Climate change impacts on fish species distribution. Approach using GIS, models and climate evolution scenario

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Plouzané, France

Impact du Changement Climatique sur la Distribution des Populations de Poissons. Approche par SIG, Modèles et Scénarios d'Évolution du Climat

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Climate Change Impacts on Fish Species Distribution. Approach Using GIS, Models and Climate Evolution Scenario

Thèse soutenue le 28 juin 2016

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I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me

Isaac Newton
25/12/1642 - 20/03/1726

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> *« If I have seen further than others, it is by standing upon the shoulders of giants »*
> *Isaac Newton*

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> *« I give infinite thanks to God, who has been pleased to make me the first observer of marvelous things » Galileo Galilei (15/02/1564 - 08/01/1642)*

RÉSUMÉ

La compréhension des interactions liant la répartition des espèces, la biodiversité, les habitats marins et le changement climatique est nécessaire voire fondamentale pour la mise en œuvre d'une gestion efficace de la conservation (p. ex. la mise en place d'aires marines protégées).

Ce travail couvre une étendue latitudinale très grande, dans une zone de l'Atlantique Est, allant des eaux tropicales aux eaux subtropicales et tempérées. La zone d'étude est située dans trois grands écosystèmes marins : le courant des Canaries, le plateau sud de l'Atlantique Européen et les mers celtiques. La région centrale de la zone d'étude est connue pour sa sensibilité aux effets du changement climatique.

Dans cette étude, nous avons exploité des données issues de grandes bases disponibles en ligne, telles que les occurrences des espèces et les données environnementales. Les principaux objectifs de notre travail sont les suivants :

1) Évaluation du changement climatique à travers l'étude de l'évolution de la température de surface de la mer.
2) Calcul des changements du nombre d'espèces étudiées par écosystème au cours par périodes décennales.
3) Détermination des niches écologiques des espèces étudiées.
4) Modélisation par SIG des distributions des espèces étudiées en fonction de leurs niches écologiques.
5) Suivi de l'évolution saisonnière des zones de répartition des espèces étudiées au fil du temps.
6) Identification des zones d'occupation préférentielle des espèces étudiées (*hotspots*), à partir de modèles de répartition des espèces.
7) Évaluation de l'efficacité des AMP selon leurs localisations par rapport aux zones de *hotspot*.
8) Prédiction des distributions futures des espèces étudiées en utilisant des modèles de prévision des températures de surface de la mer.

Nous avons considéré le changement climatique à travers l'évolution de la température de surface de la mer (SST). Les SST utilisées proviennent de données satellitaires de l'AVHRRR-NOAA de 1982 à 2012, soit 30 ans d'observations journalières. Les variations mensuelles de la SST ont été analysées en utilisant une analyse de série chronologique.

La SST augmente constamment au fil du temps dans tous les écosystèmes étudiés, avec des tendances et des magnitudes qui varient selon l'écosystème. Dans les mers celtiques, la SST moyenne a augmenté de 0,85 °C au cours de temps, alors qu'en Europe du Sud et dans le courant des Canaries les SST moyennes ont augmenté respectivement de 0,55 °C et de 0,87 °C.

Le nombre d'espèces étudiées par écosystème et par période décennale a été établi à partir des données des occurrences des espèces entre 1982 et 2012. Nous avons sélectionné 89 espèces de poissons notées «rares» ou «exotiques», observées en dehors de leur aire de répartition connue. Beaucoup de ces espèces partagent leur aire de répartition avec des écosystèmes adjacents, tels la mer du Nord, la mer Méditerranée occidentale, et le courant de

Guinée. Ainsi, la zone d'étude pour ce travail particulier a été étendue à ces écosystèmes adjacents.

Les changements du nombre d'espèces par période décennale varient entre les écosystèmes. Une augmentation du nombre d'espèces dans un écosystème a été généralement suivie par une tendance à la baisse ou à la hausse dans des écosystèmes adjacents. Dans la mer du Nord, dans l'Atlantique Européen et la mer Méditerranée occidentale, le nombre d'espèces présente une tendance à la hausse au fil du temps. Parmi les espèces étudiées dans la période récente (2003-2012), 7 espèces du courant des Canaries ont montré une tendance à la hausse en Méditerranée occidentale. Douze espèces ont montré des déplacements saisonniers entre les zones du courant des Canaries et du courant de Guinée. Six espèces du courant des Canaries et de la mer Méditerranée occidentale ont étendu leurs aires de distribution au plateau sud de l'Atlantique Européen. Treize espèces se sont déplacées de façon saisonnière entre la mer du Nord et les mers celtiques, parmi elles 12 espèces ont atteint le plateau sud de l'Atlantique Européen.

Les niches écologiques des espèces étudiées ont été estimées en utilisant les valeurs environnementales mesurées au point d'occurrence au moment de l'observation. Les occurrences et les données environnementales utilisées pour ces calculs proviennent de l'ensemble des données mondiales disponibles. Un script a été écrit en langage de programmation *Python* pour automatiser le processus d'extraction. Trois espèces vivant dans des environnements différents, ont été sélectionnées pour valider l'efficacité de cette approche: *Pomatomus saltatrix* (pélagique), *Baliste capriscus* (benthopélagique), et *Solea senegalensis* (démersal). Les résultats issus de la méthode utilisée sont cohérents avec ceux obtenus à partir d'études observationnelles ou expérimentales. En prenant *P. saltatrix* comme exemple, la température maximale tolérée par cette espèce est d'environ 30 à 33 °C en utilisant les données de la SST de jour, et de 29-30 °C en utilisant des données de la SST de nuit. Ces résultats sont proches de la valeur maximale déterminée par AquaMaps (31,78 °C), et par différentes études observationnelles ou expérimentales (variant de 30 à 34 °C). Pour la température minimum tolérée, notre étude obtient des valeurs qui vont de 5,59 à 6,35 °C, ce qui diffère de la valeur déterminée par AquaMaps (0,67 °C), mais correspond aux valeurs obtenues à partir des études observationnelles ou expérimentales (allant de 6 à 13 °C).

Les modèles de distribution des espèces ont été construits en utilisant un modèle SIG. La stratégie retenue est d'identifier des zones appropriées, fondées sur les niches écologiques estimées pour chaque espèce. Huit espèces de poissons vivant dans des environnements différents ont été choisies pour illustrer ce travail : *B. capriscus*, *Umbrina canariensis*, *Anthias anthias*, *Arnoglossus thori*, *Arnoglossus laterna*, *Arius parkii*, *S. senegalensis* et *Diplodus vulgaris*. Quatre classes de zones préférentielles de distribution propres à chaque espèce ont été déterminées :

- Classe 1 (zone de préférence maximale)
- Classe 2 (zone préférée)
- Classe 3 (zone de préférence limitée)
- Classe 4 (zone tolérée)

Les modèles produits par cette étude permettent de représenter les distributions potentielles des espèces liées à l'évolution saisonnière de l'environnement. Cette méthode a montré son efficacité dans le domaine de la modélisation de la distribution des espèces. Elle peut également être utilisée pour modéliser la distribution des espèces moins connues, ainsi que pour la modélisation des zones où les données d’occurrences sont peu nombreuses.

La flexibilité du modèle SIG nous a permis de suivre l'évolution saisonnière de distribution des espèces au fil du temps, de 1982 à 2013. Quatre espèces d’affinité climatique différente ont été sélectionnées pour illustrer ce travail: *Myctophum punctatum*, *P. saltatrix*, *Ammodytes tobianus* et *Lepidorhombus whiffiagonis*. En général, les espèces montrent une tendance à élargir leur distribution vers le nord. Ces tendances sont plus marquées dans la région centrale de la zone d’étude, sauf pendant la période automnale. Ces résultats montrent l'effet du réchauffement de l'océan sur la distribution des poissons marins.

Les zones les plus riches en espèces (zones de *hotspot*) ont été déterminées en utilisant l’ensemble des modèles de distribution des espèces étudiées. Tous les modèles ont été superposés en fonction du temps. La méthode calcule le nombre de zones superposées. Cette approche offre une alternative pour mesurer la richesse des espèces de façon saisonnière dans des zones peu connues.

En hiver, les zones de *hotspots* ont été trouvées le long des côtes marocaine et mauritanienne. Les conditions environnementales au cours de cette saison y étaient favorables pour au moins 51 espèces. En général, les eaux ouest-africaines présentent un nombre plus élevé d'espèces que celles des eaux européennes. Ces dernières voient une augmentation de leur nombre d’espèces lorsque la température de la mer augmente en printemps.

En été, la température de la mer dans les eaux européennes (surtout pour les eaux Portugaises, le golfe de Gascogne et les mers celtiques) augmente, et devient favorable à la déplacement de nombreuses espèces d’origine tropicale. En automne, la zone sud européenne était encore favorable au maintien de nombreuses espèces tropicales.

L'analyse spatiale de la superficie des AMPs (Aires Marines Protégées) par écosystème montre que les zones protégées dans les mers celtiques couvrent environ 5% de la surface de l'écosystème, ou 6% de la superficie du plateau continental. Pour la zone sud européenne, les AMPs couvrent 7% de la superficie totale de l'écosystème, ou 12% de la superficie du plateau continental disponible. Enfin dans le courant des Canaries, ces zones protégées représentent seulement 2% de la superficie totale de l'écosystème, ou 7% de la zone du plateau continental. L’analyse spatiale par pays appartenant à la zone d'étude, montre que le Royaume-Uni puis la France possèdent le plus grand nombre d'AMP ainsi que les superficies totales protégées les plus importantes.

L’efficacité des AMPs et de leur localisation a été évaluée en utilisant le modèle de richesse. A cet effet, nous avons défini une zone globale de *hotspots* favorable au maintien d’au moins 30 espèces. Le déplacement saisonnier de cette zone a été suivi de 1982 à 2013. La fréquence à laquelle cette zone touche une AMP a été comptée et la superficie alors impactée a été calculée. Nous avons sélectionné quatre pays, pour illustrer ce travail: l’Irlande, la France, le Portugal et la Mauritanie. La fréquence à laquelle les AMPs sont touchées par les zones de *hotspots* est fortement influencée par les variations de l’environnement, les zones favorables évoluant alors au fil des saisons. Ainsi, il est important de prendre en compte les variations saisonnières pour la création des AMPs afin de préserver les capacités adaptative des espèces soumises au changement global.

Les valeurs historiques de SST et deux modèles prédictifs, un modèle de contrôle (CTL) et un modèle de l'IPSL, ont été utilisés pour décrire la répartition passée et future des espèces. Deux espèces ont été choisies pour illustrer ce travail : *A. thori* et *M. punctatum*. Les périodes décennales passés et futures étudiées sont : 1990-1999, 2000-2009, 2050-2059 et 2090-2099.

A titre d'exemple, les modèles CTL de distribution de *A. thori* ont montré un léger mouvement vers le nord en direction de la Manche amorcé en 2000-2009 et se poursuivant en 2050-2059 et 2090-2099. Les modèles de distributions basés sur l'IPSL ont montré pour leur part un mouvement plus prononcé au nord atteignant la côte de l'Irlande.

Le point le plus nord de la zone préférentielle maximale de *A. thori* (la classe 1) basée sur le modèle CTL, s'est déplacé en été de la position 47,63 °N en 2000-2009 à 49,83 °N en 2050-2059 et 52.08 °N en 2090-2099. Ce mouvement était plus marqué avec le modèle IPSL pour lequel le point le plus nord de la même classe est passé de 47,63 °N en 2000-2009, à 49,83 °N en 2050-2059, et 52,08 °N en 2090-2099.

SUMMARY

Understanding connectivities among species distributions, biodiversity, marine habitats and climate change is necessary for the design of an effective conservation management, such as in the implementation of marine protected area (MPA).

Our study area covers a wide latitudinal range of the Eastern Atlantic waters, from the warm tropical/subtropical waters to the temperate waters. This area is located in three large marine ecosystems: the Canary current, the South European Atlantic Shelf and the Celtic Seas. The transitional zone in the central region has well known for its sensitivity to the detection of climate change.

In this study, we explored a largely available species occurrence records and environmental data. Our main objectives are:

1) To asses climate change through the change of sea surface temperature (SST).
2) To count the change of number of studied species per ecosystem over decadal periods.
3) To determine species ecological niches.
4) To perform species distribution modelling based on the species ecological niche using GIS technique.
5) To follow the evolution of species distribution over time under climate change.
6) To identify the areas most occupied by species (hotspot area) based on models of species distribution.
7) To compute the effectiveness of MPA placement in relation to species hotspot distribution under environmental change.
8) To predict species future distribution using projected SST data.

We studied climate change through the sea surface temperature (SST). The SST data was obtained from satellite measurement of the AVHRRR-NOAA, for over 30 years of daily observation, from 1982 to 2012. The average monthly SST was calculated from daily data, and was analysed using time series analysis.

In all of studied ecosystems, the SST has increased consistently over time, with magnitude and trend varied among ecosystems. In the Celtic Seas, the average SST has increased 0.85 °C over the past three decades, while in the South European Atlantic Shelf and the Canary Current; the averages SST have increased 0.55 °C and 0.87 °C respectivelly.

The numbers of species in each ecosystem and decadal period were measured using the species occurrences. We selected 89 fish species that had been observed outside their known natural ranges, and noted ‘rare’ or ‘alien’. We collected occurrences of these selected species, from 1982 to 2012. Many of these species shared their area of distribution with adjacent ecosystems: the North Sea, the Western Mediterranean Sea, and the Guinea Current. Thus, the study area was extended to cover these ecosystems.

The change of number of species in each decadal period differed among ecosystems. Increasing number of species in an ecosystem was generally followed by decreasing trend in adjacent ecosystems. In the South European Atlantic Shelf and the Western Mediterranean Sea, the numbers of species increased considerably over time. In recent period (2003-2012), 7 species from the Canary Current tended to be found increasingly in the Western Mediterranean Sea. Six species from the Canary Current and the Western Mediterranean Sea

extended their ranges of distribution to the South European Atlantic Shelf. Other species move seasonally among ecosystems; 12 species moved between the Canary Current and the Guinea Current. 13 species moved between the North Sea and the Celtic Seas, and 12 of these species reached the South European Atlantic Shelf.

Species ecological niches were obtained by extracting the environmental values in the location of species occurrence at the time of observation. The environmental data and the occurrence records used were at global scale. A script written in *Python programming language* was used to automate the extraction process. Three species living in different environment were selected to validate the effectiveness of this approach: *Pomatomus saltatrix* (pelagic), *Balistes capriscus* (benthopelagic), and *Solea senegalensis* (demersal). The methods yields coherent results with the results obtained from observational studies. Using *P. saltatrix* as an example, the maximum SST measured in this study are 30-33 °C using day-time data and 29-30 °C using night-time data, depending on the instrument used. These values are near with the maximum temperature determined in AquaMaps (31.78 °C), and with the values of the experimental studies that range from 30 to 34 °C. The minimum SST of this species obtained in this study is 5.59-6.35 °C, which differs from the value determined by AquaMaps (0.67 °C) but matches the values from the experimental and observational studies that range from 6 to 13 °C. These ecological niches were furthermore used for modelling species distribution.

The model of species distribution was built using the GIS Model. The common strategy of modelling was identifying areas suitable for the species based on the species ecological niches. Twelve fish species living in different environments were selected to demonstrate this method: *Anthias anthias*, *B. capriscus*, *Umbrina canariensis*, *Arnoglossus thori*, *Arnoglossus laterna*, *Arius parkii*, *S. senegalensis*, *Diplodus vulgaris*, *Myctophum punctatum*, *P. saltatrix*, *Ammodytes tobianus*, and *Lepidorhombus whiffiagonis*. Four classes of preferences were used to distinguish areas where species are likely to occur:

- The Class-1 (the most preferred zone)
- The Class-2 (the preferred zone)
- The Class-3 (the less preferred zone)
- The Class-4 (the extreme area).

The result models were capable of depicting species potential distribution following the seasonal environmental change. The results showed its effectiveness in predicting area of distribution for all species. This method can be very usefull for modeling poor-known species and for modeling in data-poor areas.

The flexibility of GIS Model allowed us to follow the evolution of species seasonal distribution over time, from 1982 to 2013. Four species with different affinity were selected to demonstrate this work: *M. punctatum*, *P. saltatrix*, *A. tobianus*, and *L. whiffiagonis*. Generally, most of the species show a northbound trend in their distribution. These northbound tendencies are more evident in the middle region, and in the period of winter, spring and summer.

The area most occupied by species was determined using the model of all species. All models were superposed based on time. The method simply computed the number of species suitable areas overlapped. This approach provides an alternative of measuring seasonal species richness in poor-data areas. The results present a complete picture of predictive number of species in an area over time.

In the winter, the areas most occupied by species were found along the coast of Moroccan and Mauritanian waters. The environmental conditions in these areas during this season were suitable for approximately 51 – 59 species. In this season, the West African waters have more species of above 41 species than in the European waters. The European waters started to have more species when the sea temperature warm in spring. In summer, as the temperature in this region increases, several areas such as Portuguess waters, the Bay of Biscay and the Celtic Seas, became suitable for many species. In autumn, most part of the southern European waters was still suitable for many warm water species.

MPAs superficial analysis presented that in the Celtic Seas, the MPAs areas covered approximately 5.23% of the total ecosystem area, or 6.71% of the total continental shelf area available in the ecosystem. In the South European Atlantic Shelf, the MPAs areas covered 7.69% of the ecosystem, or 12.46% of the continental shelf. In the Canary Current, the MPAs areas covered 2.63% of the ecosystem, or 7.66% of the continental shelf. Analysis by country (countries liying in the study area) showed that UK has the highest number of MPA and the largest protected areas, following by France and Mauritania.

Using the richness model, we assess the effectiveness of MPAs in terms of their localisation. Observation of hotspot area (suitable for at least 30 species) was conducted seasonally from 1982 to 2013. The frequency at which the hotspots intersect an MPA was counted. The superficie of the overlapped area intersected was also calculated. We selected five countries to demonstrate this work: Ireland, France, Portugal, Mauritania and Senegal. These countries were considered representative for studies of climate change effect to species distribution. The hotspot areas changed over season. Frequencies of the MPAs touched by the hotspot were strongly influenced by seasonal variations. Thus, considering seasonal variations in a conservation effort could preserve species adaptative variation under environmental changes.

Two future projected SST models, a control model (CTL) and an IPSL model, were used to predict future species distribution. Two species were selected to demonstrate this work: *A. thori* and *M. punctatum*. The periods investigated were: 1990-1999, 2000-2009, 2050-2059, and 2090-2099. These periods of ten years were determined following the decadal variability of SST in the study area.

Distribution model of *A. thori* as example, using the CTL SST model, showed a slight northwards movement towards the English Channel, from the period 2000-2009 to the period 2050-2059 & 2090-2099. Using the IPSL SST model in the same periods, the results showed a movement further north that reach the Coast of Ireland.

The northernmost point of *A. thori*'s suitable area in summer, resulting from the CTL SST model, moved from 47.63 °N (2000-2009) to 49.83 °N (2050-2059) and further north to 52.08 °N in the last period (2090-2099). This movement is more evident with the IPSL SST model where the point moved from 47.63 °N (2000-2009) to 49.8373 (2050-2059), and up to 52.0873 in the last period (2090-2099).

Overall, our works provide several alternative methods for species distribution studies and for studies poor-known species in data-poor area. The results provide evidences of ocean warming effect in shifting marine fish distribution.

TABLE DES MATIÈRES

SUPPLEMENTARY MATERIALS

TABLE DES ILLUSTRATIONS

TABLE DES TABLEAUX

INDEX DES ABRÉVIATIONS

“Knowledge is the life of the mind. Without knowledge action is useless”

Abou Bakr As-Siddiq
573-634

1 INTRODUCTION

Increase in greenhouse gases in the atmosphere induces global warming and thus drives global climate change (IPCC 2007). The rise of global temperature and the ongoing climate change have been widely accepted in the scientific community, and have been the main issues for decades, especially in recent years, when their effects have been extensively observed and broadly documented (Figure 1-1).

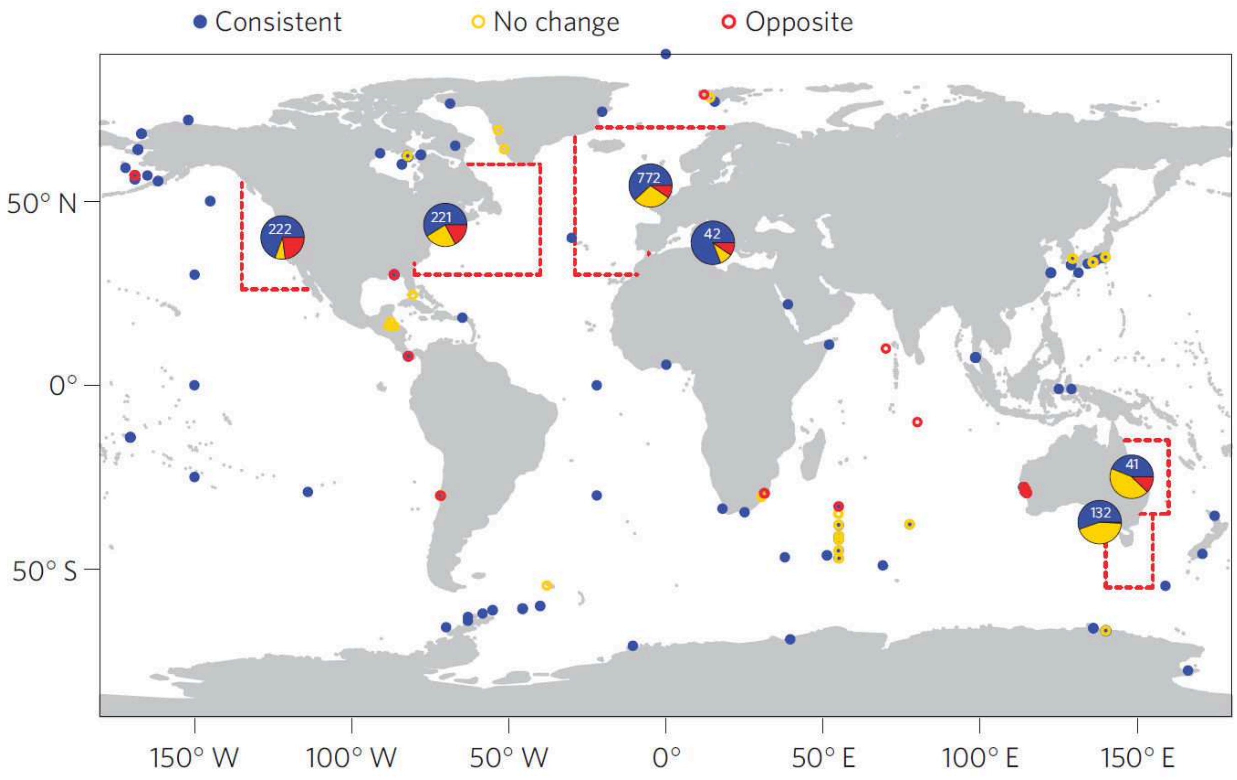


Figure 1-1: Distribution of global marine ecological climate-impact studies. Total number of observations is 1735, both single and multispecies studies. Points in blue represent locations where studies show consistent responses of marine organisms to climate change (blue, n = 1092). Points in red indicate studies in which the results are opposite to those expected (red, n = 225), while points in yellow present equivocal results (yellow, n=418). Pie charts show the proportions of each color to the total number of observations (consistent, opposite plus equivocal) within each region (Poloczanska et al. 2013).

A robust study to the effects of climate change on marine organisms has been performed as presented in Figure 1-1. It shows the distribution of global climate-impact studies on marine organisms. Majority of these studies (points in blue) confirms the effect of climate change on marine lifes.

Many reports of climate change effect on marine species distribution covered mainly studies on a global ocean scale and for a limited range of locations or taxonomic groups (i.e., ter Hofstede et al. 2010), while climate varies naturally across a range of regional and temporal scales. Climate change impacts differ geographically and seasonally, reflected by changes in the distribution pattern of marine species (Cheung et al. 2009; Margules and Pressey 2000).

There are very few studies of climate change effects on linked regions that together encompass species with wide latitudinal distribution range, especially in the region of West African as showed in

Figure 1-1. Hence, in this study, we work in three large linked marine ecosystems or ecoregions (the Canary Current, the South European Atlantic Shelf and the Celtic Sea) to observe the effect of climate change on species distribution.

The Celtic Sea and the South European Atlantic Shelf region (O'Reilly 2013) are considered as Class II, moderately productive ecosystems, while the Canary Current LME is classified as Class I, a highly productive ecosystem because it is in a major upwelling region off the coast of northwest Africa (Heileman and Tanstad 2008). Species richness in the middle region, especially in the Portuguese coastal waters, is generally higher because many species have their southern or northern distribution limits offshore of the Portuguese coast. The zoogeographic importance of this latitudinal area has long been recognised, representing the transition between north-eastern Atlantic warm-temperate and cold-temperate regions, which makes the zone an area of great sensitivity to the detection of climate change. In warm years, official landing data for commercial species have shown in general an increasing trend for the species with an affinity for subtropical/tropical waters whereas species with an affinity for temperate waters presented a decreasing trend. In colder years, landings of subtropical/tropical species presented an opposite trend (Teixeira et al. 2014).

