conclusions on the biogeochemical regions

Based on a very large dataset and using a novel statistical methodology, the present study propose objective maps of the all distinct multivariate environmental conditions types that can be encountered in the Mediterranean basin with associated strength of the boundaries and stability index. These biogeochemical regions have been environmentally characterized for all parameters considered (see supplementary figure 6 to 9).

As each biogeochemical region is delineated by complex oceanographical features that influence environmental conditions in an anisotropic way, the map proposed provide a geographical framework of environmentally homogenous regions. Nonetheless, as effects of temporal fluctuations of each parameter on the distribution of the biogeochemical regions is not considered, the dynamic of the systems is not yet fully captured. Each biogeochemical region can thus be considered as potential habitats where adapted species can maintain their populations. Results also suggest that previous 2D and univariate partitions of the basin cannot be extrapolated to the whole water column.

Results also aim to be used as a geographical framework of Mediterranean environmental conditions to (1) optimize the design of new sampling cruises, (2) spatially merge heterogeneous dataset and (3) improve the comparison of modelled and observed data.



3. Ecoregionalisation of the Mediterranean Sea: characterisation of the marine ecosystems and their potential threats

3.1 Scope of the study

The ocean is composed of a jigsaw of ecological units separated by hydrological frontiers. Each unit is characterized by a given biotope (environmental characteristics) and a biocenoses (adapted species in non-exclusive competition that form a trophic web) and are defined as « ecosystem ». In 1995, on the basis of 15 biogeochemical variables, Longhurst proposed a two level partition of the global ocean, commonly accepted by the scientific community. The first level of partition represents the main ocean climatic types named biomes and the second level of division subdivides each biome according to regional features and oceanic basin shape. A more detailed description of such biochemical regions, for the Mediterranean Sea, was presented in the previous section. The goal of this part of the study is now to delineate ecoregions of the MS.(regions that are homogenous in terms of environmental characteristics and biological communities). This partition will then provide a framework to evaluate the impact of anthropogenic pressures on each identified marine ecosystems.

Growing anthropogenic pressures (over-fishing, pollution, climate change, etc.) are assumed to have modified the natural equilibrium of the MS marine ecosystems. In this context, international consortia have advocated for a holistic approach that integrates all components of ecosystems for the implementation of an effective conservation planning (MEA, 2003; Boyen et al., 2012; IPCC, 2013). However, the Mediterranean Sea is characterized by an important influence of mesoscale activity and localised human pressures on regional biogeochemistry, hydrology and ecosystem trophodynamics (Coll et al., 2012). Consequently, large-scale partitions such as biogeochemical provinces (Longhurst, 2007) cannot be applied in this ecosystem-level-management perspective. In recent years, the increasing availability of observations (biotic and abiotic) and advances in numerical techniques has made it to define ecoregions appropriate to informing ecosystembased management.

The objectives of the present study are to (1) map the distribution of marine taxa, from phytoplankton to top predators, over the Mediterranean Sea through environmental niche modelling; (2) delineate marine ecoregions based on the distributions hence modelled; (3) quantify anthropogenic pressures for each ecoregion.

3.2 Materials and Methods

3.2.1 Biological data

Biological data is extracted from online databases for the Mediterranean basin. The harvested databases are:

• Intergovernmental Oceanographic Commission (IOC) of UNESCO. The Ocean Biogeographic Information System (OBIS, <u>http://www.iobis.org/</u>)

Global Biodiversity Information Facility (GBIF, 2012 ; http://www.gbif.org/)



- Ocean Biogeographic Information System for megavertabrate (OBIS-SeaMAP, <u>http://seamap.env.duke.edu/)</u>
- Fishbase (http://www.fishbase.org/)
- The Coastal and Oceanic Plankton Ecology Production and Observation database (<u>http://www.st.nmfs.noaa.gov/plankton/-</u>).
- LEFE-CYBER (http://www.obs-vlfr.fr/proof/index_vt.htm)
- SESAME database (http://isramar.ocean.org.il/sesamemeta/)
- CLIOTOP database (<u>http://www.imber.info/index.php/Science/Regional-</u> <u>Programmes/CLIOTOP</u>)
- Digitalized fishes and mammals atlas used in Mouillot et al (2011).

After initial duplicate deletion, the final dataset comprises only taxa (1) that are informed down to species level, (2) for which at least 30 observations were available and (3) which maps of occurrence were reviewed by experts. This resulted in localised 17 606 777 occurrences covering 1280 species from phytoplankton to top predators with high heterogeneity of sampling effort (Figure 6). Due to the heterogeneity of the sampling methodologies used in this dataset, all abundance data were converted into "presence only".