The sea absorbs the heat accumulated in the world oceans and slows the increase of the sea temperature. Despite this property, the ocean warming has immediate effects on marine environment, notably significant impacts on marine biodiversity (Poloczanska et al. 2013).

The rising of sea temperature has facilitated the introduction of organisms to areas outside their natural range. Small numbers of these organisms are able to establish a viable population and become invasive (Secretariat of NOBANIS 2012). Invasive species are considered the second most important cause of biodiversity loss after habitat destruction, accelerating the decline of native communities already under environmental stress (Streftaris and Zenetos 2006), as well as changing the local or regional species richness (Hiddink and Hofstede 2008). For example, the presence of tropical species in Atlantic European waters has been reported since 1960s (Quero et al. 1997a) and their numbers have increased rapidly, involved pelagic and coastal as well as deep-water fishes (Bañón 2004). Therefore, climate change is considered a major driver of biodiversity change (Otero et al. 2013).

Climate change impacts also depend on the biological characteristics and sensitivities of the species. In this this work, we focuses on studying fish species that had been observed outside their known natural distribution range. These species were noted as rare or alien by various sources (i.e. CIESM 2002 and Zenetos et al. 2005) such as *Acanthurus monroviae*, a tropical-Atlantic origin species. This species was noted in 2002 by CIESM as *Exotic* species that has now well established in the Mediterranean Sea. Another example is *Arius parkii*, considered *Alien* in the same area. In the Atlantic-European waters, two species: *Anthias anthias* and *Solea senegalensis*, previously unknown in the Galician waters (NW Spain) of the South European Atlantic Shelf, are now observed with high biomass (Bañón et al. 2010). 465 rare species were identified in the middle zone of the study area. These are species with temperate and/or tropical-origin. 89 species living in different environment were selected for this study based on the availability of occurrences records (the threshold value was 80 occurrences).

Growing awareness of the necessity of protecting marine environments and marine resources has highlighted the need for documenting ecosystem baseline information, for long-term monitoring and for estimating the geographic extent of critical habitats (Lundblad et al. 2006). The available measurements of species biodiversity are mostly analyzed using expert knowledge or regional observations which cannot be used directly to investigate the potential shift in their distributions under different environmental conditions. Most of existing empirical attempts to measure species biodiversity were based on occurrence records. The lack of data in many places and the fact that the analyses were restricted in taxonomic and spatial coverage (Whitehead et al. 2010) prevent the analysis of biodiversity at biogeographical scale. The large-scale species movements strongly influence the availability of species occurrences data. This data is generally more abundant in the developed countries of the north European waters than in the developing countries. The availability of occurrence data in the later countries was very poor due to the low number of surveys conducted in the area or to the limited access to the databases available in the regions. Furthermore, species occurrence records are scarce, especially for marine species because it may not be possible to sample the whole range of environmental variation (Araujo 2002). Field surveys on the sea and inventory of species occurrence records are expensive and limited by time. Quantifying patterns of biodiversity requires costly and challenging efforts, particularly in the oceans where the species cannot easily be seen and many of whom are highly mobile, with large areas of distribution that extend far into the open oceans (Tittensor et al. 2010). The use of "indicator" species, which in this study are species considered potentially invasive, to estimate species richness is then common (Fleishman et al. 2005).The acceleration of biodiversity loss has spurred the development of technique to assess and monitor biodiversity for addressing large-scale ecological questions (Chiarucci et al. 2011). The model of richness is then essential for understanding of the seasonal evolution of species richness.

In this study, we will develop several techniques to assess the climate change through the sea surface temperature, and its impacts on number of species and species distribution. We will use a large quantity of environmental data mainly from long-term satellite observations, and a huge number of species occurrence records from freely accessible from online databases as well as from unpublicized databases. We will also develop several techniques to determine species realised niches and to model species distribution under climate change. The model of species distribution will be used to create a simple model of richness of the studied species. This model will be furthermore used to asses the effectivenesse of MPA placement in the area of study. At the last phase of this study, we will predict the future distribution of the studied species using the projected model of sea surface temperature (Figure 1-2).

This study has several objectives:

(1) To determine an area for detecting climate change as the area of study.
(2) To select some fish species noted as rare/alien in the area of study.
(3) To collect occurrence records of the selected species from various databases.
(4) To assemble the satellite environmental data and the bathymetric data available.
(5) To assess the climate change through sea surface temperature for each studied ecosystem.
(6) To calculate the change of number of studied species in each ecosystem over decadal periods, as well as the route and timing of their movement under environmental changes.
(7) To determine species realised niches.
(8) To model species distribution over time based on the species realised niches.
(9) To follow the evolution of species distribution under climate change.
(10) To modelrichness of the studied species using all individual models and to identify area most occupied by species (hotspot area).
(11) To analyse the Marine Protected Areas (MPAs) found in the area of interest.
(12) To compute the effectiveness of MPAs placement through the movement of hotspots areas over time.
(13) To predict the species distribution in the future using a projected SST model.

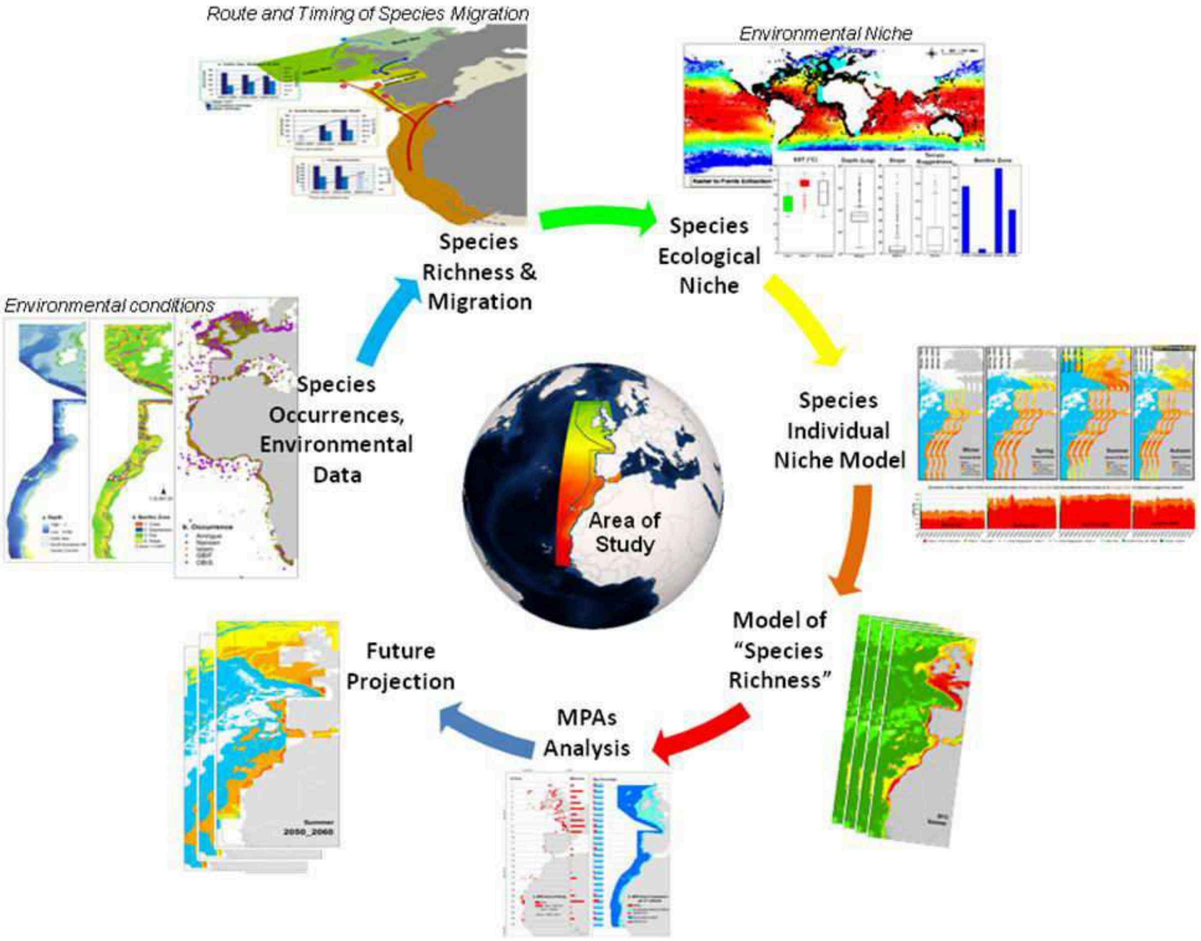


Figure 1-2: Illustration describing the scope of this study.

In the first phase of this study, we will determine the area of interest (AOI) in the Eastern Atlantic Waters (Figure 1-3). This study area covers three linked large marine ecosystems/regions: the Canary Current, the South European Atlantic Shelf and the Celtic Seas. The zoogeographic importance of these latitudinal areas, especially the region in the central, has long been recognized, for they represent the transition zone between the warm-tropical waters and the cold-temperate waters. Many species have their southern or northern distribution limits in the middle region, which makes the zone an area of great sensitivity for the detection of climate change. Many reports state the increasing trend of tropical fish presence in the middle region, which makes the zone an area of great sensitivity for the detection of climate change. Observational and historical captures have been well documented (i.e., (Teixeira et al. 2014). Unfortunately, the route and timing of the species' introduction in this area are poorly understood (Johnston and Purkis 2011). This is one of the reasons why we selected this area. In addition, despite the migration of several marine fish species in these regions, studies of species distribution are rare compared to adjacent areas, such as the relatively closed water body of the Mediterranean Sea.

In the second phase of the study, we will explore the environmental data available, such as sea surface temperature, to determine the current status of climate change in the area of interest. The most powerful way to collect such data is through the use of satellite sensors that measure different types of energy coming from the Earth. The satellite observation has made possible to work with comprehensive time series of physical oceanographic data. We will assemble 30 years of the most recent version AVHRR SST dataset Pathfinder 5.2 from NOAA polar-orbiting satellites, and 11 years of other oceanic parameters obtained from the MODIS-AQUA satellite. These environmental data are the key input for many applications. We will observe the changes in the pattern of sea surface temperature and other oceanic parameters in each ecosystem.

In the third phase of the study, we will create the maps for describing the distribution of depth, slope, terrain ruggedness and benthic zones of the AOI, in order to understand the relationship between terrain and fish biodiversity. These maps will also be used in species distribution modelling. Bathymetry data we used in this study comes from the *SRTM30_PLUS* database, while the derivative bathymetry data will be generated in this study.

In the fourth phase of the study, we will select 89 fish species from out of the 465 rare/alien fish species identified in the AOI. These species have been observed outside their known native area distributions. We will collect all of their occurrence records available on a global scale from various databases. The huge availability of species occurrence records will enable to study the decadal evolution of richness of the studied species at ecosystem level and at latitudinal level, and to study species movement under environmental change.

In the fifth phase of the study, the derivative bathymetry data along with the environmental satellite time series data, will be used to determine the species realised niches. We will compute these niches by extracting the environmental values in the location of species occurrence at the time of observation. This process will use all species occurrences available at global scale. Thus, it will minimize issues of small sample data size. A script written in *Python programming language* will be used to automate the process.

In the sixth phase of the study, we will model the distribution of each studied species by projecting their realised niches to a time series of environmental data. The model used was a *GIS Model*. The capabilities and flexibility of GIS technique, with the integration of *Python programming language* and the use of long-term marine environmental data, allowed us to demonstrate the potential evolution of the distribution of marine fish species over three decadal periods, from 1982 to 2013, and to show how marine fish distribution shift in relation to ocean warming.

In the seventh phase of the study, we will superpose all species models based on time to model the richness of the studied species over time. The model simply calculates number of species found in an area (area overlapped) at a given time/period. This richness model will then be analyzed in the next phase of the study to demonstrate the importance of marine protected areas in terms of their location, providing information for marine conservation strategies.

In the last phase of the study, we will predict species distribution using future model of sea surface temperature. We will also calculate the shift of species area distribution from the period 1990-1999 and 2000-2009, to the period 2050-2059 and 2090-2099.

Finally, this study presents some approaches that could be used to generate species ecological niches and species potential distribution for a wide range of organisms, especially for poorly-known species. The technique used is also promising to model species richness in data-poor areas. These models will enhance the prediction models available today, and the results will bring a better understanding of climate change effects on species distribution and species richness.

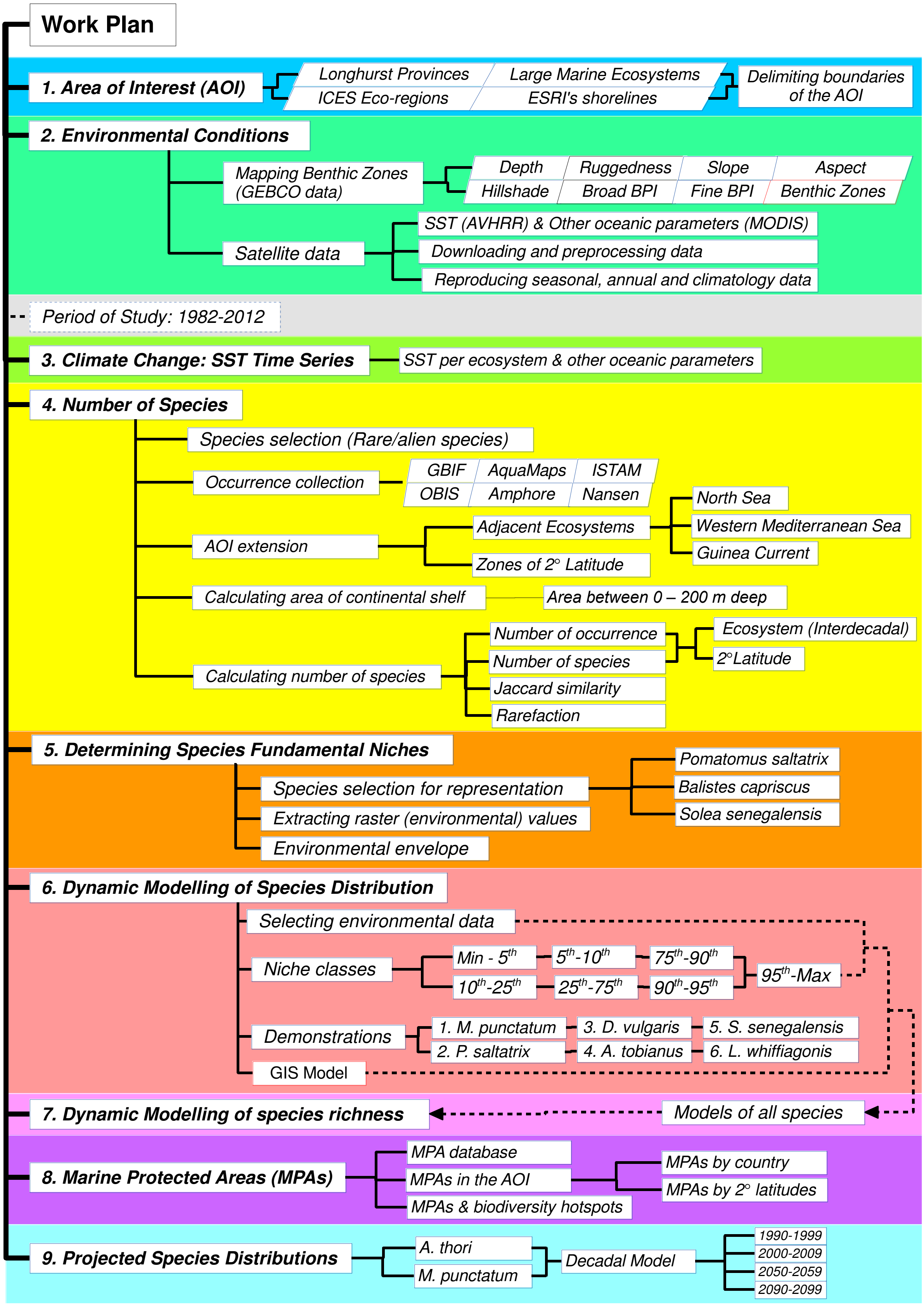


Figure 1-3: Thesis' work plan.

2 STATE OF THE ART

2.1 Climate change

2.1.1 Ongoing climate change

The ongoing changes of Earth's climate are widely accepted in the scientific community (Trenberth et al. 2006). The primary factor that caused this phenomenon seems to be the increase in greenhouse gases emissions (IPCC 2007). Among these gases, the carbon dioxide (CO_2), from the land-use or from the burning of fossil fuels, is likely to be the main responsible for the rise of the planet's temperature (Otero et al. 2013).

The climate change is expected to have significant impact such as increasing seawater temperatures, ocean acidification, more frequent extreme events and changes in oxygen levels or deoxygenating processes (IPCC 2007).

The rising temperature of sea surface affects and melts continental ice. It changes the ice coverage and increases sea water mass, sea level, and changes ocean salinity and current patterns (Cheung et al. 2009a, Fernandes et al. 2013 and Otero et al. 2013).

Due to the high specific heat capacity of seawater, sea temperatures increase much less than air temperatures, and this limits global warming by allowing heat to be absorbed in the world's oceans (Otero et al. 2013). Despite the fact that sea surface waters warm three times more slowly than that air over land (because the ocean absorbs heat), the migration of isotherms at the ocean surface faster than isotherms over land during the past 50 years (1960-2009), especially at high latitudes above 45° (Poloczanska et al. 2013).

2.1.2 Impact on marine ecology

Climate change is causing biological and ecological changes in marine systems worldwide (Cheung et al. 2011). These changes along with their impacts on marine ecosystems are predicted to be more rapid in the 21st century (Fernandes et al. 2013). Abrupt ecosystem shifts, biogeographical responds caused by these phenomena have been widely documented (Raybaud et al. 2013); see Figure 1-1. Cheung et al. (2009), Cheung et al. (2011) and Fernandes et al. (2013) explained that climate change effects on biogeochemical parameters (e.g., oxygen level, acidity) have led to changes in primary productivity, plankton community structure and also changes in physiology (e.g., growth, body size) and has subsequently changed the distribution, productivity and abundance of marine species (Figure 2-1). Such changes may be more rapid in the future (IPCC 2007). Current studies suggest that species' responses to these changes vary considerably, while their long-term impacts are not fully understood (Cheung et al. 2011).

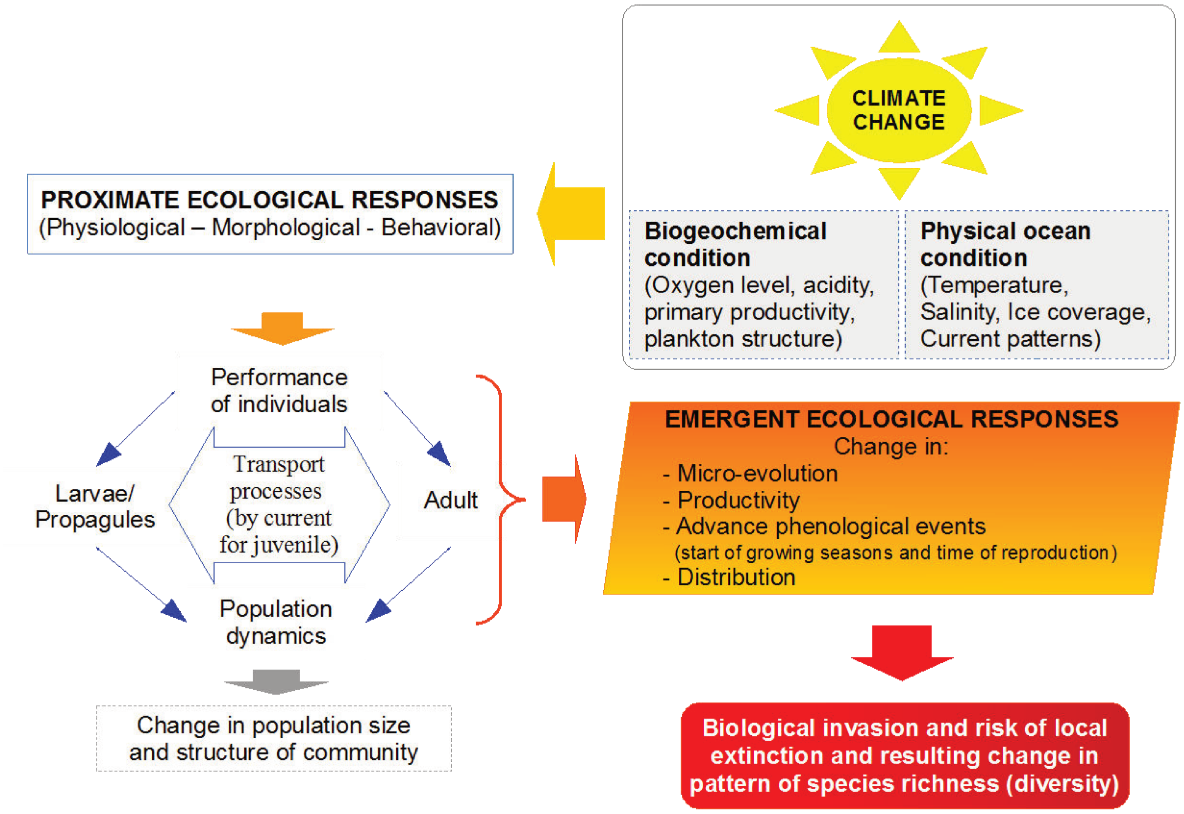


Figure 2-1: Main response pathways of ecological systems to global climate change. This diagram was modified from Occhipinti-Ambrogi (2007) with additional information from Cheung et al. (2009); Cheung et al. (2011); Fernandes et al. (2013) & Poloczanska et al. (2013). The scheme was initially introduced by Harley et al. (2006).

2.1.3 Impact on primary producers

Phytoplankton, the main primary producers in the oceans, responds rapidly to the change of environmental conditions compared to most terrestrial plants, because of its short generation time and sensitivity to temperatures (Poloczanska et al. 2013). Although current projections are uncertain, global ocean primary production may change in future (Cheung et al. 2011).

Change in primary productivity affects the planktonic community structure, which will impact the ecosystem services and marine biodiversity, because the change in phythoplankton size influences the amount of energy transferred to higher trophic levels (Cheung et al. 2011). Cheung et al. (2011) further explained that smaller phytoplanktonic organisms, normally grazed by small herbivorous microzooplanktons, are now preyed by larger planktonic consumers which may affect the food chain to a higher trophic level, such as fish.

2.1.4 Impact on species distribution

Although Cheung et al. (2011) stated that the impact of climate change on marine organisms vary considerably and that their long-term impacts were not fully understood, nevertheless, observation and theory suggest that marine species respond to climate change or ocean warming by shifting their latitudinal range and depth range (Cheung et al. 2009). Fernandes et al. (2013) even stated that climate change had already altered the distribution of marine species. Occhipinti-Ambrogi (2007) also stated that climate change could affect the species distribution and the resource dynamics in both terrestrial and aquatic ecosystem leading to biological invasions.

The rise of temperature in sea water could cause physiological stress for marine species, especially for species already near their tolerance limit (Occhipinti-Ambrogi 2007). The fastest warming rate in winter and spring might bring forward physiological events, such as the start of growing seasons and the timing of reproduction (Poloczanska et al. 2013). This is because each species may have a temporal or seasonal niche that causes differences in growth rate, patterns of mortality, timing, duration and magnitude of reproductive output (Occhipinti-Ambrogi 2007).

The common characteristics among marine organisms, such as high rates of propagule production and dispersal by ocean currents, might lead to faster expansions in distribution than those observed for plants and animals on land (Poloczanska et al. 2013). Sorte et al. (2010) stated that the rate of leading-edge expansions from 1960 to 2009 in highly mobile or dispersive pelagic organisms were 469.9±115.3 km dec^{-1} for phytoplankton, 277.5±76.9 km dec^{-1} for bony fish, and 142.1± 27.8 km-dec^{-1} for invertebrate zooplankton.

Variation of responses to environmental changes among individual species in the community are probably the result of interacting factors, such as population size, dispersal capability, dependence on habitat or prey availability, resource competition, migratory strategy, latitudinal gradient of light regime and fisheries impacts (Poloczanska et al. 2013).

2.2 Environmental data

Climate varies naturally across a range of temporal and latitudinal scales. On temporal scales, the variations follow seasonal cycles, inter-annual patterns such as the El Niño Southern Oscillation (ENSO), inter-decadal cycles such as the North Atlantic Decadal Oscillation, and multi millennial-scale changes such as glacial to inter-glacial transitions (Occhipinti-Ambrogi 2007). On latitudinal scales, there is a variation of temperatures at low and high latitude regions (Otero et al. 2013). All this natural variability is reflected in species distribution (biogeography).