Figure 6.Spatial distribution of number of observations for low and high trophic level species. Areas with white colour mean that no data have been retrieved.

To better explore ecological patterns in the distribution of species, additional information were gathered for each species: taxonomy, depth range (minimum and maximum depth where the species can occur), size (minimum, mean and maximum), main habitat of species (i.e. epipelagic, mesopelagic, bathypelagic, demersal, benthic) and mean trophic level (according to Pauly et al, 1998). Online databases and publications focussing on each species are used to inform these metadata: fishbase (www.fishbase.org), encyclopedia of life (<u>http://eol.org/</u>), OBIS-SEAMAP (<u>http://seamap.env.duke.edu/</u>), World Register of Marine Species (<u>http://www.marinespecies.org/</u>).



3.2.2 Anthropogenic pressures

Several comprehensive and validated maps of anthropogenic pressures were gathered to quantify the effect of human activities on marine ecosystems. These maps were originally computed by Halpern et al. (2009) and reinterpreted by Coll et al. (2012) by integrating new observations. The original data is spline-interpolated from the 10 x 10 km grid to our spatial grid: from 9.3°W to 36.5°E of longitude and from 30°N to 46°N of latitude with a resolution of 0.2° x 0.2° (i.e., spatial grid of the environmental parameters in MEDAR/MEDATLAS). To summarize the information, pressures listed in Table 3 were grouped into three categories: 'Climate change', 'Fishery activities' and 'Pollution'. In each category, pressures were summed and normalize by the maximal value obtained;new pressure layer (0 <values<;1) are displayed Figure 7).

Pressure type in this paper	Pressure defined by Halpern et al 2009 and Coll et at 2012			
	UV Radiation			
Climate change	Sea Surface Temperature Increase			
	Ocean Acidification			
	Fishing Pelagic Low Bycatch			
	Fishing Pelagic High Bycatch			
	Fishing Demersal Non Destructive Low Bycatch			
Fishery activities	Fishing Demersal Non Destructive High Bycatch			
	Fishing Demersal Destructive			
	Artisanal Fishing			
	Urban Runoff			
	Risk Of Hypoxia			
	Organic Pollution Pesticides			
	Nutrient Input Fertilizers			
Pollution and euthrophication index	Invasive Species			
	Commercial Shipping			
	Coastal Population Density			
	Benthic Structures Oil Rigs			

 Table 3. Groups of anthropogenic pressures



Figure 7. Spatial distribution of the groups of anthropogenic pressures: Pollution, Climate change and Fishery activities

3.2.3 Environmental niche modelling

Although we use a very large database, observations were too scarce and too heterogeneously distributed to simply interpolate the distribution of the 1280 selected species over the whole basin. Alternatively, we use environmental niche modelling to map their potential distribution. The principle of niche modelling based on presences-only is to define the conditions in which a species is most often found and then to map the probability of occurrence of this species according to these conditions. In a data poor context (which is the general case in biological studies) this is a commonly accepted way to obtain continuous distribution map. The construction of our multi-model of ecological niche required the following steps (Figure 8).

step 1. Collection of the environmental conditions related to observed occurrences.

Environmental conditions were based on the climatologies of the same 19 variables used to define bioregions (Section 2): Temperature, Salinity, Chla, O₂, pH, NO₃, NO₂, PO₄, SiO₂, depth of euphotic zone, intensity and depth of thermocline (and seasonal variability thereof), mixed layer depth and its seasonal variability, wind speed, bathymetry and class of bathymetry. When relevant, these variables were divided in 4 vertical layers (epi, meso, bathypelagic and seafloor) and in seasons or months.

Each of these variables was interpolated to the position of each occurrence, in terms of latitude-longitude but also depth layer. When the time of sampling was available, the corresponding monthly/seasonal climatology was used; otherwise, an annual climatology was used.





Figure 8. Sketch diagram of the methodology of the Part 2 on Ecoregionalisation. All step are detailed in 3.2.3



As several models are sensitive to the number of variables, only 4 variables were finally selected. The best combination has been obtained using an Escoufier vector methodology (Legendre and Legendre, 1998) and a principal component analysis. In addition, according to expert knowledge, only parameters with an ecological meaning for the considered species and/or layer were retained.