Comprehensive and consistent time series data are necessary to elucidate the effects of continuously changing environmental conditions on species distributions. Different studies tried to link physical and environemental data series to be used with fish species abundance (Stequert and Marsac 1991). One way to get such comprehensive data is through the use of satellite sensors.

2.2.1 Satellite observation

With today’s modern satellite sensors capable of observing the earth from space, satellite observations are the most powerful means to collect long-term and comprehensive oceanic data. A long period of Sea Surface Temperature (SST) records, covering over 30 years, is now available through AVHRR data. Long period data series, over 13 years of observation are also available through MODIS data for other oceanic parameters. These will allow scientists to conduct a wide variety of marine research.

2.2.1.1 Sea Surface Temperature (SST) data from AVHRR

Seawater temperature is a fundamental variable for monitoring and understanding complex interactions between atmosphere and ocean. It is one of the variables controlling the density of the oceans (Otero et al. 2013) and for which the observation has long been taking place.

An accurate knowledge of SST distribution among latitudinal and temporal range at fine spatial resolution is needed as a key input in many applications, including ecosystem assessments and fisheries support (GHRSST Science Team 2010). The SST data is widely used to reveal the role and long-term climate variability.

Among the many modern satellite sensors available today, only AVHRR (the *Advanced Very High Resolution Radiometer*) onboard the NOAA polar-orbiting satellites have produced a successful long-term global SST dataset from the same class of instrument (Casey et al. 2010). The data is based on daily observations, which is essential to monitor and understand climate variability, climate-ecosystem interaction on species distribution, and for sustainable fisheries management. The AVHRR is a radiation-detection imager that remotely determines the cloud cover, the surface temperature of Earth, the upper surfaces of clouds, or the surface of a body of water (NOAA Satellite Information System 2013).

The first AVHRR 4-channel radiometer was carried on NOAA's Polar-orbiting Operational Environmental Satellites (POES) starting with TIROS-N (launched in October 1978); see Table 2-1. The second AVHRR with 5-channel instrument was initially carried on NOAA-7 (launched in June 1981) POES Satellites. The latest AVHRR/3, with 6 channels (Table 2-1) was carried on NOAA-15 and launched in May 1998 (NOAA Satellite Information System 2013).

Table 2-1: AVHRR temporal coverage (Kidwell and Katherine 1995).

Satellite	Launch Date	Ascending Node	Descending Node	Service Dates
TIROS-N	10/13/1978	1500	300	10/19/78 - 01/30/80
NOAA-6	6/27/1979	1930	730	06/27/79 - 11/16/86
NOAA-7	6/23/1981	1430	230	08/24/81 - 06/07/86
NOAA-8	3/28/1983	1930	730	05/03/83 - 10/31/85
NOAA-9	12/12/1984	1420	220	02/25/85 - Present
NOAA-10	9/17/1986	1930	730	11/17/86 - Present
NOAA-11	9/24/1988	1340	140	11/08/88 - 09/13/94
NOAA-12	5/14/1991	1930	730	05/14/91 - Present
NOAA-14	12/30/1994	1340	140	12/30/94 - Present

AVHRR has a highly accessible data collection system and a wide range of applications, for both regional and global environmental issues (Table 2-2). It provides a daily global coverage of satellite digital imagery (Hastings and Emery 1992).

Table 2-2: AVHRR/3 Characteristics (NOAA Satellite Information System 2013).

Channel	Resolution at Nadir	Wavelength (um)	Typical Use
1	1.09 km	0.58 - 0.68	Daytime cloud and surface mapping
2	1.09 km	0.725 - 1.00	Land-water boundaries
3A	1.09 km	1.58 - 1.64	Snow and ice detection
3B	1.09 km	3.55 - 3.93	Night cloud mapping, sea surface temperature
4	1.09 km	10.30 - 11.30	Night cloud mapping, sea surface temperature
5	1.09 km	11.50 - 12.50	Sea surface temperature

The instrument channelization permits multispectral analyses which provide improved determination of hydrologic, oceanographic, and meteorological parameters. The sea surface temperature is computed using the data of two IR window channels. The IR window channels are used to measure cloud distribution and to determine the temperature of the radiating surface. On later instruments in the series, a third IR channel was added, able to remove radiant contributions from water vapour when determining surface temperatures (NOAA Satellite and Information Service 2015).

Sea surface temperature measured by the satellite sensors or by an infrared radiometer operating typically at wavelengths in the range 3.7-12 micrometers, is the sea surface skin temperature (Figure 2-2).

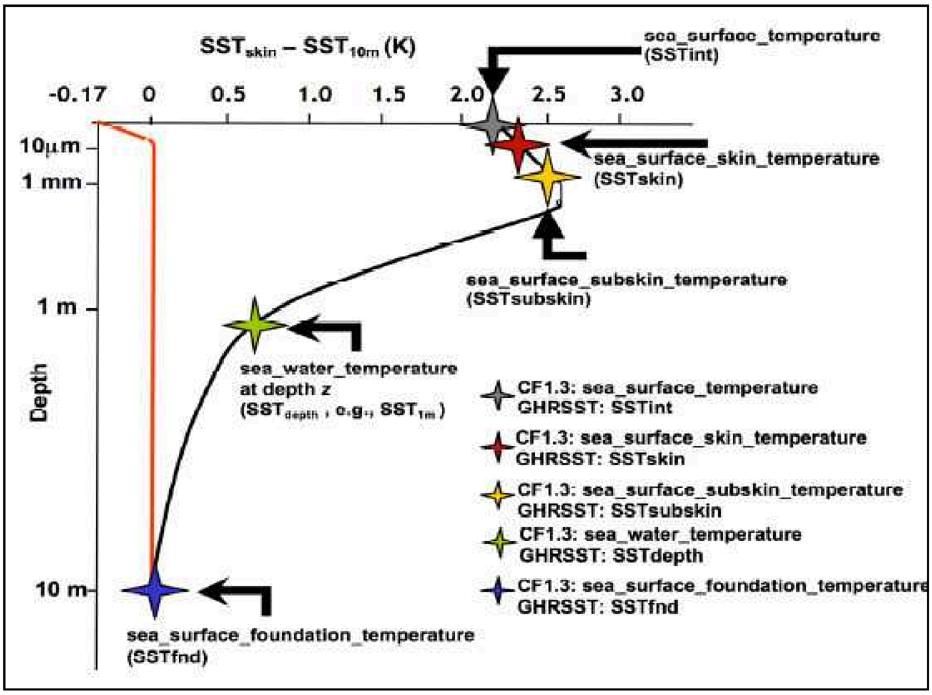


Figure 2-2: Overview of SST measurement types used within GHRSST. Night-time SST profile is presented in red line, while daytime with strong solar radiation and light winds SST profil is presented in black line (GHRSST Science Team 2010).

Sea Surface Temperature (usually abbreviated as SST) is the temperature of sea water near the surface (including the part under sea-ice, if any), and not the interface temperature, whose standard name is surface temperature (see Figure 2-2). There are several types of SST (GHRSST Science Team 2010):

- SSTskin, or the sea surface skin temperature, is the temperature measured by an infrared radiometer typically operating at wavelengths in the range 3.7-12 micrometers. It represents the temperature within the conductive diffusion-dominated sub-layer at a depth of approximately 10-20 micrometers below the air-sea interface. This definition is chosen for its consistency with the majority of infrared satellite and ship mounted radiometer measurements.
- SSTdepth or SSTz is the terminology adopted by GHRSST to represent *in situ* measurements near the surface of the ocean that have traditionally been reported simply as SST or "bulk" SST. For example, SST6m would refer to an SST measurement made at a depth of 6 m. The terminology has been introduced to encourage the reporting of depth (z) along with the temperature.
- SSTfnd or the sea surface foundation temperature is the water temperature that is not influenced by a thermally stratified layer of diurnal temperature variability (either by daytime warming or nocturnal cooling).

In general, sea surface foundation temperature is similar to a night-time minimum or pre-dawn value at depths between approximately 1 and 5 meters (Figure 2-2). In the absence of any diurnal signal, the foundation temperature is considered equivalent to the quantity with standard name *sea_surface_subskin_temperature*, or the temperature near the surface measured using the satellite instrument. Sea surface foundation temperature is measured at the base of the diurnal thermocline or as close to the water surface as possible in the absence of thermal stratification. Only *in situ* contact thermometry is able to measure the sea surface foundation temperature. Please refer to GHRSST Science Team (2010) for further information.

2.2.1.2 Chlorophyll-a and other oceanic parameters from MODIS

While AVHRR is known for providing the longest time series of Earth observation, which started back in 1982, MODIS has the most comprehensive earth observing sensor system (36-bands/group of wavelength spectroradiometer) available today. Thus, MODIS plays a vital role in validating global interactive Earth System models and predicting global climate change with higher precision (Lindsey and Herring 2013). These will provide policy makers with complete pictures of the environment protection effort (Lindsey and Herring 2013).

MODIS (*Moderate Resolution Imaging Spectroradiometer*) is a sensor onboard the Aqua satellite launched in May 2002 (Figure 2-3). The orbit of this satellite goes from south to north and passes over the equator in the afternoon. Actually there are two operational satellites that carry this instrument, TERRA and AQUA. They are working in tandem to provide completed morning and afternoon observations as well as to optimize and minimize any optical effect caused by sunlight unique to morning or afternoon (NASA, 2013). Unfortunately, due to some suspicious values in TERRA's data according to the data provider, it was suggested to use only Aqua's data over Terra. Hence in this study, we exploited only Aqua's data. Hu et al. (2007) stated that the difference of data products among sensors could be due to inconsistent sensor calibration and atmospheric correction methods.

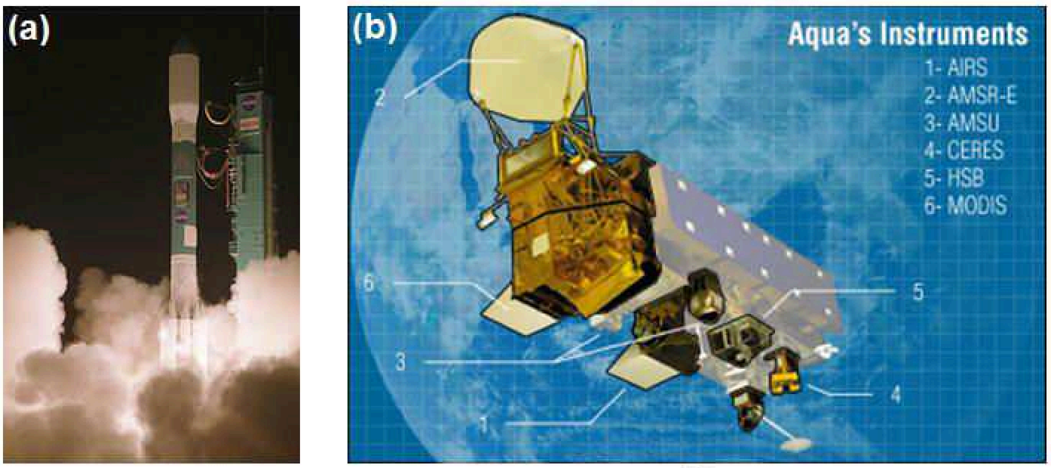


Figure 2-3: (a) Aqua Launch on May 04, 2002 (Salomonson 2002); (b) MODIS Instrument on Aqua (Graham 2011).

One of the six state-of-the-art instruments carried in Aqua is MODIS, whose specifications are presented in Table 2-3.

Table 2-3: Modis Technical Specifications (Maccherone 2013).

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud Boundaries	1	620-670	21.8	128
	2	841-876	24.7	201
Land/Cloud Properties	3 - 7	459-479,…, 2105-2155	35.3,…, 1.0	243,…, 110
Ocean color/ Phytoplankton/ Biogeochemistry	8	405-420	44.9	880
	9	438-448	41.9	838
	10	483-493	32.1	802
	11	526-536	27.9	754
	12	546-556	21.0	750
	13	662-672	9.5	910
	14	673-683	8.7	1087
	15	743-753	10.2	586
	16	862-877	6.2	516
Atmospheric Water Vapor, Surface/Cloud Temperature, Atmospheric Temperature, Cirrus Clouds, Water Vapor, Ozone, Surface/Cloud Temperature, Cloud Top Altitude	17 - 36	890-920, …, 14.085-14.385	10.0, …, 2.08	167, …, 0.35

[1] Bands 1 to 19 are in nm; Bands 20-36 are in µm; [2] Spectral Radiance values are (W/m^2-µm-sr); [3] SNR=Signal-to-noise ratio; [4] NE ΔT = Noise-equivalent temperature difference.

2.2.2 Bathymetry data and its derivative

Variation of depth and roughness of the ocean floor influence the ocean circulation and marine biological diversity (Becker et al. 2009). The marine and coastal environments are vast areas, still largely unexplored (Lundblad et al. 2004). Understanding regions deeper than 30 m is required by scientists and researchers to protect and monitor varied ecosystems (Lundblad et al. 2006). Mapping benthic terrain is thus necessary to locate and study resources associated with particular terrains. New data and mapping techniques are required to classify potential habitats in deeper water.

Many studies have tried to link topographic features with populations of particular species. For example, (Schmahl et al. 2003) used multibeam bathymetric maps to guide submersible cameras that allowed the researchers to identify detailed biotopes and species within geomorphic zones, e.g., coral species zones within midshelf banks less than 36 m deep or within banks less than 50 m deep, or on the soft bottom. Another study used side scan sonar mosaics to link species with their habitat locations in order to find relationships between population abundance and the benthoscape. With the use of backscatter imagery, they classified large scale benthoscapes such as muddy sands, fine sands and muds, boulders, cobbles and outcro (Lundblad et al. 2006).

The studies mentioned above used bathymetry data in their investigation. This bathymetry data could serve as an effective base layer in geographic information system (GIS). The application of GIS to the characterization of marine benthic habitats increases the speed of seafloor mapping efforts. It allows visualization and imaging of seafloor characteristics (Greene et al. 2005).

Weiss (2001) made a unique classification scheme for understanding watershed metrics by using topographic position and landform analysis. He used algorithms that perform an analysis on each grid cell in an elevation model to form a topographic position index (TPI). The TPI value of each grid cell indicates its position relative to the overall landscape (higher than, lower than, or the same elevation). By combining TPI with slope position, Weiss (2001) created methods to apply a landform classification scheme to watersheds in his area of study. In this study, we used his method to classify the benthic zone of our area of study. According to Lundblad et al. (2006), the method used by Weiss (2001) is well suited to benthic classifications that serve as predictor for habitat suitability and biodiversity.

Iampietro and Kvitek (2002) incorporated GIS in their study to quantify seafloor habitats for the near shore environment of the entire Monterey peninsula in central California, USA. They also used Weiss's methods to develop TPI grids that, at a fine scale, can describe micro- and macro-scale habitats, while at a broad-scale they can describe meso- and mega-scale habitats.

Quantitative assessments of benthic terrain, such as topographic position, can help to understand how patterns, processes and species are spatially related, despite the fact that these measurements are rarely reported (Lundblad et al. 2006). Qualitative analysis describes process on slopes at different scales.

Coops et al. (1998) also developed and tested procedures to predict topographic position from digital elevation models for species mapping. Topographic position describes topography with spatial relationships. Divisions of topographic position may be quantified differently depending on the scale of the landscape in the area of interest.

2.3 Species diversity of potentially invasive fish

Accounting for spatial scale becomes challenging when measuring species diversity (Chiarucci et al. 2011). Species richness, Shannon-Weiner Index, Evenness or True Diversity index are the most common mathematical indices intended to measure species diversity (Table 2-4).

Table 2-4: Species diversity and evenness indices (adapted from Jost 2006).

No	Name	Symbol	Formula
1.	Species Richness	S	$\sum_{i=1}^{S} P_i^0$
2.	Shannon-Weiner Index	H'	$-\sum[Pi\ \ln(Pi)]$
3.	Shannon evenness	E_H	$H'/\ln S$
4.	True Diversity	-	$\mathrm{Exp}(H')$

**Pi* = the proportion of individuals in the *i*-th species (*Pi* = *ni/N*) where *ni* is the number of individuals of species *i* in the sample; and *N* is the total number of individual sampled.

There is no general agreement among researchers about which index should be used in measuring or comparing species diversity (Rossi 2011). It depends on the availability of information, especially for species abundance.

Species richness is used broadly as a measure of biodiversity at large biogeographical scale with various objectives. It does not incorporate species abundance, information that often is not available. Thus, species richness is a basic surrogate for the more complex concept of ecological diversity (Rossi 2011).

This paper focuses on fish species that have been considered by several studies as rare or alien species, and have or might become established in the north eastern European Atlantic waters, outside their natural dispersal areas. We used the term richness of the studied species instead species richness, because we selected only species which had a distribution range that is expected to be still expanding, based upon data assembled from several public sources. Based on this data, we were able to simulate the spatial pattern of the fish distribution in the north eastern Atlantic waters.

2.4 Species ecological niche

Ecological niche, according to Hutchinson (1957) is, for a given species, a range of tolerance of several environmental factors taken simultaneously. This concept has been widely used in species distribution modelling in order to understand the anthropogenic impact (Peterson 2003) and/or climate change effects on an ecosystem, such as the presence of potentially invasive species. In our study area, we observed 89 fish species out of the 465 potentially invasive marine fish species identified. These species have been noted as rare or alien in various articles as they were observed outside their known natural range (i.e., Oral 2010; Bañón et al. 2010; Zenetos et al. 2010).

Ecological niche modelling that relies on the niche concept (Franklin 2009) has seen an impressive attention (Peterson and Nakazawa 2007) due to the need for information on species geographical distribution and the vast availability of environmental data for addressing this information need, such as remote sensing and global positioning system technology (Franklin 2009).

The common basic application of niche modelling is to predict a species' environmental requirements, i.e., its ecological niche, with climate data as predictors (Hijmans and Elith 2013). With this basic common application, the major distinction among these methods is the kind of species data (Elith et al. 2011) and the type of environmental data they use. New improved techniques with geographic information systems and statistical learning methods (Franklin 2009) have been developed over the last two decades (Elith et al. 2011). Methodological details, such as the algorithms used and model evaluation have now been addressed (Peterson and Nakazawa 2007). In addition, the sample size of occurrence data and the number or types of environmental data incorporated have now been criticized (Soberón et al. 2002; Beck et al. 2014).

The niche modelling method associates the environmental variables and species' occurrence records to identify the species environmental requirements. These environmental requirements are the ecological niche within which a population can be established. Thus, they control this species distribution. The niches are then projected onto environmental data available across a study region to have the areas that are suitable for the species (Pearson 2007; Phillips et al. 2004). So, before performing species distribution modelling, one should first know the environmental requirements of the species, referred to in this study as the species' environmental envelope, which is defined by Walker and Cocks (1991) as the set of environments where the species' environmental requirements can be satisfied and/or within which it is believed that the species can persist.

2.5 Species distribution modelling: GIS model

The knowledge of the areas in which a species occurs and the range where the species can establish are fundamental for adequate conservation strategies, but these pieces of information are rarely available in the variety of checklists or field guides (Boitani and Fuller 2000).

Models, since they present a clear picture of how we believe environmental factors relate to one another, are very useful to assess invasion risk (Leung et al. 2013).

Species distribution modelling (SDM) is also known as climate envelope-modelling, habitat modelling, and environmental or ecological niche-modelling (Hijmans and Elith 2013). The model estimates the relationship between the locations where the species has been observed (known as species' occurrence records) and the environmental conditions of that location (using climate data as predictors) (Franklin, 2009). Using these associations, the model tries to identify environmental conditions within which populations can be maintained. The areas where environmental conditions are suitable for the species can then be estimated across a study region (Pearson 2007). This model has much potential, and it is widely used for many purposes, including biogeography, conservation biology and ecology (Elith et al. 2011).

Most existing models describe only part of the pictures, or perhaps provide an incomplete view of the invasion risk. Presenting model components, structure and dependencies for the consideration of managers and researchers, one can provide guidance for estimating and combining the most relevant processes (Leung et al. 2013).

There are two well known methods for constructing species distribution modelling: GARP and MaxEnt (Maximum Entropy). The comparisons between methods usually lie in (Phillips et al. 2004):

- Their performance as a function of the number of sample points available, so as to determine the all-important question of how much data is enough.
- The effectiveness of regularization, to avoid over-fitting on small sample sizes; and
- The effectiveness of numerical acceleration methods.

Some studies suggest that the MaxEnt method holds great promise for modelling because this method often achieves substantially superior performance in controlled experiments relative to GARP. Another limitation of GARP is the difficulty to interprete results, while it is desirable for a species distribution model to allow interpretation in order to deduce the most important limiting factors for the species (Phillips et al. 2004). MaxEnt is an approach to species distribution modelling, a method for modelling presence-only data. It estimates a distribution across geographic space (Elith et al. 2011).

Methods that require only presence data are often the choice of the species distribution modeler. The data available in many large databases typically has no information about the non-observation species at any given location and, more critically, many locations have not been surveyed.

2.5.1 Strategy in species distribution model

Modelling species distribution is a critical problem in conservation biology. Before performing the model for a given threatened species, one needs to know the location where the species occurs (prefer to live) and its requirements for survival (Phillips et al. 2004).

Availability of detailed presence/absence occurrence data allows the use of a variety of standard statistical techniques. However, for most species, only presence data is available (Phillips et al. 2006). Nevertheless, the availability of satellite environmental data and the improvement in computer system have increased the use of species distribution modelling in many applications.

The most common strategy for estimating the actual or potential geographic distribution of a species is to characterize the environmental conditions that are suitable for the species, and then to identify where suitable environments are distributed in space.

Hijmans and Elith (2013) explained the steps that are usually taken in species distribution modelling:

- Compiling locations of occurrence of a species by assembling material from available sources/databases.
- Extracting the values of environmental parameters at the location where the species was observed from spatial databases.

- Using the species' environmental values to predict the likelihood of presence.
- Use the model to predict the potential distribution across an area of interest (and perhaps for a future or past climate).

Location of occurrence data is usually list of georeferenced localities (geographic coordinates: latitude and longitude) where the species has been observed that is available and accessible in several online database, such as OBIS and GBIF. Environmental conditions/records at each occurrence record are essential for projecting species potential distribution (where the conditions are suitable for the species) in a set of environmental variables. Unfortunately, this type of information is often absent in the databases, leaving only the species' geographic location. A new modelling technique is then required to deal with this type of data that is hugely available.

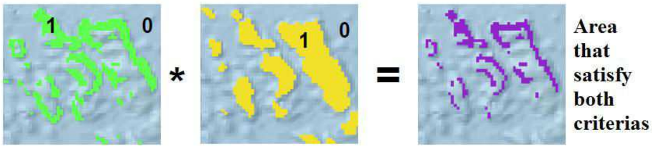
Another alternative which gives modeler many options is the GIS Model. Utilization of GIS is a powerful means to identify areas of high biodiversity and species' potential habitats by integrating available marine data or information (Lundblad et al. 2006). Its flexibility and ease in adding, modifying, and analyzing data has proven to be extremely effective in the compilation and presentation of maps of various types and scales (Greene et al. 2005). This may lead to more efficient management of marine protected areas, simpler decision making supported with detailed information, advancements in marine and coastal research, science and management, georeferenced mapping, modelling and decision making, which are essential to marine habitat management.

2.5.2 GIS model

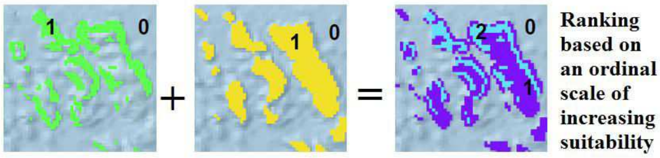
A GIS model is a sequence of steps or functions of GIS analysis, such as binary, ranking, rating and weighted rating analysis where grids are multiplied, added, averaged and weighted-averaged, or many others approaches (Wright 2011). GIS analysis models provide a simple and manageable view of reality, to capture spatial relationships of objects with their attributes, which furthermore helps people to understand, describe or predict how things work and are related in the real world.

Below are some explanations with illustrations of how basic GIS models work (Wright 2011):

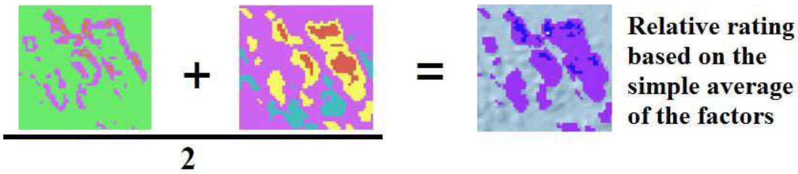
a. Binary model (multiplication). This model will depict only areas that meet all habitat parameters. The model treats cells as 0 and 1. Generally, the value of cells or areas which do not meet a defined parameter is set to 0, while the areas or cells that do meet a defined parameter are set to 1, so that there will be only two possible states in this model: yes (1) or no (0).



b. Ranking model (addition). This model depicts several states with their potentially good habitat ranked relative to each other.



c. Rating model (addition): using a simple average of the two states that use a consistent scale to characterize the habitat. Each parameter will be given a consistent scale based on their potentiality as a good habitat and then the final map depicts habitat suitability based on the average of all input (habitat of all parameters).



d. Rating model (weighted average): parameters are weighted based on their percentage of influence and with more than two states that use a consistent scale to characterize the habitat. This model expresses the relative importance of each parameter to the overall habitat suitability.

2.6 Model of richness

Information on species richness is often required to establish management priorities in conservation. At a local scale, the hotspots approach to species preservation is risky (Smith et al. 2001), while at a continental or national scale it needs to be prioritized. At a biogeographical scale, the methodologies to obtain this information and to understand its spatial variations are still debatable. Nevertheless, it is a major research axis in biogeography and macroecology.

Lack of funding raises the question of how to support the most species at the least cost (Myers et al. 2000). For terrestrial species, many efforts and studies have been undertaken, while for marine species, the studies are still few. Identifying biodiversity hotspots is necessary.

An alternative way to maintain overall biodiversity is by focusing effort of protection on the areas occupied by most native species (Fleishman et al. 2005). Although it could be effiecient (Myers et al. 2000), the questions of how to achieve broad conservation goals remain. Thus, identifying and conserving species at biogeographical scales require a great deal of effort. In addition, the areas within the core of species' ranges or the nontransition zones might play a fundamental role (Araujo 2002).

Araujo (2002) stated that biodiversity hotspots could be selected on the basis of species richness. The hotspot in this study is considered to have the most numbered species. Protecting hotspots would not safeguard all of their species indefinitely (Myers et al. 2000). Nevertheless, the well-established theory of island biogeography suggest that "when an area loses a large proportion of its original habitat and especially when the remaining habitat is severly fragmented, it will eventually lose some of its species through what are technically known as 'ecological equilibriation' or 'delayed fallout effects'" (MacArthur and Wilson 1967). So, it makes sense to take immediate actions to safeguard the hotspot areas to avoid an exceptionally large extinction (Myers et al. 2000).

Effort of conservation could be maximized by integrating both species richness pattern and the process that generate it. Smith et al. (2001) suggested that preserving populations occurring along environmental gradients was one strategy allowing to conserve the maximum amount of adaptation variations, because, environmental gradients are important in diversification and speciation.

2.7 Marine Protected Area (MPA)

There are several definitions/roles of Marine Protected Areas (MPAs). But in practice, MPAs are the areas where natural and/or cultural resources are given greater protection than the surrounding areas (NOAA's Nat. Marine Protected Areas Center 2013), for long-term conservation of coastal and ocean resources (Table 2-5).

Table 2-5: MPAs in the zone of study by country by designation.

No	Attribute	Ire	UK	Fra	Spa	Por	Mor	W. Sah	Mau	Sen	Gam
1.	Total number of MPA	101	275	105	67	33	29	1	7	14	3
2.	IUCN Category										
	a. Ia										
	b. Ib										
	c. II				1				2	4	
	d. III										
	e. IV	12	80	17	2	5				3	
	f. V		56	4	7	7					
	g. VI					2					
	h. Not Reported	1	28	1	4		18	1	1	4	1
	i. Not Applicable	88	111	83	53	19	11		4	3	2
3.	Designation										
	- Ramsars site, Wetland of International Importance (Ramsar Convention)	21	38	5	13	8	11		3	2	2
	- UNESCO-MAB Biosphere Reserve	1	2	1	5					1	
	- World Heritage Site		2						1		
	- Site of Community Importance (Habitats Directive)	44	38	43	24	5					
	- Special Protection Area (Birds Directive)	22	31	34	11	6					
	- Area of Special Scientific Interest		4								
	- Site of Biological and Ecological Interest (SIBE)						10				
	- Site of Special Scientific Interest (GB)		46		1						
	- Special Area of Conservation (SAC)		1								
	- Marine Protected Area									4	
	- Protected Landscape					2					
	- Marine Nature Park			1							
	- National Park		4				2	1	2	4	1
	- National Park – Core Area										
	- National Park (State Network)				1						
	- Nature Park				6	5					
	- Park				1						
	- Regional Nature/Natural Park			3							
	- Bird Reserve									1	
	- Biological Reserve						3				
	- Local Nature Reserve		3								
	- Marine Nature Reserve		3		1						
	- National Hunting and Wildlife Reserve			1			1				
	- National Nature Reserve		27	11							
	- Nature Reserve	9		1	3	5				1	
	- Reserve						2				
	- Satellite Reserve								1		
	- Special Reserve									1	
	- Area of Outstanding Natural Beauty		7								
	- Area of Outstanding Natural Beauty (NI)		1								
	- Heritage Coast		20								
	- Marine Consultation Area		24								
	- National Forest					2					
	- National Scenic Area		24								
	- Natural Landscape				1						
	- Other Area	1		5							
	- Refuge for fauna	3									

Ir = Ireland; UK = United Kingdom; Fra = France; Spa = Spanyol; Por = Portugal; Mor = Morocco; W. Sah = Western Sahara; Mau = Mauritania; Sen = Senegal.

Table 2-5 presents the number and type of MPA of each country in the zone of interest. Well-designed and effectively managed marine protected areas networks could be an alternative tool to reduce the threat of climate change to marine ecosystems, which furthermore contribute to achieve multiple objectives such as fisheries management, biodiversity conservation and adaptation to changes in climate and ocean chemistry. The main issue is that the role of this MPA network and related impact of climate change for marine fish is still unclear.

MPAs could also serve as an "insurance policy" to conserve or protect spawning and nursery areas, protect habitats and help sustain local communities (NOAA's National Marine Protected Areas Center 2012)

MPAs could cover a large range of habitats from coastal areas to open ocean including inter-tidal zones and estuaries. For migratory species that live among different ecosystems and use different habitats at different stages of their lives, including species with wide range of distributions, marine protected area networks can provide protection by connecting these diverse habitats or ecosystems.

MPA networks require broad-scale analysis of conservation efforts to coordinate data collection and to have an accurate representation of the broad extent of protection effort as well as to address a lack of understanding about the effectiveness of current measures (Corrigan et al. 2011). Individual MPAs and the MPA networks play a major role in enhancing our understanding to develop strategies to mitigate climate change effects (Otero et al. 2013).

Managing MPA is itself a challenge. Nowadays, the effect of climate change has already been observed at some sites but is still not explicitly incorporated in most MPA management plans (Otero et al. 2013).

The MPA data we used in this study were obtained from *Protected Planet* online database. Protected Planet (http://protectedplanet.net) is a portal to search, discover and download information from the World Database on Protected Areas (WDPA). It was created to showcase the wealth of global protected areas information already contained in the WDPA (Figure 2-4). The database holds data from governments and non-governmental organizations (NGOs), convention secretariats and also data coming from research institutions, academia or local communities on protected area systems. The WDPA contains comprehensive and regularly updated information on the different types of protected areas, including government, private and community managed reserves ranging from those strictly protected for conservation purposes, to those where sustainable use of natural resources is allowed (Corrigan et al. 2011).

The WDPA database has started approximately 30 years ago as a basic global database of national parks and has since evolved into the only global spatially referenced information source on marine protected areas. It was created in 1962 and is the authoritative world collection of data on protected areas. It is a joint initiative between IUCN and UNEP-WCMC. It has developed into a GIS database mapping more than 170,000 terrestrial and marine protected areas with a standards database so that various analyses can be conducted and credible statistics generated (Corrigan et al. 2011).

The latest official statistics for global MPA coverage revealed that 2.8% of the global ocean is protected, 9.7% of the territorial seas (0-12 nautical miles), 4.6% of Exclusive Economic Zones (EEZ: 12-200 nautical miles), and 0.14% of the High Seas (beyond 200 nautical miles) (IUCN and UNEP-WCMC 2013).

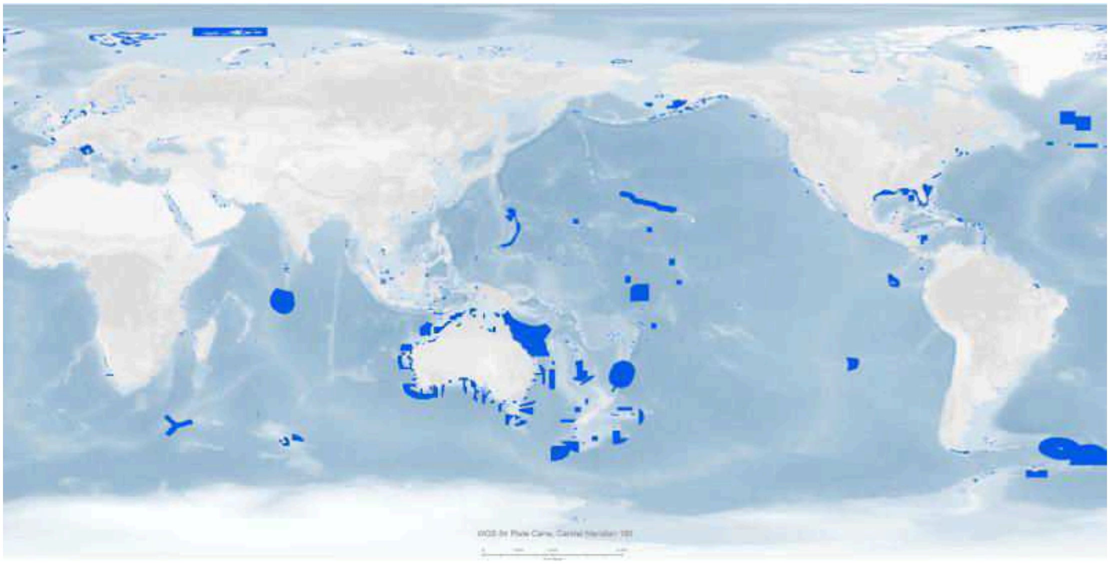


Figure 2-4: The official map of MPAs generated from the WDPA data (IUCN and UNEP-WCMC 2013).

2.8 Zone of study

The Flanders Marine Institute (VLIZ) has made the initial efforts of producing a unique georeferenced standard of names of marine places and areas. This project was funded initially through the EU Network of Excellence MarBEF and other European initiatives. They established an integrated database of marine areas that covers the regional and global geographic information of the world (Claus et al. 2013). The marine georeferenced data, such as marine ecosystems, used in the determination of the area of interest (AOI), were obtained from the official website of this project. Detailed information on the project and the georeferenced data available can be obtained at http://www.marineregions.org.

The zone of interest of this study extends from Senegal waters northward to Ireland waters, from approximately 11° N to 61° N and 0° W to 21° W. Based on the International Hydrographic Organization Sea Areas dataset (IHO) described in (VLIZ 2005), the zone of interest is located in the waters of North Atlantic Ocean, including the Bay of Biscay, Celtic Seas, Bristol Channel, Irish Sea, St. George's Channel and Inner Seas off the West Coast of Scotland (Figure 2-5).

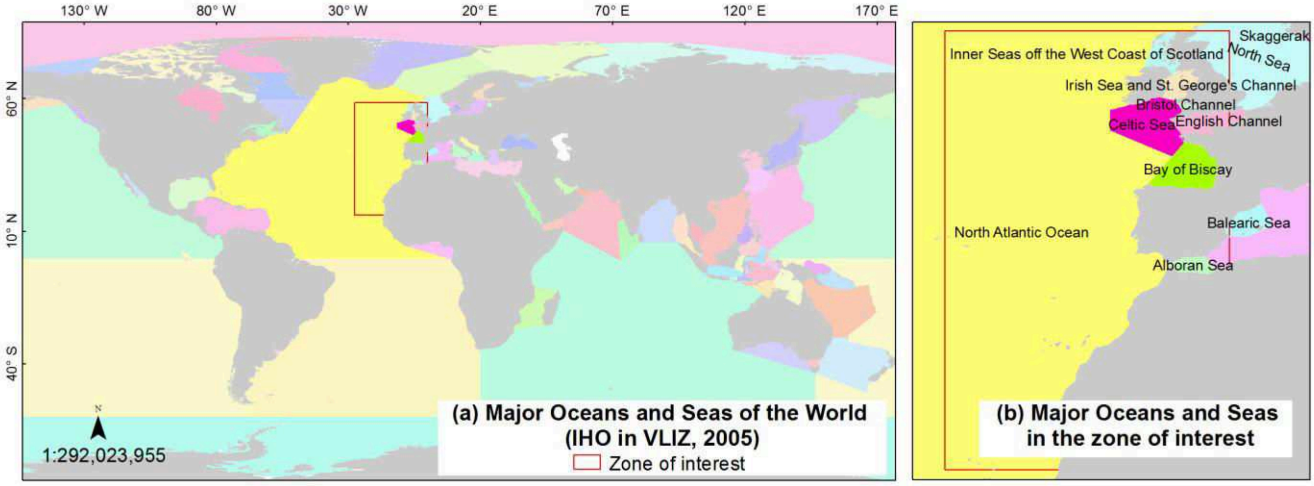


Figure 2-5: Map of major oceans and seas of the (a) world and (b) zone of interest. The areas were mapped by the International Hydrographic Organization (IHO).

The VLIZ also provides georeferenced data on marine ecosystems such as Large Marine Ecosystems (Figure 2-6), Longhurst Biogeographical provinces (Figure 2-8) and ICES Ecoregions (Figure 2-9 and Figure 2-10).

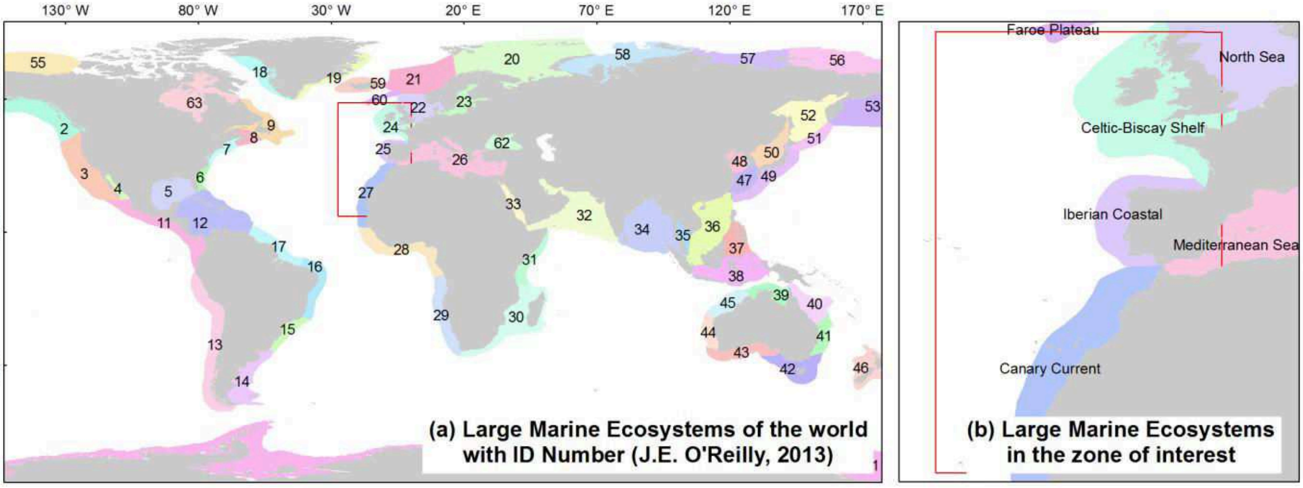


Figure 2-6: Large Marine Ecosystems (LME) of the (a) world and (b) zone of interest.

Sherman and Hempel (2009) defined 64 large marine ecosystems (LMEs) over the global ocean (Figure 2-6 and Figure 2-7). Sherman et al. (2011) stated that these LMEs produced 80% of the world’s annual marine fisheries yields. Introduction on the Large Marine Ecosystems of the world is available online at http://lme.edc.uri.edu.

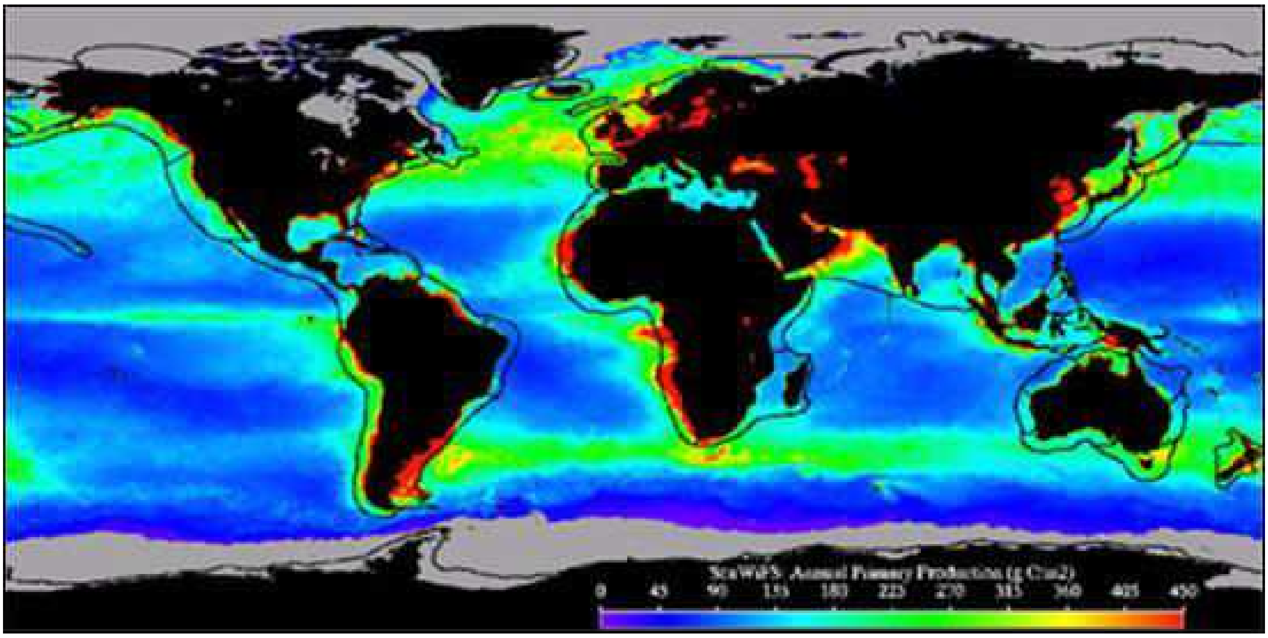
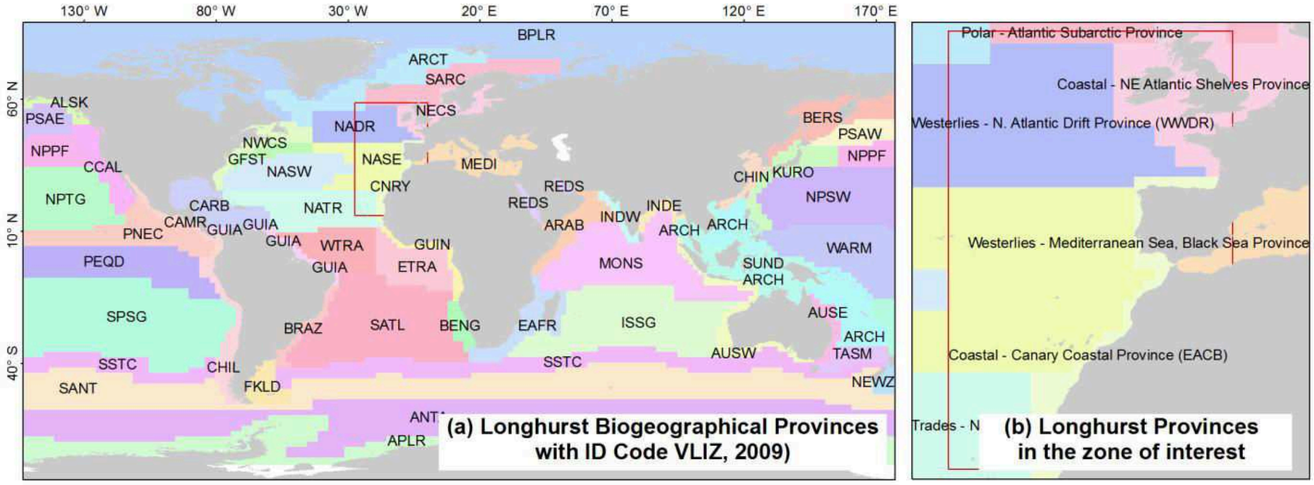


Figure 2-7: Global map of average primary productivity and the boundaries of the 64 Large Marine Ecosystems (LMEs) of the world, available at www.lme.noaa.gov. The annual productivity estimates are based on Sea WiFS satellite data collected between September 1998 and August 1999, and on the model developed by Behrenfeld and Falkowski (1997). The color-enhanced image provided by Rutgers University depicts a shaded gradient of primary productivity from a high of 450 gCm-2yr-1 to a low of 10gCm-2y-1.

Longhurst et al. (1995) divided the world oceans into provinces based on the prevailing role of physical forcing as a regulator of phytoplankton distribution (Figure 2-8). Originally, Longhurst recognized four principal biomes (the Polar Biome, the Westerlies Biome, the Trade-Winds Biome and the Coastal Boundary Zone Biome) recognizable in every major ocean basin. At the next level of reduction, these ocean basins were partitioned roughly in ten provinces (VLIZ 2009).

Figure 2-8 presents the initial static boundaries of the Longhurst Biogeographical provinces. This dataset was developed at the Bedford Institute of Oceanography, Canada. In the real conditions, the boundaries of these provinces are not fixed in time and space but are dynamic and move under seasonal and interannual changes in physical forcing.



(a) Longhurst Biogeographical Provinces with ID Code VLIZ, 2009)

(b) Longhurst Provinces in the zone of interest

Figure 2-8: Map of Longhurst Biogeographical Provinces of (a) the world and (b) the zone of interest.

In European waters, the International Council for the Exploration of the Sea (ICES), also known as *Conseil International pour l'Exploration de la Mer* (CIEM) provides advice on ecosystem/ecoregion overview, description of the ecosystem components and the major ecological events and trends. These ecoregions are mainly based on biogeographic and oceanographic features, including existing political, social, economic and management conditions (ICES 2016).

The delitineation of the ICES Ecoregions was initially described in ICES Advice report in 2004 (Figure 2-9). Ten years later in 2015, the new ICES Ecoregions were introduced (Figure 2-10). The new delineation was updated to account for additional policy objectives and to reconcile legislations (Nathalie 2015).

The next section presents a short discussion of the main physical process and phenomena, mainly based on Mason et al. (2005). Detailed related information can be found in this article. This brief discussion aims to highlights the relevant physical processes that are common in the eastern Atlantic boundary system, and have potential effect on biological process and hence supports our research in species distribution.

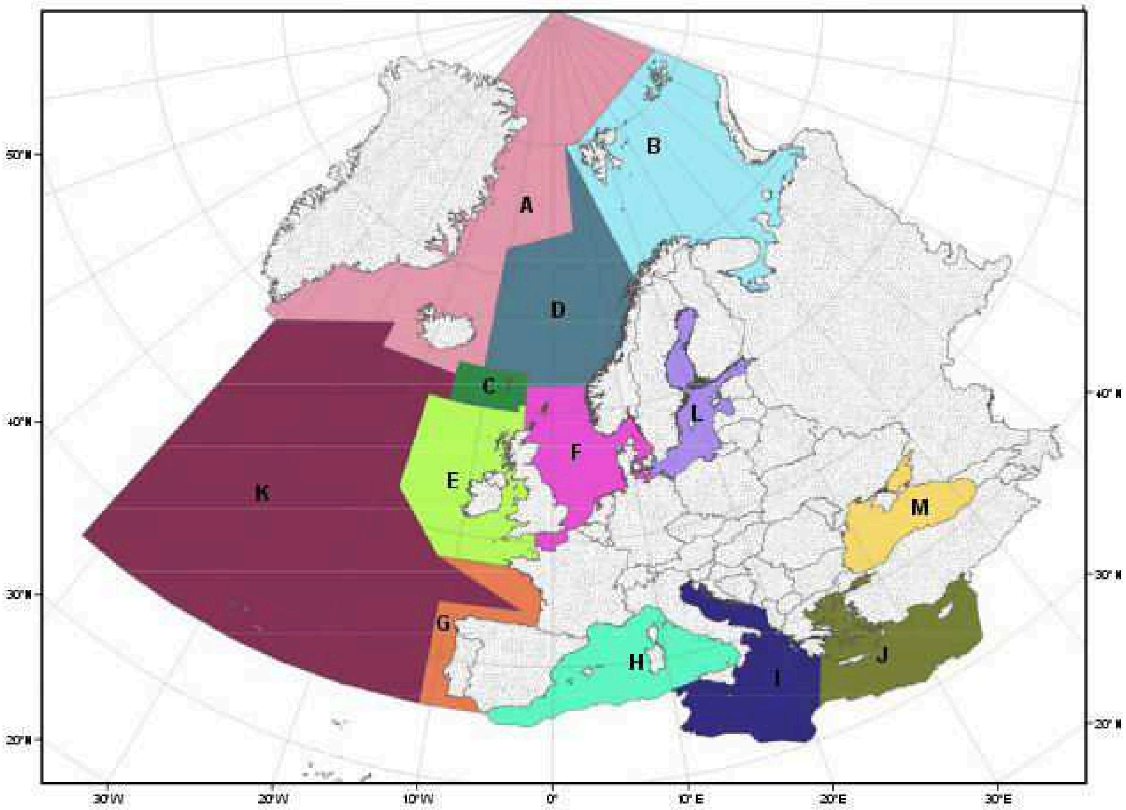


Figure 2-9: ICES' Ecoregions based on ICES Advice ACFM/ACE report (2004). A. Greenland and Iceland Seas; B. Barents Sea; C. Faroes; D. Norwegian Sea; E. Celtic Seas; F. North Sea; G. South European Atlantic Shelf; H. Western Mediterranean Sea; I. Adriatic-Ionian Seas; J. Aegean-Levantine Sea; K. Oceanic northeast Atlantic; L. Baltic Sea; M. Black Sea (http://ices.dk/marine-data/maps/Documents/ICES_Ecoregions.pdf).