Step 2. Environmental niche models

In this study, a multi model approach was adopted to best approximate the environmental tolerance of each species. By accounting the spatial variability of each model due to the difference in the statistical approach used, we can indeed assume that the environmental range of the species is better delineate. However, owing to the quality of the data, only Environmental Niche Models (ENM) dealing with presence only data were selected : Domain, Bioclim (from Biomod package Thuillier et al., 2008), Maxent (Phillips et al., 2004), NPPEN (Beaugrand et al., 2011) and ENFA

Step 3. Numerical validation of the distribution

The spatial distribution of each species and ENM has been numerically tested using the Hirzel et al. (2006) methodology. This test was selected, as it is one of the most accurate for ENM on presence only. This test consists in the confrontation of relative presence (sum of the presence divided by the total of observations of the species in the MS) with associated probability of occurrence at different spatial resolution. The test was permutated by changing the spatial resolution of both parameters and thus by re-computing both probability of occurrence and relative occurrence. Then, a coefficient of regression (here a spearman coefficient of regression) was calculated using all data from all permutations. Values of the coefficient of regression were therefore considered as an index of quality of the model. All specificity of the methodology can be retrieved in Hirzel et al. (2006).

Step 4. Model averaging

For each species, probabilities of presence computed from the five ENM have been averaged using weight values computed in step 3. Only ENM with a Hirzel's index value > 0.5 have been considered for the averaging procedure. In addition, each model was weighted by the value of the index. The annual mean and standard deviation of the spatial distribution of the probability of presence of 6 emblematic species resulting from this computation are presented Figure 9





Figure 9.Spatial distribution of several emblematic species of the Mediterranean Sea extracted from the average probability of presence of the 5 ENM computed.

3.2.4 Identification of the marine ecoregions

To characterize the Mediterranean ecoregions that represent specific environmental and ecological composition, the clustering methodology has been used as for the identification of the biogeochemical regions (Figure 1). Firstly, the clustering methodology was performed to identify the primary producers (*i.e.*, Trophic level (TL) between 1 and 2), primary consumers (TL between 2 and 3), secondary consumers (TL between 3 and 4) and top predators (TL between 4 and 5) assemblages (Figure 10). Secondly, based on the spatial distributions of each trophic assemblage (4 layers) and biogeochemical regions (4 layers), the clustering methodology (see step 2.3 of §2.2 Material and Methods) was used to find a trade off between all agglomerative methodologies. Therefore, each ecoregion represents a specific species association and environmental interval (Figure 11). In addition, to visualise the main anthropogenic pressures per ecoregion, the spatial coordinates of each ecoregion are used to average merged anthropogenic pressures. Mean anthropogenic pressure are mapped on figure 12 as well as the sum of the pressures.



3.3 Results and Discussion

3.3.1 Mediterranean marine communities



Figure 10.Spatial distribution of primary producers (i.e., Trophic level between 1 and 2), primary consumers (TL between 2 and 3), secondary consumers (TL between 3 and 4) and top predators (TL between 4 and 5).

Figure 10 maps the different trophic assemblages (here named communities). Each cluster represents a specific marine species association from primary producer (PP) to top predator (TP). Open seas areas appear more divided by the lower trophic communities (PP and Primary Consumers) while coastal areas are more partitioned by high trophic levels (Secondary Consumer and TP). This result is attributed to the opposite pattern of biodiversity between trophic level driven by an important physiological evolution (increase of thermal regulation capacity) and functional trait changes (planktonic versus nektonic) throughout the trophic levels. Therefore, differences in communities' distribution can be attributed to change of forcing factors throughout the trophic web. For example, PP community's distribution can be directly attributed to nutrient types and concentration, index of stratification and euphotic depth that influence both their abundance and species occurrence, while TP community's distribution will be more influenced by temperature and food availability.





3.3.2 Distribution of the Mediterranean marine ecosystems

Figure 11.Spatial distribution of the Mediterranean marine ecosystems.

Based on the spatial distribution of each trophic community and environmental variable, the distributions of the marine ecosystems of the Mediterranean Sea have been captured (Figure 11). Each ecoregion detected here represents a characteristic species association from primary producers to top predators (i.e., biocenoses) forced by similar environmental conditions (i.e., biotopes).

The map of the 25 ecoregions delineates well the characteristics of open seas and more coastal features, such as the Northern current or the Levantine basin, as well as known ecosystems, such as the Gulf of Lions, and the southern area off Tunisia including Gulf of Gabes. More surprisingly, several ecoregions are distributed as boundaries of bigger and well-known systems. This result confirmed the assumption of Van der Spoel et al. (1996) and Odum (1974) that boundaries between two main ecosystems need to be considered as an ecosystem as well. Indeed, ecotones (i.e., boundary between two ecosystems) are characterized by a trade off between species associations originated from adjacent ecosystems.