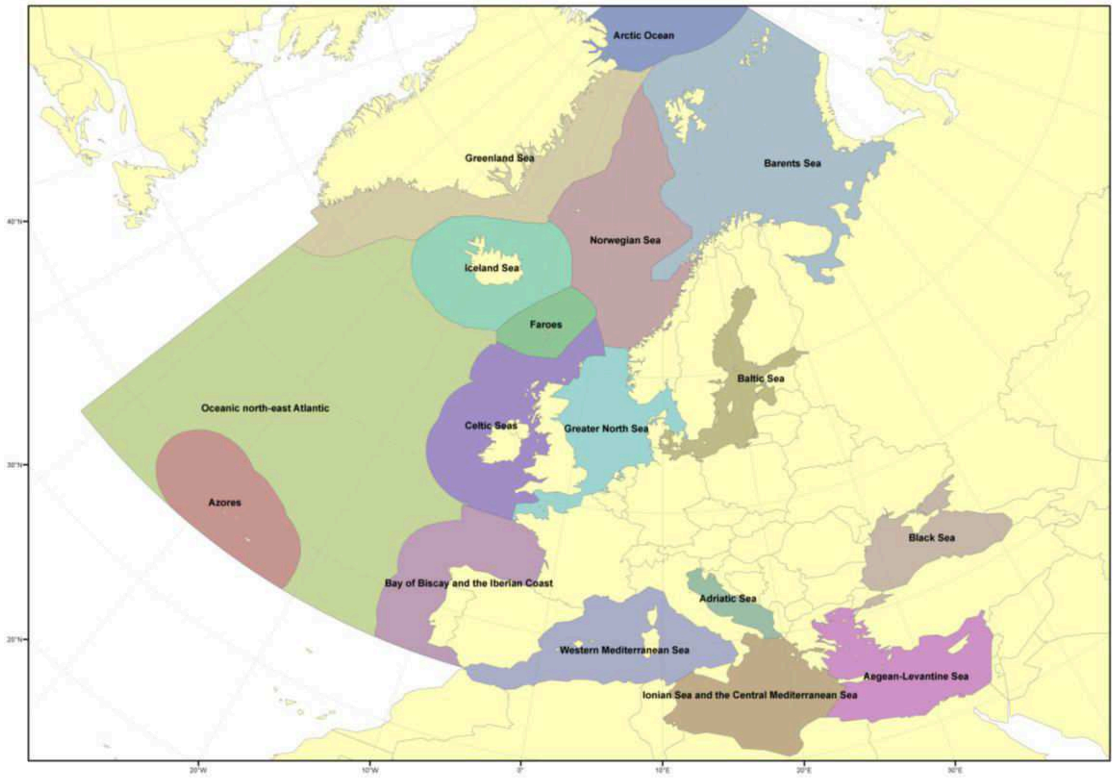


Figure 2-10: Updated version of ICES Ecoregions, introduced in 2015 (ICES 2016).

2.8.1 Principal currents

The main large-scale currents in the AOI are the North Atlantic Current (NAC), the Azores Current (AC) and the Canary Current (CaC) (Figure 2-11). These currents are associated with the eastern part of the anticyclonic North Atlantic sub-tropical gyres (Stramma 2001). A major portion of the NAC that heads northeastward becomes the North Atlantic Drift Current (NADC), while the rest continues eastward toward northern Europe.

The broad and slow, generally southward-flowing Portugal Current (PoC) enables the exchange between the NAC and the AC (Perez et al. 2001), which, along with the PoC that passes around Madeira, supplied the CaC eastward (Barton et al. 2001).

In summer, the CaC is stronger in the area of the African coast, while in winter the stronger part of the CaC is found west of the Canary Islands (the archipelago that lies at the transition zone between coastal and oceanic waters). The CaC is seasonally constant.

In the area of Iberian Peninsula (IP), there is a subsurface, density-driven poleward current. This current is found along the northwest European and northwest African shelf edges. It is called the Iberian Poleward Current (IPC).

In the Strait of Gibraltar, the dense and high-salinity Mediterranean Water (MW) passes below 1000-m in the Gulf of Cadiz. The MW current is characterised by its temperature signature that spreads as a tongue far into the North Atlantic. This current forms a poleward undercurrent that flows along the slope of the Iberian Peninsula.

The slope currents (red line on map in Figure 2-11) is thought to be generated by a topographic feature called the Joint Effect of Baroclinicity and Relief (JEBAR) (Huthnance, 1995; Hill *et al.*, 1998). The basic idea is that an offshore pressure gradient develops as a result of differences between shelf and oceanic meridional gradients in steric height (sea level contractions/expansions related to temperature), which drives a poleward along-slope flow; see Trowbridge *et al.* (1998) for a review of topographic effects in the coastal ocean.

The poleward flow is persistent and bound to the continental slope. In the 300 m deep area, the subsurface current (undercurrents) flows with speeds of about 0.1 m/s (Mason et al. 2005). At certain times, the location of the poleward flow extends upwards to the sea surface. This current is typical of eastern boundaries and upwelling systems. The upwelled water is often drawn from the poleward undercurrent. The poleward flows are typically in the areas more than 50 m deep, and so it could have some effects on the early life stages of pelagic fishes. Its direction is often against prevailing equatorward winds, indicating that this current is influenced by larger-scale, non-local forcing mechanisms or an offshore pressure gradient (sea level rising toward the coast). However, the current could be also a result of a region-specific local forcing such as buoyancy-driven coastal currents. For a complete review of poleward flows; see Neshyba et al. (1989).

There are also buoyancy-driven coastal currents, which are coastal currents resulting from the outflows of freshwater rivers. In the higher latitudes, these currents are narrower and more intense. The buoyancy-driven coastal currents may also be influenced by the wind and other forcing mechanisms, such as density. Upwelling-favourable winds tend to spread buoyant plumes offshore, while downwelling-favourable winds do the opposite. In the major river outflows, where the buoyant plumes are large and persistent, the plume acts potentially as a barrier to biological transfer across it.

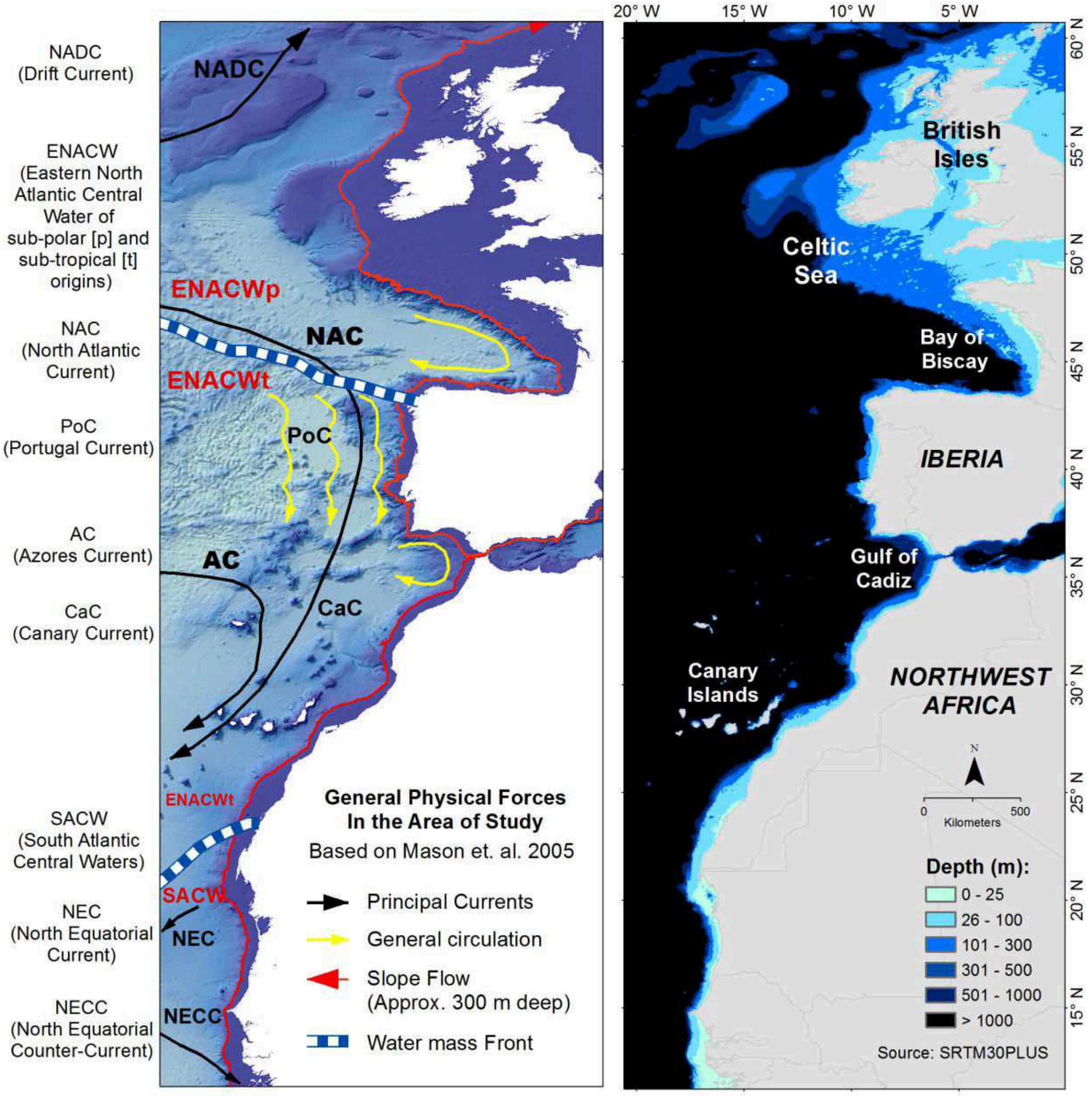


Figure 2-11: Principal currents in the study area. The North Atlantic Current (NAC), the Azores Current (AC), the Canary Current (CaC) and the Portugal Current (PoC) are the main large-scale surface currents in this area. The Eastern North Atlantic Central Water of sub-polar origin (ENACW$_P$), sub-tropical origin (ENACW$_T$), and the South Atlantic Central Water (SACW) are the principal water masses in the area. NADC is the North Atlantic Drift Current, while NEC and NECC are the North Equatorial Current and the North Equatorial Counter-Current respectively. The general circulation in the Bay of Biscay and the Gulf of Cadiz are indicated (Mason et al. 2005).

2.8.2 Water masses and the major frontal boundaries

There are two major zonally-orientated oceanic water masses fronts in the AOI (Mason et al. 2005): the high-salinity North Atlantic Central Water (NACW), dominated in the region above 600 m and, to the south, the less saline and richer in nutrients South Central Atlantic Water (SACW); see Figure 2-11. The NACW has considerable latitudinal variability: (1) between the Canary Islands and Iberia, there is the sub-tropical Eastern North Atlantic Central Water (ENACW$_T$) spreading generally eastward and flowing towards Iberia, (2) the ENACW$_p$ of sub-polar origin, which is cooler and fresher. The slightly warmer ENACW$_T$ is transported southward by the Canary Current

(CaC). Upwelling is present in these water mass boundaries, i.e., Cape Finisterre and Cape Blanco (see Mason et al. (2005) for further detail).

2.8.3 The coastal boundary layer

Shallow bottom and coastline irregularities slow the flows alongshore. These slow near-shore flows are typically along coastal boundaries. In the proximity of the solid coastal wall, the cross-shore flows are inhibited. The vertical circulation caused by wind-driven upwelling circulation or estuarine circulation could favor the presence of persistent cros-shore flows although the flows remain weak near-shore. These weak currents are associated with weak dispersion of propagules such as fish eggs and larvae, whose tendency for near-shore retention engenders what was called "sticky water" by Wolanski (1994). The scales and strengths at which the coastal boundary layer may be observed are variable. Further information about coastal boundary layer is detailed in Largier (2003).

2.8.4 Fronts

Fronts are narrow zones of enhanced gradients of water properties that separate water masses. Their dimensions range horizontally over from 100 m to 10000 km along-front or from 10 m to 100 km across-front, and vertically from 1 m to 1 km down-front. They persist from several hours to many years. The front areas are more biologically productive, due to the increase in nutrient and plankton concentrations, which may benefit the adult fish, larvae and eggs. Fronts are ubiquitous features of eastern ocean boundaries that act as barriers reducing the export of particles from coastal waters overlying the continental shelf (e.g., Bakun, 1996). Thus, they also act as potential barriers to planktonic dispersal and adult migration.

There is also another type of feature called a tidal mixing front, which is a surface-water temperature discontinuity that marks the transition from a tidally mixed to a vertically stratified water column. It occurs seasonally in relatively stationary positions in the Celtic Seas and the English Channel. The seasonal presence of tidal mixing front is considered to have less influence on fish stock structures than more permanent features (detailed is available in Mason et al. 2005).

In contrast to tidal mixing fronts, there is a shelf-break front that separates (usually fresher) shelf waters from slope and oceanic waters. It generally persists throughout the year but is likely to have a relatively low impact on (shelf-based) fish stock structures (detailed in Mason et al. 2005).

2.8.5 Internal waves

Internal waves that may occur in the Celtic Seas and off Western Iberia typically have much larger amplitudes and longer periods (10-20 minutes to several hours) than surface gravity waves (several seconds or minutes). Internal tides are internal waves with the same period as the tide. They transport energy and momentum which could be remotely available for mixing. When this energy enters shallower water or reaches the continental shelf, the denser, colder and richer in nutrients water within the wave rises and brings a biological impact (detailed is available in Ryan *et al.* 2005).

2.8.6 Eddies

An eddy is generated from water flows that travel along a curved or uneven coastline. Water recirculation within eddies can retain propagules over significant time scales, enhancing recruitment of non-local eggs and larvae. This time scales could be reduced by bottom friction and stronger current, but in the semi-enclosed bays, this retention remains significant (Largier, 2003). Thus, eddies can be seen as agents of dispersal as well as of retention. The spatial scales of eddies vary from 10 to 100 km. In the area of study, eddies could be found in the Bay of Biscay, off western Iberia, off northwest Africa and off the Canary Islands.

2.8.7 Upwelling

The characteristics of the world ocean vary because of numerous geological processes (Becker et al. 2009). On the seabed, the topographic features often play an important role in the formation of several physical phenomena, including upwellings and shadow zones. The presence of capes or promontories are often associated with intensified coastal upwellings, or with triggering instabilities in upwelling-related to coastal jets that lead to downstream shadow zones. The local circulation may be modified by the presence of offshore canyons that intersect the continental slope, producing enhanced upwelling. Therefore, these phenomena may have a strong link with the life cycles of various fish species for which retention of eggs and larvae are important (Mason et al. 2005). At a smaller spatial scale, habitat characteristics, such as seafloor type, strongly influence the species. Hattab et al. (2014) stated that models that do not account for species-habitat relationships may give unrealistic predictions.

A coastal upwelling (downwelling) occurs when equatorward (poleward) winds induce net offshore (onshore) surface Ekman transport, resulting in transport divergence (convergence) near the coast (Mason et al. 2005).

Upwelling and downwelling circulations redistribute not only heat and salt, but also nutrients and biological fields. Thus, they enhance primary production in the region concerned and futhermore affect high trophic levels through food chain-related processes. The biological impacts of upwelling and downwelling are discussed in Graham and Largier (1997) and Brink (1998).

One of the key features of a fully-developed upwelling situation is that the offshore surface layer is transported away from the coast. This phenomenon could be a source of dispersion as it brings along passive particles such as eggs and larvae. However, the persistent upwelling and consequent offshore advection could become a significant boundary for fish populations. The inshore side of the upwelling front which typically has low cross-shelf circulation may act as barrier, retaining propagules near to the coast.

Downwelling processes are essentially the same as for upwelling, except that the cross-shelf and alongshelf flows are reversed. Downelling favours the transport of propagules alongshore, although this, in terms of biological production, tends to be unfavourable.

The northern regions of the AOI are considered moderately productive ecosystems, while southern regions are considered highly productive ecosystem (Heileman and Tanstad 2008).

The Celtic Seas region is considered a Class II, moderately productive ecosystem (150-300 $gCm^{-2}yr^{-1}$) (Aquarone et al. 2008a). This region undergoes a seasonal climatic cycle which strongly affects the pelagic ecosystem through forcing factors. Many fish species in this region share their range of distribution with the North Sea and the South European Atlantic Shelf.

The South European Atlantic Shelf region is considered a Class II moderately productive ecosystem, driven by climate and upwelling (Aquarone et al. 2008b). This ecosystem is characterized by favorable conditions for the production of *clupeoids* and other small pelagic fishes. The ongoing warming in this area causes substantial restructuring of local ecosystems, with intensive fishing being the secondary driving force. Many species of northern ecosystem origin were found abundant in colder periods, while in warmer periods, the region is dominated by tropical fish species from the Canary Current or the Western Mediterranean Sea. Thus, this ecosystem is known as the transition zone between the north-eastern Atlantic cold waters and the eastern Atlantic warm waters (Teixeira et al. 2014).

The AOI encompasses climatic conditions from tropical to temperate.The near-surface circulation in the North and South Atlantic Oceans is primarily driven by the wind. Over the sub-tropical African coasts, the wind displays a predominantly equatorward component which is favourable to the upwelling.

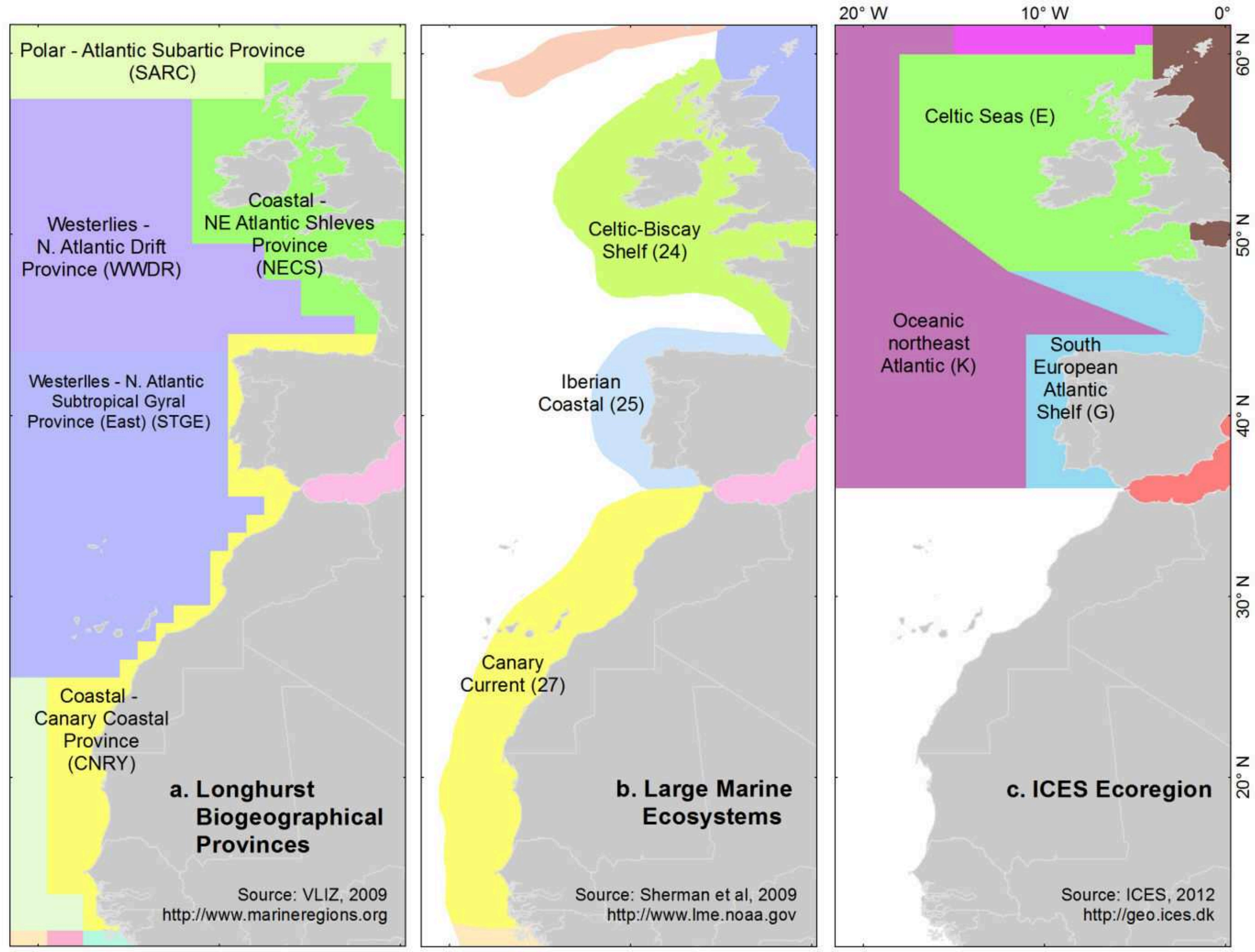
The Canary Current is a major upwelling region off the northwest coast of Africa, classified as a Class I, highly productive ecosystem (>300 $gCm^{-2}y^{-1}$) (Heileman and Tanstad 2008). The hydrographic conditions and climatic variability are the primary driving forces that influence the biomass changes and the small pelagic species distribution. Many endemic and migrant species inhabit this area, making the Canary Current a unique ecosystem of global significance. Many fish species in this region share their area of distribution with the Guinea Current in the south and with the Western Mediterranean Sea in the north. Several species from the Canary Current were also reported to be observed in the South European Atlantic Shelf when temperatures became suitable (Quero et al. 1997a; Bañón 2004).

3 MATERIALS AND METHODS

3.1 Area of Interest (AOI)

The Area of Interest (AOI) is a term used in this study referring to the study area. Delineation of the AOI is a first key step in this work, especially when performing region-based analysis or when selecting species occurrence records for number of species.

The limit of the AOI was drawn based on the boundaries of several ecosystems found in the area. There are, at least, three definitions of ecosystems used as basis in the AOI determination: Longhurst Provinces, Large Marine Ecosystems/LME and ICES' Ecoregions (Figure 3-1).


a. Longhurst Biogeographical Provinces

Source: VLIZ, 2009 http://www.marineregions.org

b. Large Marine Ecosystems

Source: Sherman et al, 2009 http://www.lme.noaa.gov

c. ICES Ecoregion

Source: ICES, 2012 http://geo.ices.dk

Figure 3-1: Three definitions of ecosystem used as basis in delimiting the area of interest (AOI): (a) Longhurst Provinces; (b) Large Marine Ecosystems/LME; and (c) ICES' Eco-regions.

3.1.1 Longhurst biogeographical provinces

Longhurst biogeographical provinces were developed at the Bedford Institute of Oceanography, Canada, by A.R. Longhurst, based on the role played by the physical forcing that regulate the distribution of phytoplankton around the world (Figure 3-1a).

Figure 3-1a presents the fixed boundaries of Longhurst's Provinces. In the AOI, there are two main biological provinces: the Canary Coastal Province and the Northeast Atlantic Shelves Province. However, these boundaries are dynamic and move under seasonal and inter-annual changes in physical forcing.

3.1.2 Large Marine Ecosystems (LME)

The limits of the Large Marine Ecosystems (LME) were defined by Sherman and Hempel (2009), based on the distribution and trends of several trophic components, such as phytoplankton, zooplankton, fish and shellfish, as well as political and economic boundaries, oceanic currents, and bathymetric gradients. According to this definition, there are three Large Marine Ecosystems (LMEs) that lie in the AOI (Figure 3-1b): the Canary Current/LME#27, the Iberian coastal/LME#25 and the Celtic-Biscay Shelf/LME#24.

3.1.3 ICES eco-regions

ICES or the International Council for the Exploration of the Sea or *Le Conseil International pour l'Exploration de la Mer* (CIEM) is a global organization of 20 member countries whose objective is to increase the scientific knowledge of the marine environment and its living resources.