The global distribution of the ecoregions reveals a coherent ecosystemic spatial framework at the exception of the Aegean Sea. Indeed, this particular sea shows a patchy distribution of the clusters. This could reflect high heterogeneity of marine habitats likely influenced by inputs from the Black Sea. Indeed, owing to the scarce resolution of the data used, sub-mesoscale and local features cannot be captured and thus can bias the methodology in some specific areas.

3.3.3 Anthropogenic pressures on each marine ecosystem

The mean anthropogenic impacts have been computed for each of the 25 ecoregions identified in the Mediterranean Sea (Figure 12). Globally, climate change pressures are high everywhere with a marked gradient from west to east. Pollution and fisheries pressures are more localized in coastal areas and in the western basin. The cumulated pressure map shows that coastal areas appear as more pressured than open sea areas both in northern and southern parts. Hot spots of potential perturbed ecosystem are very localized and encompass: the Algero-Tunisian coast, the Adriatic Sea, the Aegean Sea, the Gulf of Gabes, the Catalan coasts, the Gulf of Lions and the Egyptian coasts.





Figure 12. Mean anthropogenic pressure and cumulative impact per ecoregion.



Interestingly, some large open sea regions are characterized by low cumulated pressures, mainly in the Central part of the MS: in the Southern and Northern Ionian Sea and in the Tyrrhenian sea

The present analysis reveals that all the ecoregions of the Mediterranean basin undergo at least one type of pressure (see Supplementary Figure 10). Indeed, relation between fisheries and pollution pressures per ecoregions tend to be highly positively correlated suggesting that regions with the highest fishing activities are also the most polluted. Climate change and others pressures are negatively correlated, which suggests that stronger climate change likely impact regions with relatively low pollution and fishery activities. It has to be noted nonetheless, that these last relations are hardly significant. Consequently, spatial distributions of hot spots of perturbation can directly be attributed to regions with high human density that mechanically increase the number of anthropogenic activities in near coast areas; while open sea areas are mainly pressured by long term change of environmental conditions.

3.4 Conclusions on marine ecoregions

The present study have succeed to identify all the marine species (with enough observations to be modelled) that can be encountered in the Mediterranean basin from primary producers to top predators, in both pelagic and neritic domains and to characterize their potential spatial distributions. This work allows to better capture the trophic complexity of marine ecosystems providing a more realistic picture of the Mediterranean spatial trophic organisation. Indeed, known macro-environmental structures already defined in previous studies are here refined on the basis of trophic assemblages. 25 ecoregions subdivide the Mediterranean macro-environmental partition defined previously by delineating all significant environmental and trophic forcing affecting the biogeochemical processes and biodiversity patterns.



4. General conclusions on the ecoregionalisation of the of the Mediterranean Sea

For the subtask 1.6.6 of the PERSEUS FP7-Project, we have: (i) partitioned the Mediterranean Sea into biogeochemical regions (both in 2- and 3-dimensions), (ii) partitioned the Mediterranean Sea into 25 ecoregions, and (iii) quantified the anthropogenic pressures for each of the ecoregion. The ecoregionalisation approach performed in this study provides applicable tools in a context of ecosystemic fisheries management and biodiversity management, especially for the on-going implementation of the EU's Marine Strategy Framework Directive (MSFD). We have hence provided an ecological geographical framework characterizing the main species assemblages and environmental features, with a quantification of the various environmental and anthropogenic forcing. The regions undergoing the highest risks of perturbation have been identified and mapped, and now require adapted conservation strategies to reach a stable equilibrium for the sustainability of marine ecosystems.





Supplementary materials

Supplementary Figure 1. Annual climatology of Temperature, salinity and [Chla] for each identified layer



Supplementary Figure 2. Annual climatology of NO3, PO4 and SiO2 concentration for each identified layer





Supplementary Figure 3. Annual climatology of dissolved Oxygen concentration, pH and NO2 concentration for each identified layer



Supplementary Figure 4. Annual climatology of Thermocline Depth and Intensity, Mixed layer and Euphotic depth and wind speed





Supplementary Figure 5. FOM and distribution of the effectiveness of the boundaries for each layer





Supplementary Figure 6. Environmental chacterisation of each epipelagic biogeochemical regions





Supplementary Figure 7. . Environmental chacterisation of each mesopelagic biogeochemical regions





Supplementary Figure 8. . Environmental chacterisation of each bathypelagic biogeochemical regions





Supplementary Figure 9. . Environmental chacterisation of each seafloor biogeochemical regions





24 25



Supplementary Figure 10. Mean merged Anthropogenic impact per ecoregions. The orientation of the histogram shows if the value is higher or lower than the mean of the whole of the parameter in the whole basin.