In 2004, ICES divided the European waters into 13 ecoregions of which two ecoregions lie in the area of interest (Figure 3-1c): the Celtic Seas/E and the South European Antlantic Shelf/G. In 2015, ICES presents new ecoregions by modifying, adding or dividing the old ecoregions into 17 ecoregions for which a map is available at *http://geo.ices.dk/documents/ICES_ecoregions_20150113.png*. In this study, we still used the ecoregions version 2004 because the new ICES Ecoregions were only available in 2015 when the process of this study had entered its last stage.

3.1.4 Shorelines: GSHHG versus ESRI

There are two types of shoreline available that can be used as boundaries for the landside of the AOI: The GSHHS/*Global Self-consistent, Hierarchical, High-resolution Shoreline* and the ESRI's Shoreline.

The GSHHS dataset was produced by the National Oceanic and Atmospheric Administration (NOAA) from two well-known public domain datasets: The World Data Bank II (which contains coastlines, lakes, political boundaries and rivers) and the World Vector Shoreline (WVS) which only contains shorelines along the ocean/land interface (Wessel and Smith 1996).

The ESRI shoreline was derived from ESRI world countries dataset, which can be used at both large and small scales. Originally, this dataset was designed to be used as base map.

A small studies of shoreline comparison between GSHHG's and ESRI's revealed that the shorelines provided by ESRI showed more consistency at several sites tested comparing than that of the GSHHG (Figure 3-2). The accuracy and the consistency of shorelines play an important role when selecting species occurrence records or conducting ecosystem-based analysis. Thus, in this study, we selected the ESRI shoreline to perform the two processes above.

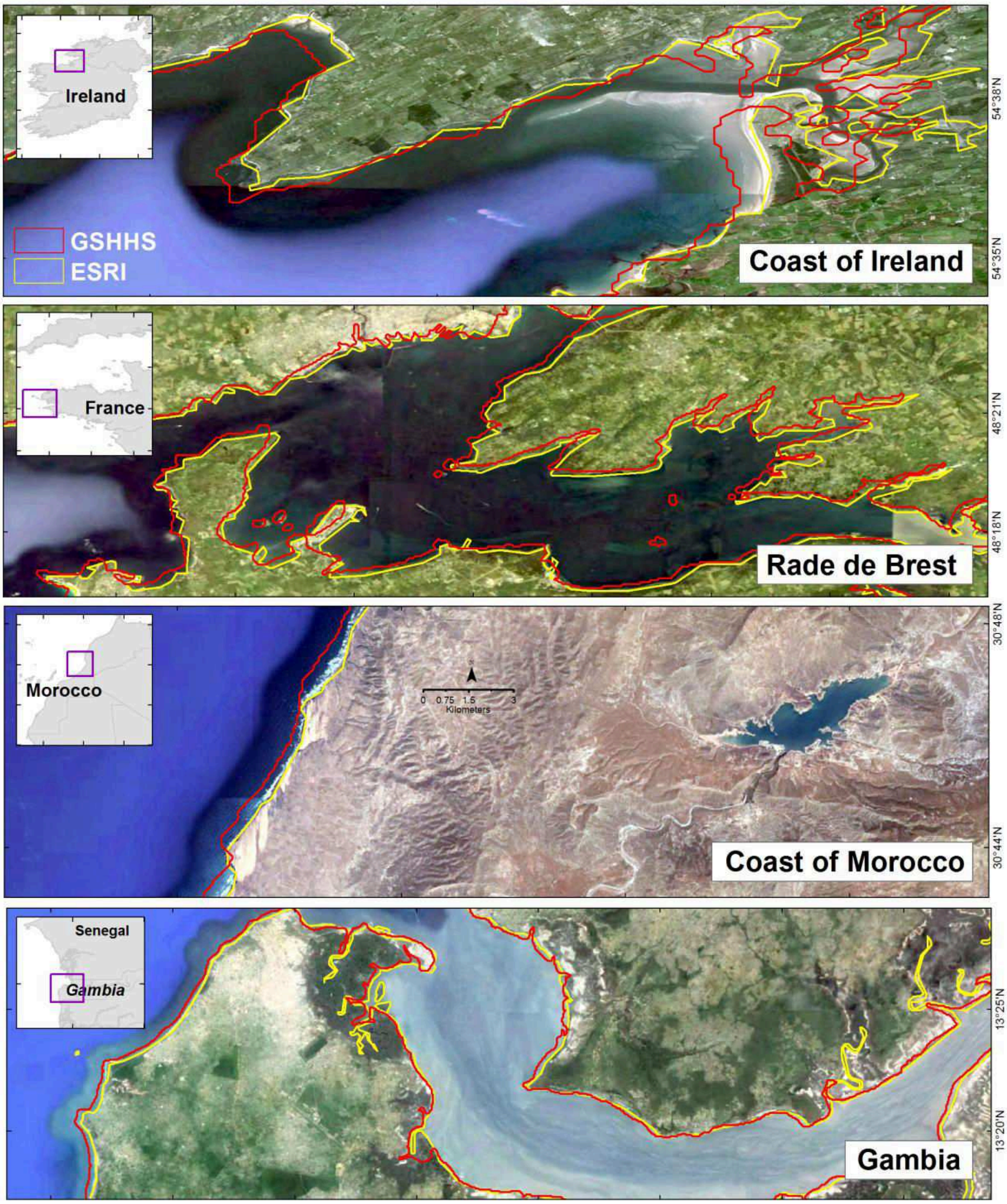


Figure 3-2: GSHHG's shorelines (red lines) versus ESRI's shorelines (yellow lines).

3.1.5 Delimiting boundaries of the AOI

The boundaries of the AOI were constructed from several ecosystems/ecoregions defined by different sources, as described above (Figure 3-3). The southernmost boundary of the AOI was taken from the southern limit of the Coastal-Canary Province defined by Longhurst. The southern part of the AOI was determined using the the LME Canary Current defined by Sherman and Hempel (2009), while the northern part of the AOI in the European waters was taken from two ICES' Ecoregions: the South European Atlantic Shelf/G and the Celtic Seas/E.

In terms of shorelines, many studies, i.e., Elizabeth and Paul (2013) in their project of MARSPEC, used shorelines from GSHHS. In this study, we selected the shorelines from ESRI to limit the AOI, for its higher accuracy and consistency, especially when delineating the land-side in the area of estuaries.

The process of delimiting the AOI is a spatial georeferenced polygon editing process (Figure 3-3). Files of ecosystems/ecoregions mentioned above were obtained in the form of polygon shapefiles. These shapefiles were downloaded through a portal of Marine Regions (http://marineregions.org) except for shorelines shapefiles. The shapefiles of GSHHS were obtained from NOAA National geophysical Data Center (http://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html), while the shapefiles of ESRI shorelines were downloaded from the ESRI website:

http://www.arcgis.com/home/item.html?id=3864c63872d84aec91933618e3815dd2.

Every step of polygon editing, combining or merging was conducted using both *ArcGIS 10.1* and *QGIS 2.0.1* software. ArcGIS has advantages when working with shapefiles and raster data, while QGIS was used when working with table data.

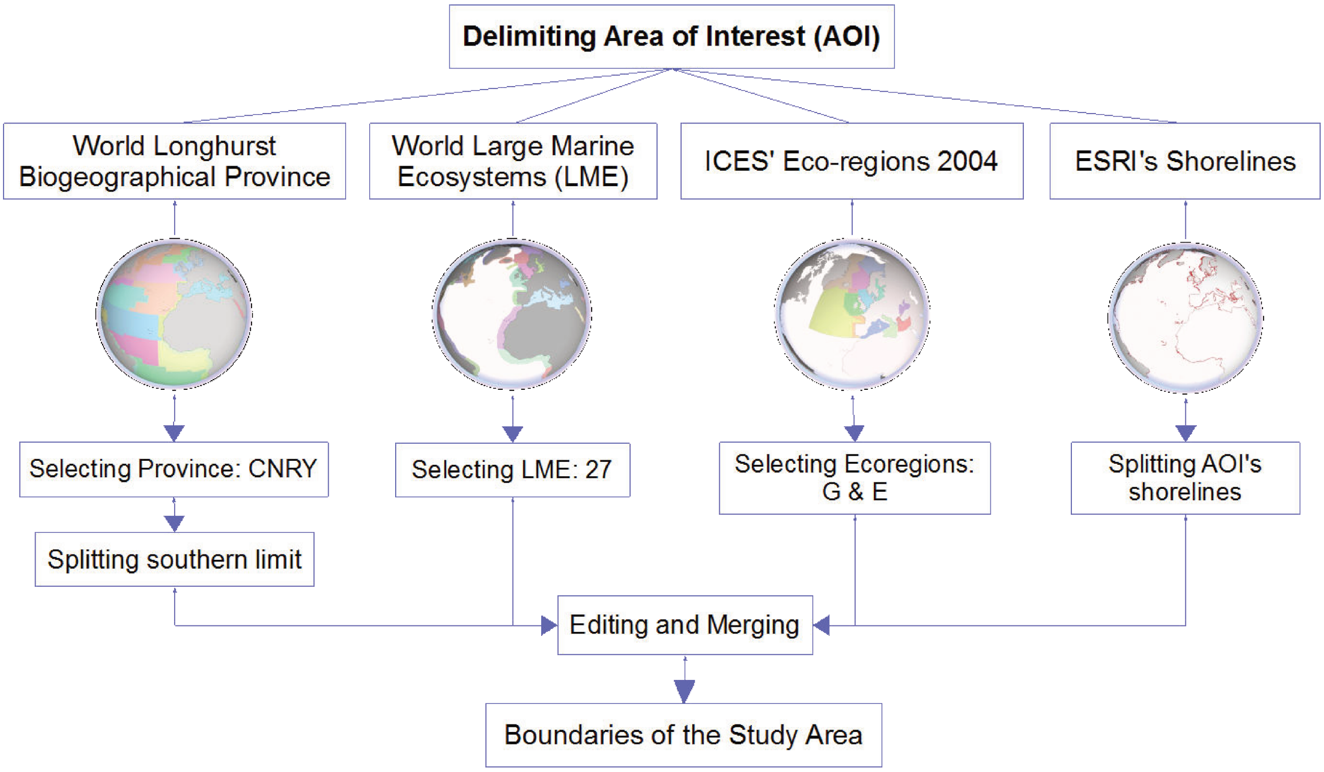


Figure 3-3: Short flowchart presenting process of delimiting the Area of Interest (AOI).

Figure 3-3 presents the flowchart of AOI boundaries delineation. The Canary Coastal Province (Code: CNRY) was separated from the world Loghurst Biogeographical Provinces. The southernmost limit of this province was cut using the splitting tool of ArcGIS software. This southern limit was then determined to be the southernmost limit of the AOI.

The LME Canary Current polygon (ID Number: 27) was selected and separated from other ecosystems in a new polygon shapefile. The southern limit of this LME was removed using the split tool and modified, with the southernmost limit of the Canary Coastal Province, to form the southern part of the AOI in the West African waters.

Two ecoregions from ICES, the South European Atlantic Shelf (G) and the Celtic Seas (E) were separated from other European ICES'-Ecoregions by selecting the polygons of the two ecoregions and save into a new polygon shapefiles to form the northern part of the AOI in the European waters.

The shorelines from ESRI in the AOI were cut using the split tool from ArcGIS software and then merged and connected with the ecosystems in the southern and northern part of the AOI to form complete boundaries of the study area (AOI).

3.2 Environmental conditions

This subchapter provides information on incorporation of marine data to GIS (geographic information system) which were furthermore used to identify areas of high biodiversity or species potential habitats through species distribution modelling.

3.2.1 Bathymetry and its derivatives

The bathymetric data we used in this study came from the SRTM30_PLUS V9.0 dataset, a 30 arc-second digital elevation model of global elevation and seafloor topography, available online at *http://topex.ucsd.edu/WWW_html/srtm30_plus.html*. The 30 arc-second grid spacing equates to approximately 1 kilometer at the equator and decreases in the East/West (longitudinal) direction as latitude increases (NOAA/NGDC 2013). Thus, the calculation of area or distance across a group of cells should take into account the difference between resolution and pixel or grid cell size.

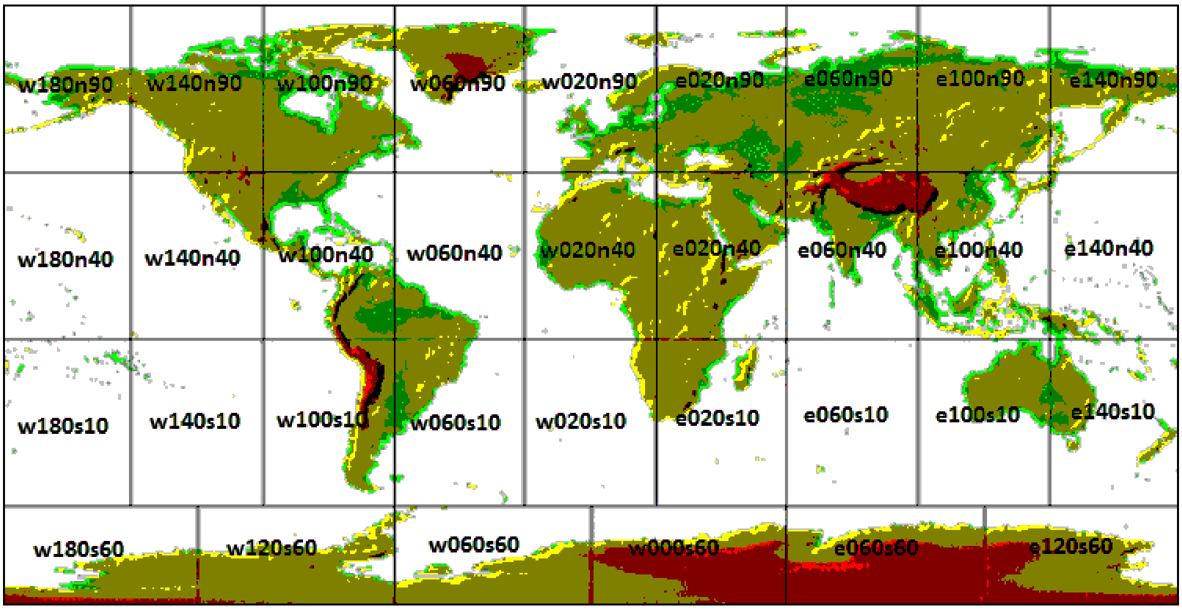


Figure 3-4: SRTM30PLUS data coverage with tiles and filenames. Area of interest lies on four tiles: w020n40, w020n90, w060n40 and w060n90.

The SRTM30PLUS data consists of: (1) land and ice topography coming from the SRTM30 and ICESat topography; and (2) ocean bathymetry based on a new satellite-gravity model where the gravity–to-topography ratio was calibrated using 298 million edited soundings (Becker et al. 2009). In the structure of SRTM file, the AOI lies on four tiles: named w020n40, w020n90, w060n40 and w060n90 (Figure 3-5).

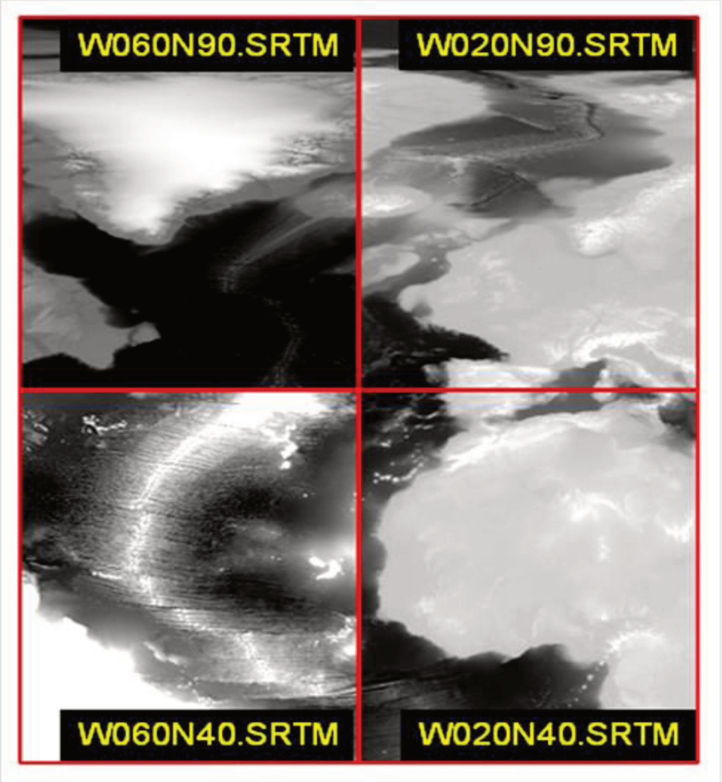


Figure 3-5: SRTM30PLUS data tiles that cover the AOI.

3.2.1.1 Depth and Hillshade

The SRTM30PLUS dataset as *.srtm formatted file, was converted into a common GIS format (GeoTiff) of a *32_bit_float Tiff file* (a 32-bit data type supports decimals). The format conversion was conducted to facilitate data exploitation when working with various spatial data from different sources. The raster original scale was kept at 0.00833. This scale was also used in this study as reference scale for other raster data. The four tiles of the SRTM30PLUS dataset that covered the AOI were combined into a single file. Land topography values were removed by changing the raster values greater than zero into NULL or no-data. The AOI extraction process was then conducted using the following geographic limit: 11°0’0” N to 61°0’00” N and 0°0’00” W to 21°0’00” W. Other areas beyond these limits or outside the AOI were excluded, thus, reducing the size of the file and accelerating the process of future analysis (Figure 3-6a). A flowchart describing the environmental bathymetric data preprocessing is presented in Figure 3-7.

Hillshade is a grayscale 3D model of the surface which brings 3D visualization into a DEM raster data (Figure 3-6b). It takes into account the shading of the image by using the altitude and azimuth properties to specify the sun’s position. The hillshade map was obtained using the Hillshade tool of the ArcGIS^{TM} Spatial Analyst extension. Further explication on how the hillshade function works is available at ESRI (2011).

Structures were not derived in this study because we have no sufficient information, such as information from direct observation using underwater camera data. Theoretically, in structures habitat classification, the depth variable was added to identify different flat structures that may represent different habitats such as: (1) Narrow depression, (2) Local depression on flat, (3) Lateral mid-slope depression, (4) Depression on crest, (5) Broad depression with an open bottom, (6) Broad flat, (7) Shelf, (8) Open slopes, (9) Local crest in depression, (10) Local crest on flat, (11) Lateral mid-slope crest, (12) Narrow crest, and (13) Steep slope (Lundblad et al. 2006).

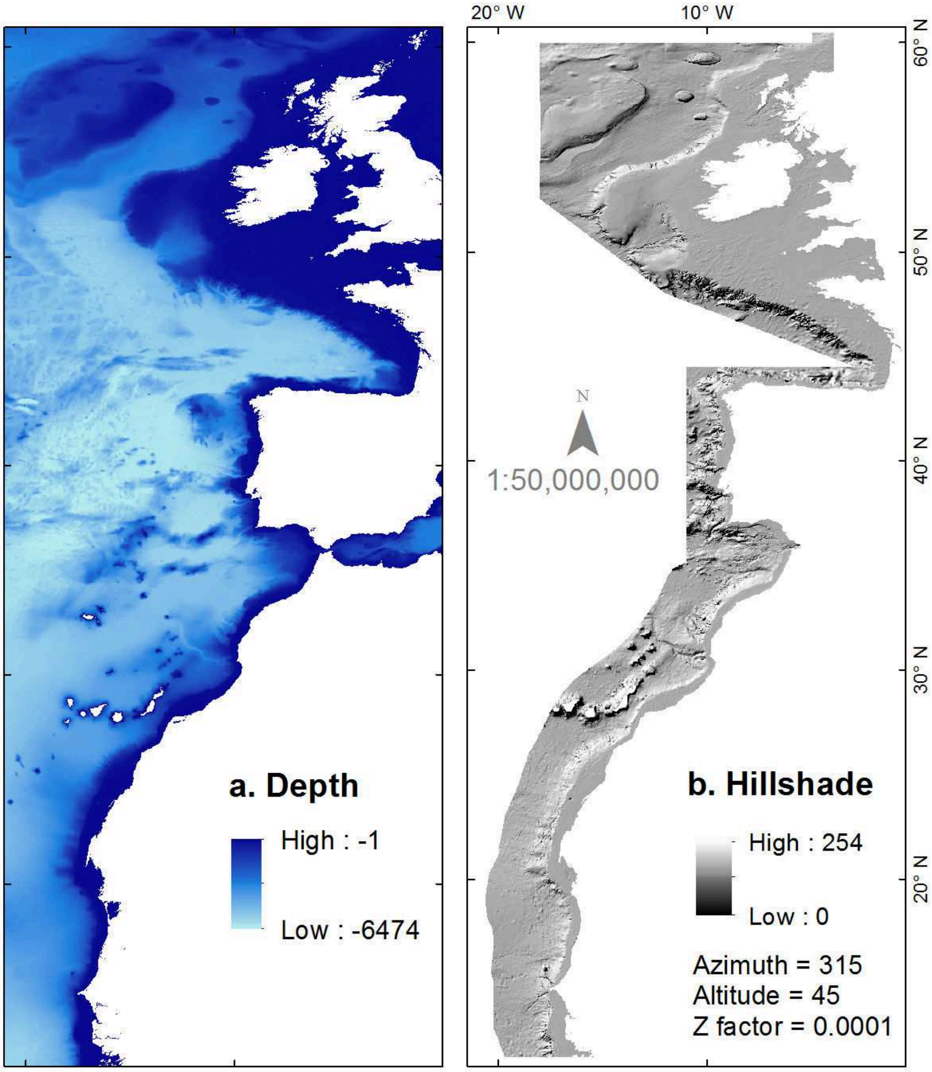


Figure 3-6: (a) Depth and (b) Hillshade in the AOI.

Working in larger and deeper areas requires a technique for mapping potential habitat. Derivative bathymetry data we used in this study are depth, slope, terrain ruggedness or rugosity and Bathymetric Position Index (BPI). An other bathymetry derivative that could be used as complementary information is Aspect of the slope direction. Using the BPI dataset and other bathymetric derivative, we produced a map of benthic zones. It is a simple classification of the sea floor. These derivatives could help in locating and associating resources with particular terrains.

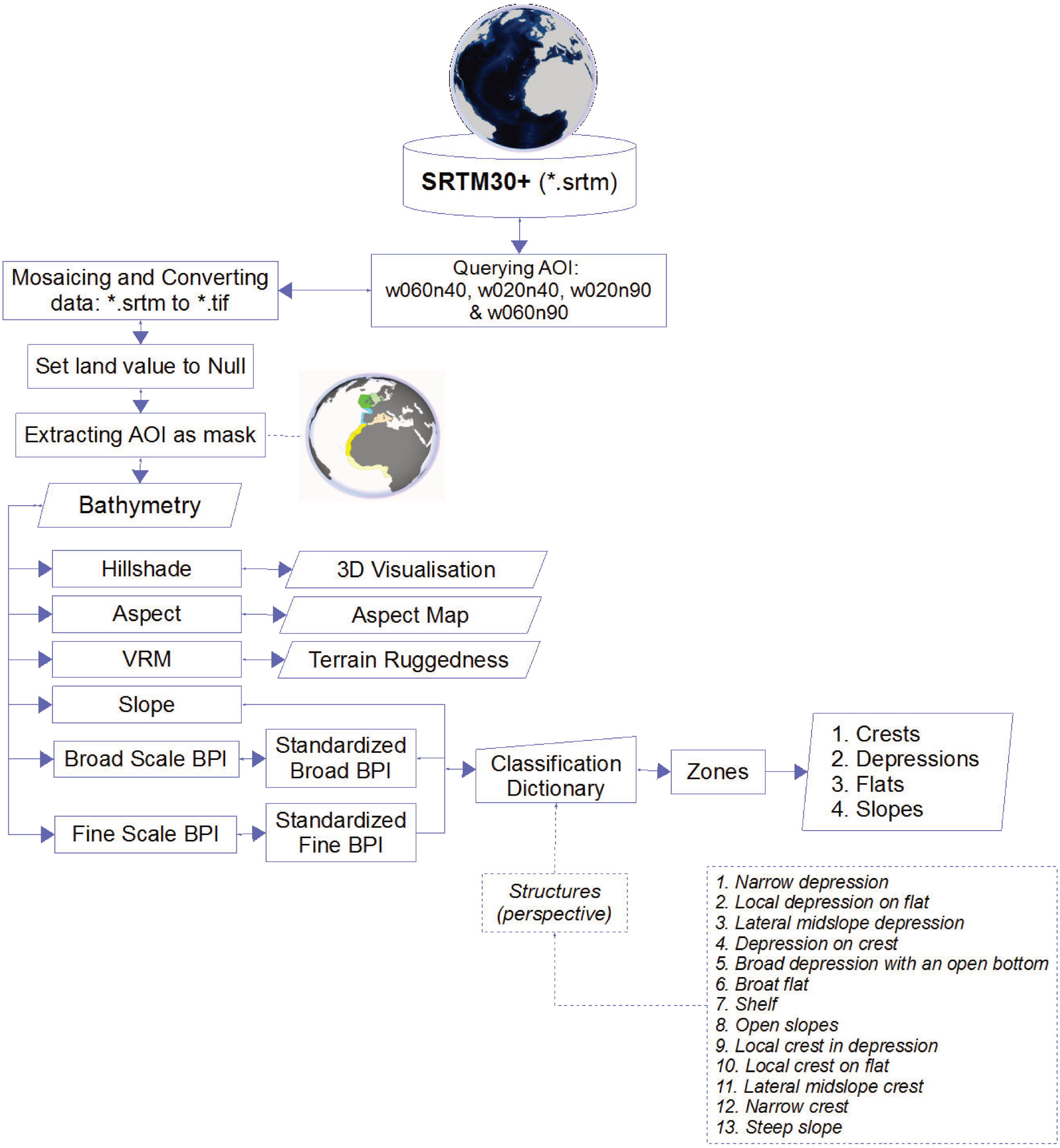


Figure 3-7: A flowchart showing the datasets used to derive benthic zones.