5. References

5.1. Cited references

- Beaugrand, G., Lenoir, S., Ibañez, F., Manté, C., 2011. A new model to assess the probability of occurrence of a species, based on presence-only data. *Marine Ecology Progress Series*, 424, 175-190.
- Behrenfeld, M.J., 2010. Abandoning Sverdrup's Critical Depth Hypothesis on phytoplankton blooms. *Ecology*, 91, 977-989.
- Boyen, C., Heip, C., Cury, P., Baisnée, P.-F., Brownlee, C., Tesmar-Raible, K., Allen, I., Arvanitidis, C., Austen, M., Bolhuis, H., 2012. EuroMarine Research Strategy Report: Deliverable 3.2. Seventh Framework Programme Project EuroMarine.
- Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W.W.L., Christensen, V., Karpouzi, V.S., Guilhaumon, F., Mouillot, D., Paleczny, M., 2012. The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. *Global Ecology and Biogeography*, 21, 465-480.
- Cheung, W.W.L., Sarmiento, J.L., Dunne, J., Frölicher, T.L., Lam, V.W.Y., Palomares, M.L.D., Watson, R., Pauly, D., 2012. Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nature Climate Change*.
- Durrieu de Madron, X., Guieu, C., Sempéré, R., Conan, P., Cossa, D., D'Ortenzio, F., Estournel, C., Gazeau, F., Rabouille, C., Stemmann, L., 2011. Marine ecosystems' responses to climatic and anthropogenic forcings in the Mediterranean. *Progress in Oceanography*, 91, 97-166.
- D'Ortenzio, F., Ribera D'Alcalã, M., 2009. On the trophic regimes of the Mediterranean Sea: a satellite analysis. *Biogeosciences*, 6, 139-148.
- Gabrié C., Lagabrielle E., Bissery C., Crochelet E., Meola B., Webster C., Claudet J., Chassanite A., Marinesque S., Robert P.,Goutx M., Quod C. 2012. Statut des Aires Marines Protégées en mer Méditerranée. MedPAN & CAR/ASP.Ed: MedPAN Collection. 260 pp.
- GBIF. 2012. Recommended practices for citation of the data published through the GBIF Network. Version 1.0 (Authored by Vishwas Chavan), Copenhagen: Global Biodiversity Information Facility. Pp.12
- Hartigan, J.A., Wong, M.A., 1979. A k-means clustering algorithm. JR Stat. Soc., Ser. C, 28, 100-108.
- Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., 2008. A global map of human impact on marine ecosystems. *Science*, 319, 948.
- Hirzel, A.H., Le Lay, G., Helfer, V., Randin, C., Guisan, A., 2006. Evaluating the ability of habitat suitability models to predict species presences. *ecological modelling*, 199, 142-152.