3.2.1.2 Slope and Aspect

Slope is the first derivative of a digital elevation model (DEM). It measures the steepness or rate of change of elevation for each DEM cell (Lundblad et al. 2006). We used the ArcGIS^{TM} slope tool with a Z-value of 0.0001 to derive slope from bathymetry data. The tool calculates the maximum rate of change between each cell and its eight sourrounding cells. Detail on the mathematic calculations producing slope data is available on (ESRI 2012a).

Aspect can be considered as the slope direction, which is the maximum rate of change in value from each cell to its neighbours, and its value represents the compass direction of the slope in degree (ESRI 2012b).

3.2.1.3 Terrain ruggedness (VRM)

Terrain ruggedness is the measurement of the roughness of the surface of the ocean floor. It is variously defined as topographically uneven, broken or rocky and steep (Sappington et al. 2007). The terrain ruggedness of the benthic environment can be useful to indentify areas with potential high biodiversity, where “roughness” may be an effective proxy for species habitat (Wright 2011; Wright et al. 2013).

There are at least three widely recognized methods for quantifying terrain ruggedness. They are Land Surface Ruggedness Index (LSRI), Terrain Ruggedness Index (TRI) and Vector Ruggedness Measure (VRM). The first two methods are strongly correlated with slope and do not directly measure the variability in topographic aspect and gradient (Sappington et al. 2007). Hence, in this study, we used the VRM method to produce terrain ruggedness maps derived from bathymetry data. Detailed information on VRM technique can be found in Sappington et al. (2007).

Output ruggedness values range from 0 (no terrain variation) to 1 (complete terrain variation). Typical values for natural terrains range between 0 and about 0.4. These values are unit-less and not directly comparable between study sites (Wright et al. 2013). The script for calculation VRM, originally created by Mark Sappington, was adapted for ArcGIS v10 by the Massachusetts Office of Coastal Zone Management.

3.2.1.4 Bathymetric Position Index

The Bathymetric Position Index (BPI) is a measure of elevation of a geo-referenced location relative to its surrounding location. It evaluates the differences between a focal point and the mean elevation of the surrounding cells within a user-defined rectangle, annulus, or circle (Lundblad et al. 2006). BPI is actually a modification of the Topographic Position Index (TPI) algorithm used in the terrestrial environment. Weiss (2001), during his study of terrestrial watersheds in Central Oregon, developed a terrain classification using TPI algorithm. Using the same principle, this application can be carried into the benthic environment (Wright et al. 2013).

The BPI dataset was created from an input bathymetric dataset by applying an algorithm that utilizes a focal or neighborhood function. Neighborhood functions produce an output raster in which the output cell value at each location is a function of the input cell value and the values of the cells in a specified "neighborhood" surrounding that location (Wright et al. 2013). The resulting grid values are converted to integers to minimize the storage size of the grid and to simplify symbolization (Lundblad et al. 2006).

Algorithm of an output BPI dataset in the form of ArcGIS’s formula modified from Lundblad et al. (2006):

BPI = Int((inputRasterBathymetry – FocalStatistics(inputRasterBathymetry, neighborhoodBPI, “MEAN”, “”)) + 0.5)

Where,

Int : Integer (a function in ArcGIS^{TM} to set result as integer)
Neighborhood : NbrAnnulus (innerRadiusBPI, outerRadiusBPI, “CELL”)
InnerRadius for Broad BPI : 10
OuterRadius for Broad BPI : 50
InnerRadius for Fine BPI : 1

The 0.5 is added before the integer conversion to force floating point values and to round up if the value has a decimal greater than 0.5 and to round down if the value has a decimal of less than 0.5. The variable is not necessary if a user chooses to allow the floating point values to be rounded downward consistently for positive and negative values (Lundblad et al. 2006).

An elevation grid data that has a 1 meter resolution may be analyzed with an annulus. The annulus, having an inner radius of 2 units and an outer radius of 4 units (for instance), would be used to spatially analyze each grid cell in comparison to its neighboring cells that fall within that annulus (Lundblad et al. 2006); see Figure 3-8. The scale factor of the resulting grid is 4, where scale factor is the resolution multiplied by the outer radius".

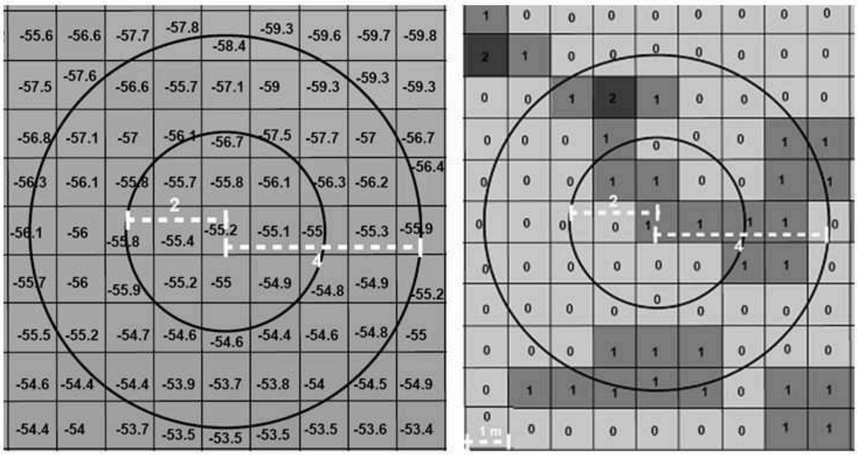


Figure 3-8: Example of the variables used to derive bathymetric position index (BPI) from bathymetry. Left: The grid cells here (1 m resolution) represent bathymetry as negative values. The annulus has an outer radius of 4 and an inner radius of 2. Therefore the BPI scale factor is 4 as a result of multiplication of outer radius with bathymetry resolution. Right: The grid cells represent a derived BPI grid. Negative values are lower than their neighbors. Positive values are higher than their neighbors. Values of zero are flat areas or areas with constant slope (Lundblad et al. 2006).

In the example given by Lundblad et al. (2006): "the cells with a value of 1 are higher than those with the value of 0, and those with values of 2 are higher than the others. The diagonally linear pattern of cells with the value of 1 starting from the top, left corner of the grid may represent a crest in the benthoscape. Furthermore, the grid cells with values of 2 along that pattern may be narrow crests on top of the larger crest. Also, the other groups of BPI values of 1 may represent small mounts within the benthoscape. The values of 0 are all flat areas and/or constant slopes. Whether they are flats or slopes would be determined by another algorithm that considers slope along with BPI. This example does not include negative BPI values. If negative values were present in this grid sample, they would represent patterns of depressions.

The cells in the output grid of BPI are assigned values within a range of positive and negative numbers. Positive cell values within a BPI dataset denote features and regions that are higher than the surrounding areas. Therefore, areas of positive values generally characterize ridges and other associated features within the benthic terrain. Likewise, negative cell values within a BPI dataset denote features and regions that are lower than the surrounding areas. Areas of negative cell values generally characterize valleys and other associated features within a bathymetric dataset. BPI values near zero are either flat areas (where the slope is near zero) or areas of constant slope (where the slope of the point is significantly greater than zero); see Figure 3-9 (Weiss 2001). Larger numbers represent benthic features that differ greatly from surrounding areas, such as sharp peaks, pits or valleys (Lundblad et al. 2006).

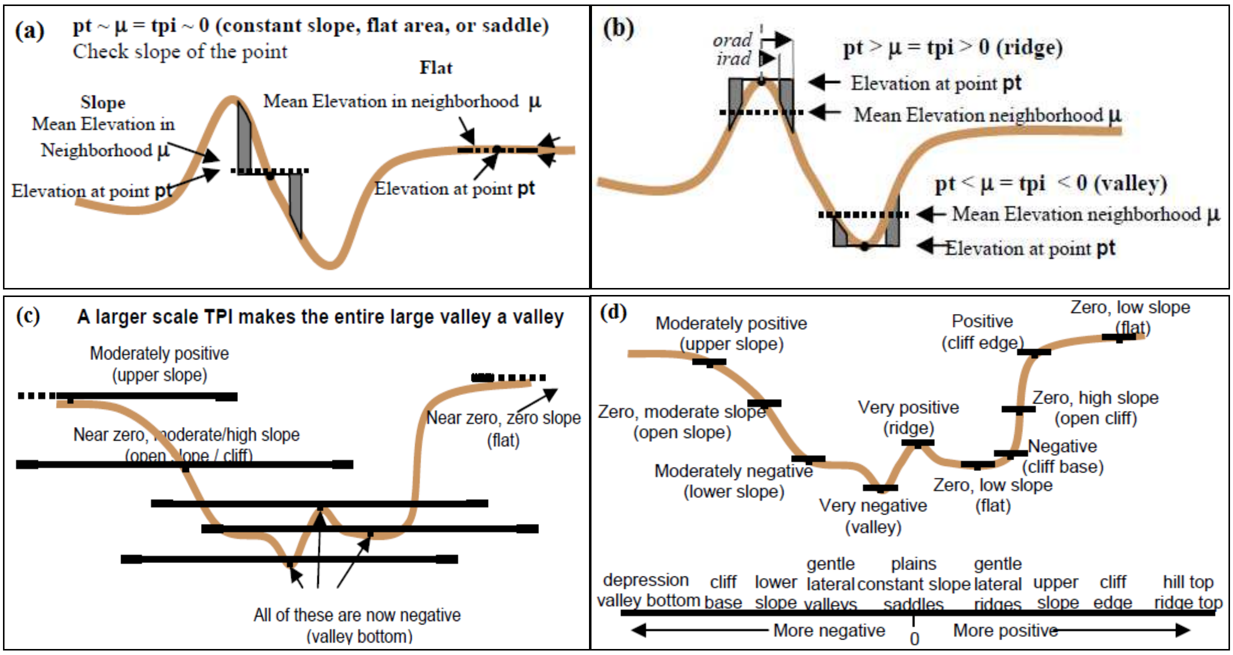


Figure 3-9: Topographic Position Index (TPI) technique used in Bathymetric Position Index (BPI). (a) Areas where the BPI value is near or equal to zero. The slope of the terrain at the given point is used to determine the bathymetric position; (b) Positive and negative BPI value derivation for ridges and valleys; for (c) fine scale BPI values and (d) broad scale BPI values (Weiss 2001).

Broad BPI and Fine BPI

Bathymetric position is an inherently scale-dependent phenomenon (Weiss 2001). Two different scale factors of two BPI datasets are created during the benthic terrain classification process. Broad scale BPI datasets with larger analysis neighborhoods (thus, with a larger scale factor) and fine scale BPI datasets which have smaller analysis neighborhoods (thus, with a smaller scale factor). Broad BPI datasets are useful in identifying larger benthic terrain regions, while fine scale BPI dataset are created for identifying smaller benthic terrain features.

Standardizing BPI Grids

Weiss (2001) suggested that bathymetric data tends to be spatially autocorrelated (i.e., locations that are closer together are more related than locations that are farther apart). Therefore, the range of BPI values increases with scale, whereas broad (small) scale BPI datasets that use a larger analysis neighborhood would have smaller BPI values and furthermore affect the averaging small variations in the terrain. Fine (large) scale BPI datasets uses smaller neighborhood that would have larger BPI values. The Fine scale BPI will be furthermore used in the detection of smaller localized variations in the terrain. Standardization of the raw BPI values is then needed to allow the classification of BPI datasets at almost any scale.

Standardized output dataset used the following algorithm. This algorithm was performed using Raster Calculator tools in ArcGIS$^{\text{TM}}$ software:

$$\mathit{BPI{<}scalefactor{>}\_std} = \mathit{int}((((\mathit{BPI{<}scalefactor{>}} - \mathit{mean}) / \mathit{std\ dev}) * 100) + 0.05)$$

Where:

Scalefactor	: Outer radius in map units * input bathymetric dataset resolution (cell size).
Mean	: Mean cell value across BPI dataset.
Std dev	: Standard deviation of cell values across BPI dataset.

3.2.1.5 Benthic zone classification

The method presented in this subchapter explains how the use of shallow water classification scheme in larger and deeper areas allows producing benthic zone maps from several bathymetric derivative data. Benthic terrain classification may lead to efficient management, such as in marine protected areas.

In this study, we used available bathymetric data to delineate potential benthic habitats within coastal regions down to areas more than 200 m deep, using a habitat classification scheme that has been successfully used to classify habitats in much of the shallow water regions around the coast of the U.S.A. The work described here is a first step in meeting objectives for fish species distribution modelling in the ecosystems. This approach can then be used to relate topographic features with populations of particular species and other environmental studies.

Seafloor classification maps were generated from bathymetry maps and standardized broad and fine bathymetric position index (BPI), as presented in Figure 3-10.

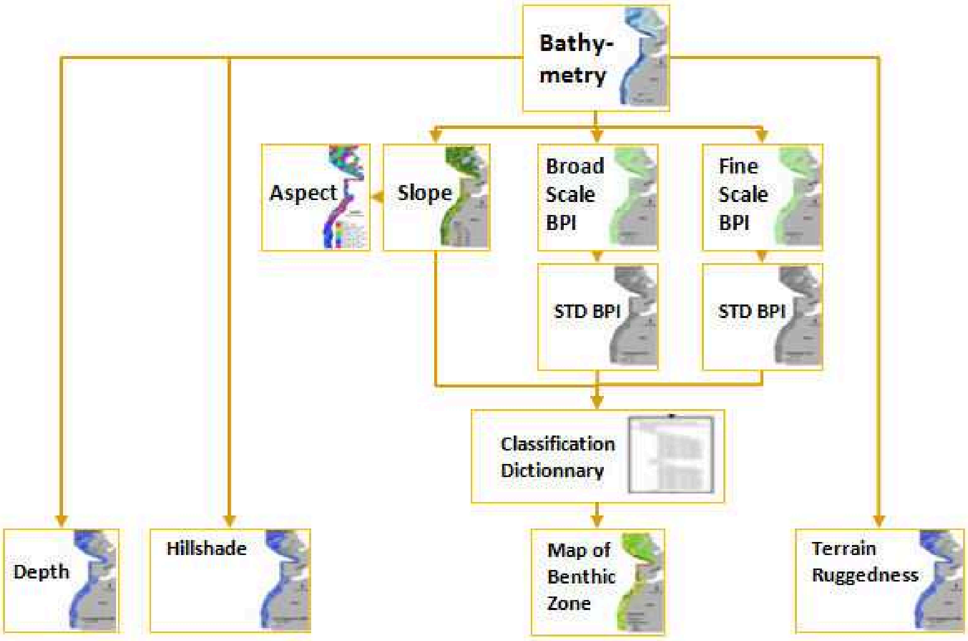


Figure 3-10: A flowchart showing the datasets of bathymetric data and derivative produced in this study.

To produce a benthic zones map, we used four simple benthic classification zones: crest, depression, flat, and slope areas. This is is a single common classification scheme. Each zone was converted into a categorical value of 1 (crest or the high points in the terrain), 2 (depression or the low points in the terrain), 3 (flat or the flat points in the terrain with slope values below 5°), and 4 (slope or the sloping points in the terrain with slope values higher than 5°). Further details about benthic zone classification can be found in Lundblad et al. (2006). Using the same method of classification that was used for American Samoa seafloor by Lundblad et al. (2006), the seafloor maps were produced for the study area.

The algorithm that combines the bathymetric datasets used standard deviation units, where 1 standard deviation is 100 grid value units. The following is an example of how BPI zones were derived (Lundblad et al. 2006).

Combining attribute of BPI zones and slope, the following algorithm create a classified output grid:

```
If (B-BPI >= 100) out_zones = 1
Else if (B-BPI >= -100) out_zone = 2
Else if (B-BPI>-100 and B-BPI>100 and slope <= gentle) out_zone = 3
Else if (B-BPI>-100 and B-BPI <100 and slope>gentle) out_zone = 4
End if
```

Where:

B-BPI : Broad scale BPI grid.

Out_zones : Name of the output grid.

- Crest (1): High points in the terrain where positive BPI values are greater than one standard deviation from the mean in the positive direction.
- Depression (2): Low points in the terrain where nevative BPI values are greater than one standard deviation from the mean in the negative directions.
- Flats (3): Flat points in the terrain where near zero BPI values are within one standard deviation of the mean and the slope values are less than 5°.
- Slopes (4): Sloping points in the terrain where near zero BPI values are within one standard deviation of the mean and the slope values are greater than 5°.

Slope : Slope grid derived from bathymetry.

Gentle : User-defined slope value indicating a gentle slope.

Specific values for slope and depth are sensitive to interpretation at specific study sites. Each study site has a unique composition of depth and slope ranges. This study defined gentle slopes at 5°. Steep slopes were defined at 70° as referenced from Lundblad et al. (2006).

Weiss's (2001) landform scheme is also valuable, as it classifies slope position and landform types as predictors of habitat suitability, community composition, and species distribution. In this study, similar landform classes are interpreted only to describe the seafloor and as a baseline for future habitat studies, given the availability of future data on species counts and distributions. The terminology used in the classification scheme (for zones) presented here is well-matched with the NOAA/NOS Biogeography Program's scheme for shallow water classifications (NWHI 2003). This biogeography scheme is being extended into deeper water by scientists at CRED, who are working primarily with multibeam and underwater video data in 20-200 m water depths.

3.2.1.6 Calculating benthic zone surface area

The surface area of each benthic zone was calculated using a script written in *Python programming language*. The processes were conducted as follow:

- Preparing a raster of benthic zones. The raster of benthic zones has several values that range from 1 to 4, representing each type of benthic zone.
  1 = Crest.
  2 = Depression.
  3 = Flat.
  4 = Slope.
- Separating the raster into four different rasters based on their value (raster of crest, depression, flat, and raster of slope). This process was conducted using the *Copy Raster Tool* available in *ArcGIS*^{TM} software. The tool copied the raster by keeping only one value/zone specified and made the other values into null (deleting any other value); see Figure 3-11.

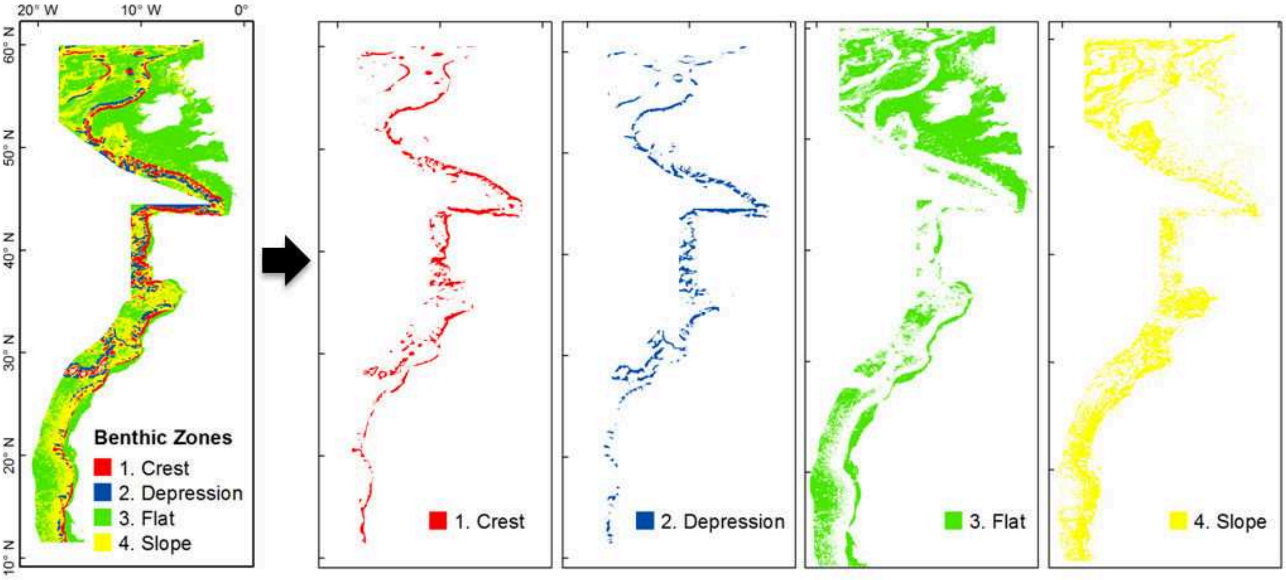


Figure 3-11: Benthic Zones.

- Converting raster class to polygon shapefile. The raster of each benthic zone needs to be converted into a polygon feature of shapefile before calculating its surface area.
- The shapefile of each benthic zone was separated by ecosystem to perform calculation by ecosystem. The process of dissolving polygon attribute was conducted before separating polygons by ecosystem boundaries using clip tool.
- Re-projecting the polygon coordinate system to UTM (Universal Transverse Mercator), in order to compute geometry. To facilitate the re-projection process, we performed a clip by polygon feature using a shapefile of ESRI World UTM zones downloadable at http://www.arcgis.com/home/item.html?id=715d4d6a36cc4b019bd84cb34ce37647 (Figure 3-12a). The world UTM zone shapefile was cut using the polygon of each benthic zone. The results were polygons of benthic zones completed with attribute of UTM zones (Figure 3-12b).
- Computing the surface area of each projected benthic zone polygon in kilometer square using Geometry calculation tool (Figure 3-12c).

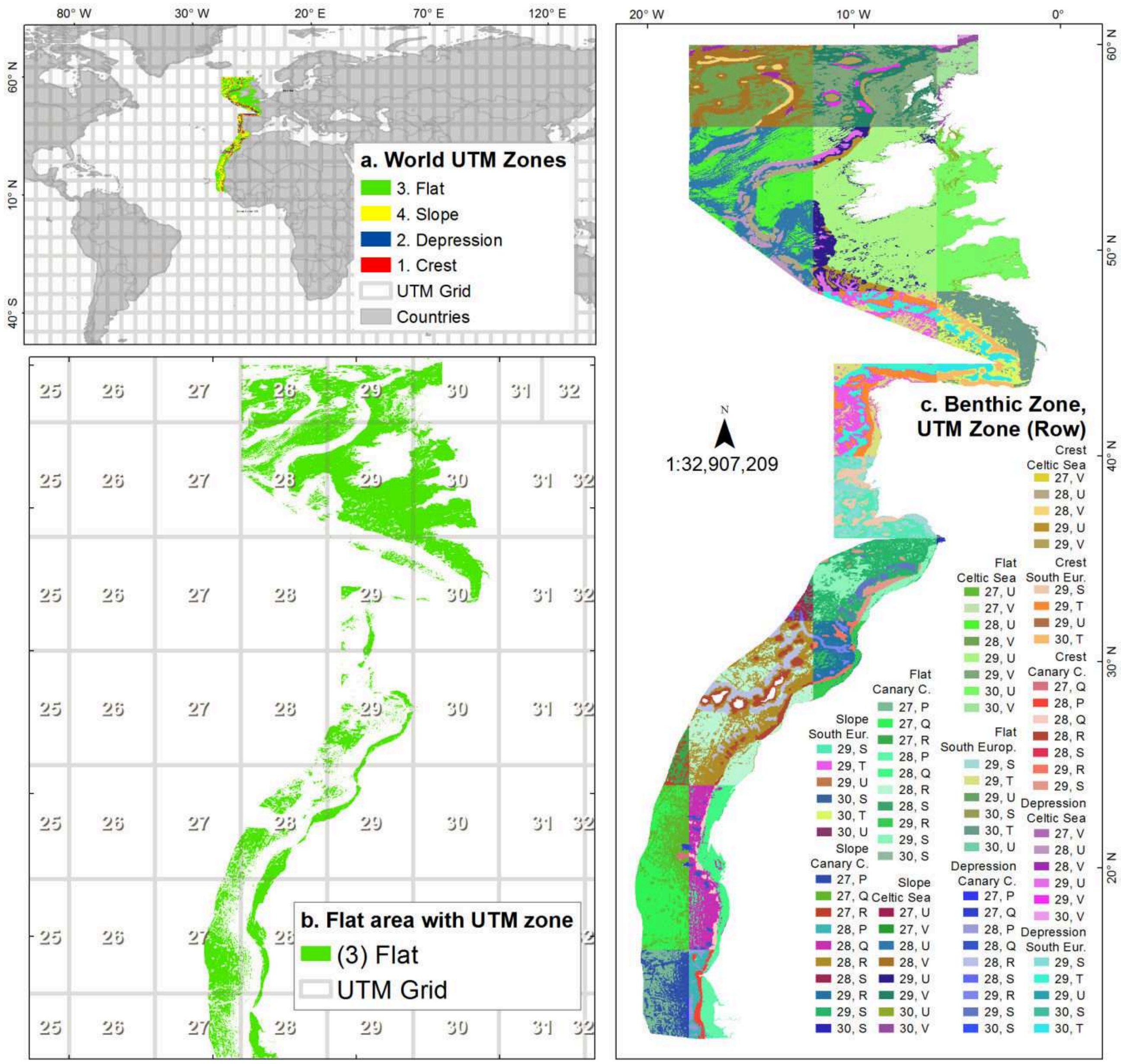


Figure 3-12: UTM Zone determination. (a) World UTM Zones; (b) Example of benthic zone area (flat area) with UTM zone; (c) Benthic Zone with UTM Zone.