- Intergouvernemental Panel on Climate Change (I.P.C.C)., 2013. *Impacts, Adaptation, and Vulnerability*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
- Legendre, P., Legendre, L., 1998. *Numerical Ecology*. Amsterdam: Elsevier Science BV.
- Longhurst, A., 2007. *Ecological geography of the Sea*. London: Academic Press.
- MEDAR Group, 2002 MEDATLAS/2002 database. Mediterranean and Black Sea database of temperature salinity and bio-chemical parameters. Climatological Atlas. IFREMER Edition
- Millenium Ecosystem Assessment (M.E. A.), 2005. *Ecosystems and human well-being*: Island Press.
- Mouillot, D., Albouy, C., Guilhaumon, F., Ben Rais Lasram, F., Coll, M., Devictor, V., Meynard, C.N., Pauly, D., Tomasini, J.A., Troussellier, M., 2011. Protected and threatened components of fish biodiversity in the Mediterranean Sea. *Current Biology*, 21, 1044-1050.
- Moutin, T., Van Wambeke, F., Prieur, L., 2012. Introduction to the Biogeochemistry from the Oligotrophic to the Ultraoligotrophic Mediterranean (BOUM) experiment. *Biogeosciences*, 9, 3817-3825.
- Oliver, M.J., Glenn, S., Kohut, J.T., Irwin, A.J., Schofield, O.M., Moline, M.A., Bissett, W.P., 2004. Bioinformatic approaches for objective detection of water masses on continental shelves. *Journal of Geophysical Research*, 109, C07S04.
- Odum, E.P., 1971. *Fundamentals of ecology*. Philadelphia: Saunders.
- Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres, F., 1998. Fishing down marine food webs. *Science*, 279, 860-863.
- Phillips, S.J., Dudík, M., Schapire, R.E., 2004. A maximum entropy approach to species distribution modeling. *Proceedings of the twenty-first international conference on Machine learning* (p. 83): ACM.
- Quackenbush, J., 2001. Computational analysis of microarray data. *Nature Reviews Genetics*, 2, 418-427.
- Reygondeau, G., Beaugrand G., Guidi L., Stemann L., Koubbi P., Henson S. A., Maury, O.in revision. First approach for a biogeography of the mesopelagic layer. *Plos One*.
- Reygondeau, G., Longhurst, A., Martinez, E., Beaugrand, G., Antoine, D., Maury, O., 2013. Dynamic biogeochemical provinces in the global ocean. *Global Biogeochemical Cycles*, 27, 1046-1058.
- Sherman, K., 2005. The Large Marine Ecosystem Approach for Assessment and Management of Ocean Coastal Waters. *Sustaining Large Marine Ecosystems: The Human Dimension*, 3-16.
- Spalding, M.D., Fox, H.E., Allen, G.R., Davidson, N., FerdaÑA, Z.A., Finlayson, M.A.X., Halpern, B.S., Jorge, M.A., Lombana, A.L., Lourie, S.A., 2007. Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas. *BioScience*, 57, 573-583.





- Sverdrup, H.U., 1953. On Conditions for the Vernal Blooming of Phytoplankton. *ICES Journal of Marine Science*, 18, 287-295.
- Thuiller, W., Lafourcade, B., Engler, R., Araújo, M.B., 2009. BIOMOD–a platform for ensemble forecasting of species distributions. *Ecography*, 32, 369-373.
- UNEP-MAP-RAC/SPA, 2010b. Fisheries conservation and vulnerable ecosystems in the Mediterranean open seas, including the deep seas. By S. De Juan and J. Lleonart, Ed. RAC/SPA, Tunis, 103p.
- van der Spoel, S., 1994. A biosystematic basis for pelagic biodiversity. *Bijdragen tot de Dierkunde*, 64, 3-31.
- Vierros, M., Bianchi, G., & Skjoldal, H. R. (2008). The Ecosystem Approach of the Convention on Biological Diversity. The Ecosystem Approach to Fisheries, Berlin Heidelberg, Federal Environmental Agency.
- Yeung, K.Y., Haynor, D.R., Ruzzo, W.L., 2001. Validating clustering for gene expression data. *Bioinformatics*, 17, 309-318.
- Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. *Journal of the American statistical association*, 58, 236-244.

5.2. Presentation to International conferences

April 2013 European Geosciences Union 5egu^o General Assembly, Vienna, Austria

G. Reygondeau, J-O. Irisson, C. Guieu, S. Gasparini, S. D. Ayata & P. Koubbi. Toward a dynamic biogeochemical division of the Mediterranean Sea in a context of global climate change. Oral communication.

October 2013 CIESM, Marseille, France

G. Reygondeau, J-O. Irisson, C. Guieu, S. Gasparini, S. D. Ayata & P. Koubbi. Ecoregionalisation of the Mediterranean sea: Environmental, ecological features and potential threats. Oral communication.

June 2014 IMBER, Bergen, Norway

G. Reygondeau, J-O. Irisson, C. Guieu, S. Gasparini, S. D. Ayata & P. Koubbi. Ecoregionalisation of the Mediterranean sea: Environmental, ecological features and potential threats. Oral communication.

September 2014 ICES, Malaga, Spain

G. Reygondeau, C. Albouy, T. Hattab, F. Benedetti, J O Irisson, S D Ayata, S Gasparini, B Mckenzie C Guieu and P Koubbi.. Mediterranean biodiversity (from phytoplankton to top predators) and present threats. Oral communication.



October 2014 Global challenge and sustainable solutions, Copenhaguen, Denmark

G. Reygondeau, C. Albouy, T. Hattab, F. Benedetti, J O Irisson, S D Ayata, S Gasparini, B Mckenzie C Guieu and P Koubbi.. Mediterranean biodiversity (from phytoplankton to top predators) and present threats. Oral communication.