3.2.2 Satellite data

The satellite data product used in this study is a Level-3 data consisting of global maps of sea surface temperature and ocean color. The Level-3 data was chosen due to the extent of our study area. Our study deals with fully global ocean parameters maps when determining species ecological niche.

3.2.2.1 Sea Surface Temperature (SST) from AVHRR

The AVHRR SST data we used is a current daily L3 Pathfinder version 5.2 dataset that covers 30 years of observation from 1982 to 2012. The L3 product was intended for general use. No gap filling procedure takes place in the data. Further information about specification of this data was provided by the GHRSST, and is accessible at the following link: *http://data.nodc.noaa.gov/pathfinder/Version5.2/GDS_TechSpecs_v2.0.pdf*.

3.2.2.2 Chlorophyll-a and other oceanic parameters from MODIS

The MODIS data of oceanic parameters incorporated in this study were the SST at daytime (referred to as SST), the SST at night-time (referred to as SST4 because the algorithm used is the short-wave MODIS bands at 3.959 and 4.050 µm), chlorophyll concentration (CHLOR_a), coloured dissolved organic matter (CDOM_index), diffuse attenuation coefficient at 490nm (KD_490), particulate organic carbon concentration (POC), particulate inorganic carbon concentration (PIC), photosynthetically available radiation (PAR) and instantaneous photosynthetically available radiation (IPAR).

The MODIS Level 3 product is an image of two-dimensional array of an Equidistant Cylindrical (also known as *Platte Carre*) projection of the globe, as monthly HDF-formatted file (Feldman and McClain 2012). Further information concerning naming conventions, common attributes, data time, scene coordinates, data description, and data arrays are available in the following link: *http://oceancolor.gsfc.nasa.gov/DOCS/Ocean_Level-3_SMI_Products.pdf.* Other MODIS data products can be accessed at *http://oceancolor.gsfc.nasa.gov/WIKI/OCProd.html.*

3.2.2.3 Downloading and preprocessing satellite data

Environmental satellite data preprocessing is detailed stepwise as follows (see flowchart in Figure 3-13):

- Downloading AVHRR data: Daily AVHRR SST data of daytime and nighttime can be downloaded through a wide variety of mechanisms including direct FTP access at *ftp://ftp.nodc.noaa.gov/pub/data.nodc/pathfinder* (which we used). Others mechanisms to download AVHRR data are available at *http://www.nodc.noaa.gov/sog/pathfinder4km/available.html.*
- Downloading MODIS data: MODIS data for ocean color can be obtained through the *Oceancolor* website (*http://oceancolor.gsfc.nasa.gov*), either directly by browser or by data archives. Downloading through data archives requires command lines used in the UNIX operating system language. Since this study was done in the Windows envrionment, we had to previously install *the Windows grep* software, which is distributed freely at *http://www.wingrep.com.* Few modifications from the original command were conducted in order to allow *Unix* code to be typed in Windows' command-line utilities (cmd.exe). Example of code for downloading Chlor-a product is as follow:

  ```
  wget -q -O - http://oceandata.sci.gsfc.nasa.gov/MODIST/Mapped/Monthly/4km/chlor/ |perl –ne
  “print if /CHL/”|wget -N --wait=0.5 --random-wait --force-html -i –
  ```
- Rearrangement of AVHRR daily data: The AVHRR SST files are *NetCDF*-formatted file. Each file contains one global daily image, from day 304 (first of November) 1981 to day 365 of December 2012. The files were rearranged to facilitate *mosaic* or combining process. Example of an original SST file in netCDF format is "*19811101025755-NODC-L3C_GHRSST-SSTskin-AVHRR_Pathfinder-PFV5.2_NOAA07_G_1981304_day-v02.0-fv01.0.nc*". Mosaic or combining daily files into a mean monthly file were conducted using *BEAM VISAT software version 4.10.* This software was made freely available by *The European Space Agency*. The software was originally developed to facilitate the utilization of image data from Envisat's optical instruments. Further information concerning this software is available at h*ttp://www.brockmann-consult.de/cms/web/beam.*

- Rearrangement MODIS data: Unlike the AVHRR data that are separated in daily files, MODIS data was already in the form of monthly file. The MODIS Level-3 product used in this study was a monthly period data, accumulated from daily data for the specific instrument and resolution (Feldman and McClain 2012). The data are *HDF*-formatted file and were converted into a GeoTIFF common file as a standard public domain metadata using the BEAM VISAT software version 4.10.
- AVHRR Data Quality Level: AVHRR SST data came with the variable “quality data” whose values range in incremental scale from 0 to 5. The quality data info is integrated in the *NetCDF* format. The native Pathfinder processing systems return quality levels ranging from 0 to 7 (where 7 is the best quality and 0 is the worst. Value of ‘-1’ represents missing data). We applied the quality level in the AVHRR data preprocessing in order to get rid of data of dubious quality. The summary of theses quality levels is presented in Table 3-1.

Table 3-1: AVHRR Data Quality level.

Pathfinder native processing quality levels	Summary in six quality levels	Description
-1	0	Missing data
0	1	Bad or Invalid data (e.g., cloud, rain, to close to land – under no conditions use this data)
1	2	Worst quality (worst quality of usable data)
2-3	3	Low quality
4-6	4	Acceptable quality
7	5	Best quality

- MODIS Data Quality Level: Quality level for MODIS data, known as *l2_flags*, was also applied based on corresponding conditions, such as atmospheric correction failure, land, and so forth. The MODIS Level 3 was the accumulated data of all L2 products of the specified instrument and resolution. Detailed information concerning MODIS quality flag is available at the following link *http://oceancolor.gsfc.nasa.gov/DOCS/Ocean_Level-2_Browse_Products.pdf.*
- Cropping the area of study: Most of the analyses performed in this study were concentrated in the area of interest (AOI). To accelerate the process of raster analyses, global raster oceanic data were cropped to the fixed area with the following geographic limits: 11°0’0” N to 61°0’00” N and 0°0’00” W to 21°0’00” W. These geographical limits covered all of the AOI. The results of this process were saved in a common GIS format, *GeoTIFF*, to facilitate working with GIS software. Processing monthly data for all parameters from 2002 to 2013 were conducted using a loop function written in the *Python programming language* and run under *ArcGIS^{TM}* environment.
- The SST unit in the original AVHRR dataset was the Kelvin. For consistency with the SST unit measured by MODIS in degree Celsius, the AVHRR SST data unit was converted from Kelvin to Celsius. This process was conducted using *Map Algebra Tool* from *ArcGIS^{TM} Spatial Analysis* (°C = K – 273.15). A *Python* script was used to facilitate the processing of all data series.
- Areas with no-data attached, such as terrestrial values or areas covered by clouds during acquisition were set to Null to avoid miscalculating in the future analysis such as when

calculating statistics of SST variations by ecosystem. This process was conducted using the *"Set Null" tool* of *the ArcGIS^{TM}'s Spatial Analysis tools*. The integration of *Python programming language* in *the ArcGIS^{TM}* software allowed us to automate this process for a large number of files (data from 1982 to 2013).

3.2.2.4 Producing seasonal data, seasonal climatology data, and decadal seasonal climatology data

Seasonal data, seasonal climatology data and annual climatology data were produced only in the AOI using the monthly data resulting from the previous process above. Terms of season used in this study are as follow:

- Winter : January, February and March.
- Spring : April, May, and June.
- Summer : July, August, and September.
- Autumn : October, November, and December.

Combining monthly data to seasonal data was conducted using the *Mosaic tool* of the *ArcGIS^{TM}* software. A script written in *Python* programming language was used for automation (Figure 3-13).

Seasonal data (winter, spring, summer and autumn) consists of the combined monthly data from the same season of the same year. For SST AVHRR data (SST daytime or night time), using data acquired from 1982 to 2012 (374 monthly files), we produced 128 seasonal files as final results. As for MODIS data, using data acquired from 2002 to 2013 (138 monthly files), we produced 44 seasonal files for each parameter.

Seasonal climatology data in this study consists of the combined seasonal files of all year by average, resulting in four files of seasonal climatology data: winter, spring, summer and autumn. As for year climatology data, it consists of a single combined file from all monthly files put together by average.

Annual data consists of the combined monthly data of the same year. For SST AVHRR data, from 1982 to 2012, we produced 31 annual raster data. As for MODIS data from 2002 to 2013, we produced 12 annual raster data.

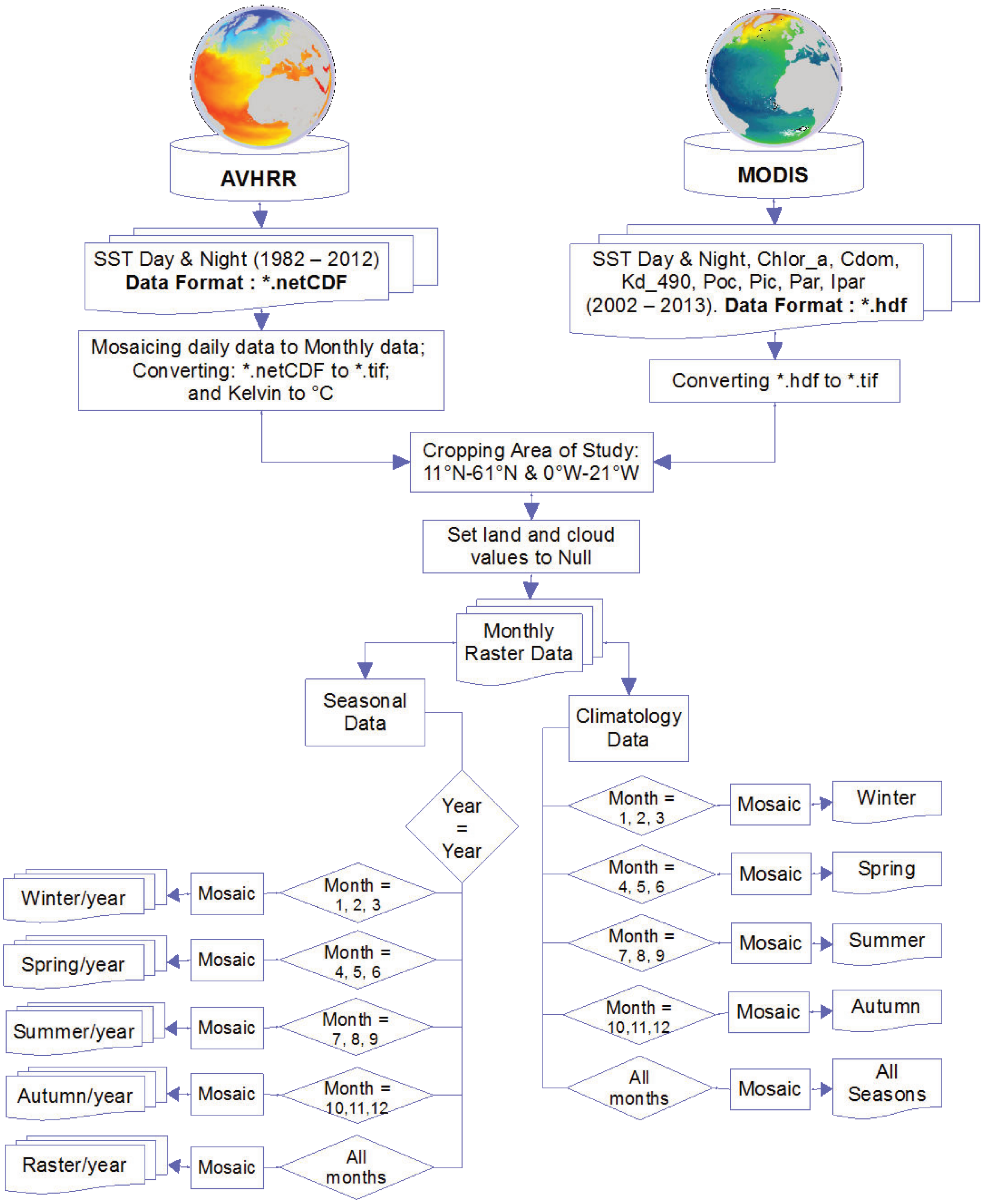


Figure 3-13: Flowchart of satellite raster data preprocessing.

3.3 SST: time series analysis

We observed the change of sea surface temperature (SST) in the AOI and in adjacent ecosystems, such as the North Sea, the Western Mediterranean Sea and the Guinea Current, in the period between 1982 and 2012. An analysis of SST changes in adjacent ecosystems was conducted because the area of distribution of many marine fish species encompassed the AOI and the sourrounding ecosystems. For example, in summer, many species considered in this study were found in the North Sea, while in winter, these species were observed in the Celtic Seas or in the South European Atlantic Sea (AOI).

We explored the most recent version of AVHRR SST dataset (Pathfinder version 5.2) from NOAA polar-orbiting satellite (1982 – 2012) and other oceanic parameters from MODIS (2002 to 2013). We introduced Geographic Information System as a tool to observe the monthly changes of the oceanic parameters by ecosystem. We performed a time series analysis to understand the rise of an observed series (Cryer and Chan 2008).

3.3.1 Calculating SST statistic in each ecosystem

Mean monthly SST values were obtained for each ecosystem using the *Zonal statistics as table tool* of *ArcGIS*^{TM}. The tool works by summarizing the raster statistics of a given zones/polygon (AOI) in a shapefile. This tool calculates the statistics, such as the mean value, minimum, maximum, standard deviation and number of pixels for each ecosystem polygon. A script written in *Python* was used to automate the process for all SST rasters. The *Python code* lists all of the monthly SST rasters, and takes each raster for calculation, and puts the result in a DBF-formatted file. This process was conducted for the first raster of the first month (January 1982) to the last raster of the last month (December 2012). The DBF files resulting from this process were then opened in *R* for further analysis; see Figure 3-14 for flowchart of the time series analysis.

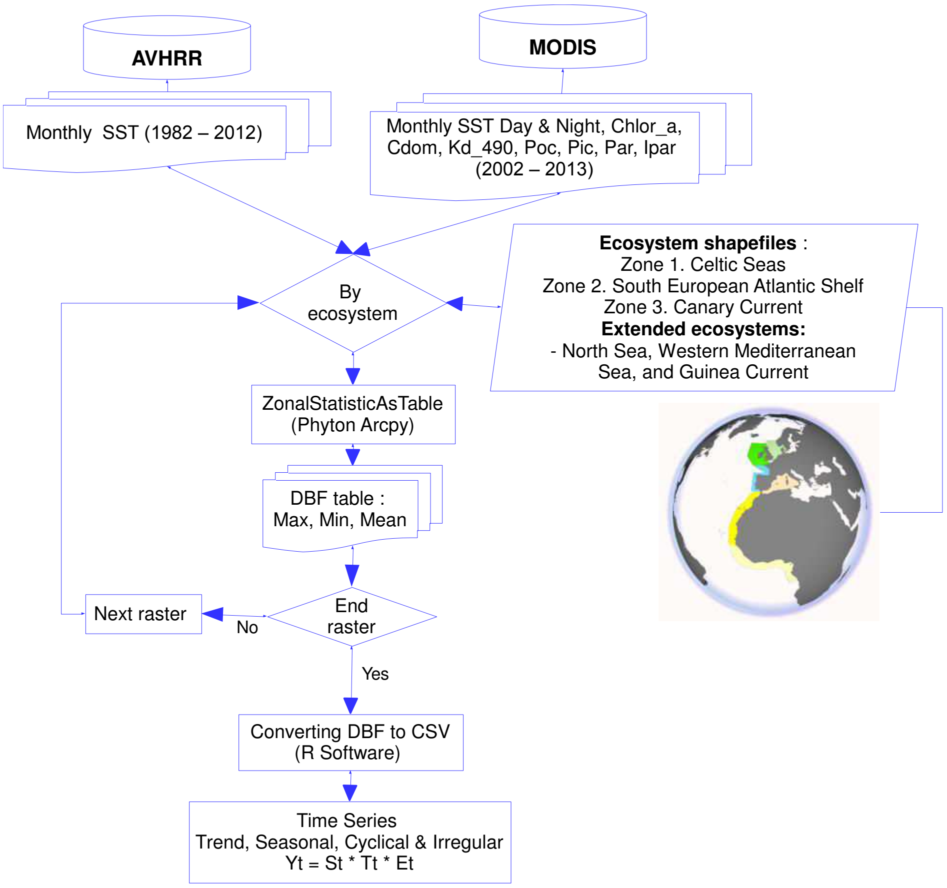


Figure 3-14: Flowchart of the time series analysis.

3.3.2 Decomposing data time series: trend, seasonality and residual

Decomposing the data separates a series of data into the trend, seasonal and residual components. The relative influence, in percentage of the overall variation, of each of the components was then investigated. Each component will give us a view of total variation of the data over time period, influence of seasonal component and residual component.

Influences of each component in the time series analysis were obtained in percentage using the equation below:

*Influence of Trend Component = (Variation of Trend/Total Variation) * 100%.*

*Influence of Seasonal Component = (Variation of Seasonal Component/Total Variation) * 100%.*

*Influence of Residual Component = (Variation of Residual Component/Total Variation) * 100%.*

Some computations were conducted using readily and freely available statistical softwares, such as *Insight*, to carry out the calculations and do the plotting.

3.4 Species studied

Although the records of the tropical fish present in the Atlantic-European waters have become more common in recent years and have involved a large number of pelagic, demersal and deep-water fish species (Bañón 2004), the histories of their distributions are not well understood (Summerson et al. 2007). Moreover, the routes and timing of their movement are not well documented (Johnston and Purkis 2011).

In this section, we describes the materials and methods of species selection for this study, data sources of species occurrences, AOI extension to adjacent ecosystems, continental shelf area, and richness calculation by ecosystem and by 2° latitudes.

3.4.1 Species selection

This work focuses on studying fish species that had been observed outside their known natural range. These species, such as *Acanthurus monroviae*, a tropical-Atlantic origin, were noted as rare or alien by various sources (i.e., CIESM 2002 and Zenetos et al. 2005). *A. monroviae* was noted in 2002 by CIESM as *exotic;* this species is now well established in the Mediterranean Sea. Another example is *Arius parkii*, considered *Alien* in the same area. In the Atlantic-European waters, two species, *Anthias anthias* and *Solea senegalensis*, previously unknown in the Galician waters (NW Spain) of the South European Atlantic Shelf, are now observed with high biomass (Bañón et al. 2010).

Overall, we identified 465 rare species were from various sources in the middle zone of the study area. These are species of temperate or tropical origin. We concentrated our study by selecting several species. Criteria used in the species selection were mainly based on the availability of occurrence records (the threshold value was 80 occurrences). Criteria were also based on biological characteristics, commercial value and species affinity to the temperate or sub/tropical zone. Following these criteria, 89 fish species were selected.

A checklist of the selected species along with the information of affinity, number of occurrence in each ecosystem, and sources of article used for species identification are available in subchapter Results and Discussion, and Annex 4.

3.4.2 Data sources

Species occurrence records in this study were derived mostly from OBIS/*Ocean biogeographic information system* (http://www.iobis.org) and GBIF/*Global biodiversity information facility databases* (http://www.gbif.org). In these databases, the data density in the area of well-financed or more economically developed countries (i.e., surveys conducted in the European waters) was much higher than that of the developing countries (i.e., surveys conducted in the West African waters). Hence, for the area with less available occurrence records, such as in the Canary Current and the Guinea Current, we added data from three more surveys conducted in those areas: the ISTAM Project/*Improve scientific and technical advices for fisheries management* (http://halieut.roazhon.inra.fr/istam), the database from the AMPHORE Project/*Marine Protected Areas and fisheries management by optimization of Resources and Ecosystems* (http://bit.ly/2cSHJVp), and the Nansen survey (Sætersdal et al. 1999). Thus, these incorporated data sources have mutually complementary coverage.

There were also species occurrence records available from AquaMaps database (http://www.aquamaps.org). Unfortunately, the occurrence records from this database have no information on time of observation. Hence, they were not used in time-based analysis process. However, trade off the use of these data allows the capability to investigate patterns at large spatial and temporal scales.

In the study area, we gathered information on species name, location expressed in latitude and longitude, and time of observation (month and year) from the various databases mentioned previously. The data were combined into a single *.csv file* using the free *R statistical software* allowing vast array of data processing. The rows with latitudinal and longitudinal information were then converted into point features of the common GIS format *shapefile* using the freely available GIS software *QGIS^{TM} 2.0*.

Heterogeneous data sources at this biogeographic extent vary in degrees of confidence. Hence, maintaining quality data required detailed investigation. Suspicious occurrence records with latitude of 0° and longitude of 74.25°N were removed from our database (Figure 3-15). These suspicious occurrences could probably come from false coordinate or absent coordinate information and species misidentification. Moreover, these coordinate values were located outside of any ecosystems studied.

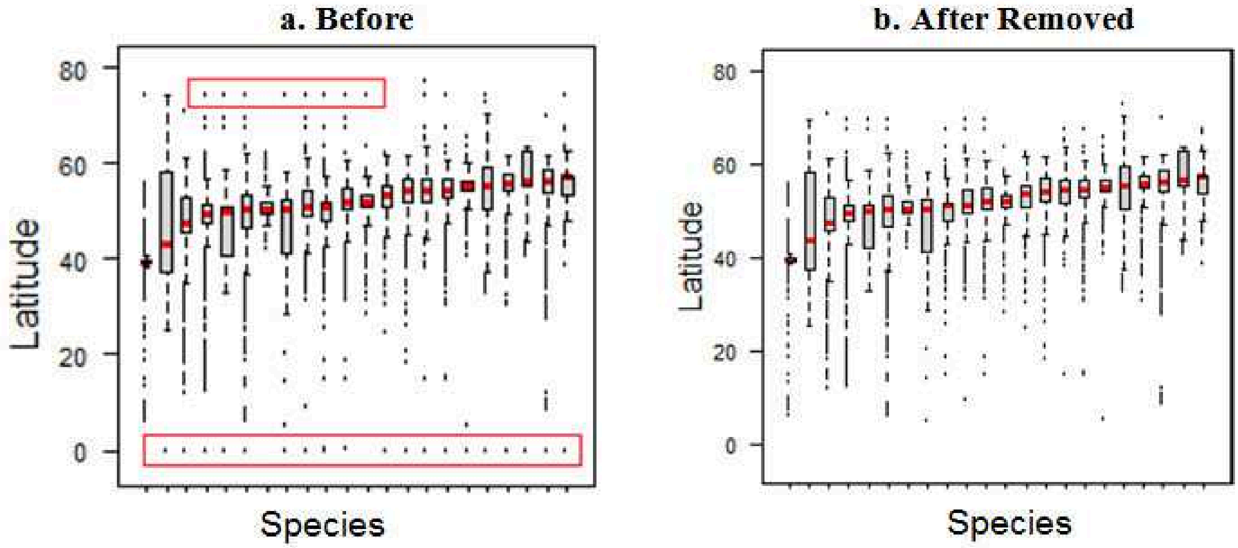


Figure 3-15: Example of species occurrences distribution by latitude (one species equal one box-plot). (a) Occurrences with suspicious records (outliers in the red rectangles). (b) Occurrences without suspicious records.

Our analysis only deals with the information wheter a species is present or not in an area. Conflict rose from different sampling techniques used in occurrence data collection or from different data sources are thus negligible.

3.4.3 AOI extension

Species seasonal movements among ecosystems influence pattern of species richness. Our preliminary study suggested that the increasing of number of species in an ecosystem was always followed by the decreasing number of species in adjacent ecosystems. Hence, for this particular study of richness of the studied species, we extended our area of interest to the adjacent ecosystems.

3.4.3.1 Adjacent ecosystems

The ecosystems of the study area and the adjacent ecosystems extend from the northern coast of the UK to the coast of the Republic of the Congo: the North Sea, the Celtic Seas, the South European Atlantic Shelf, the Western Mediterranean Sea, the Canary Current, and the Guinea Current (Figure 3-16a). The boundaries of the northern ecosystems in the European waters were defined by ICES. The boundaries of the southern ecosystems in the African waters were based upon the LME (see subchapter 3.1).

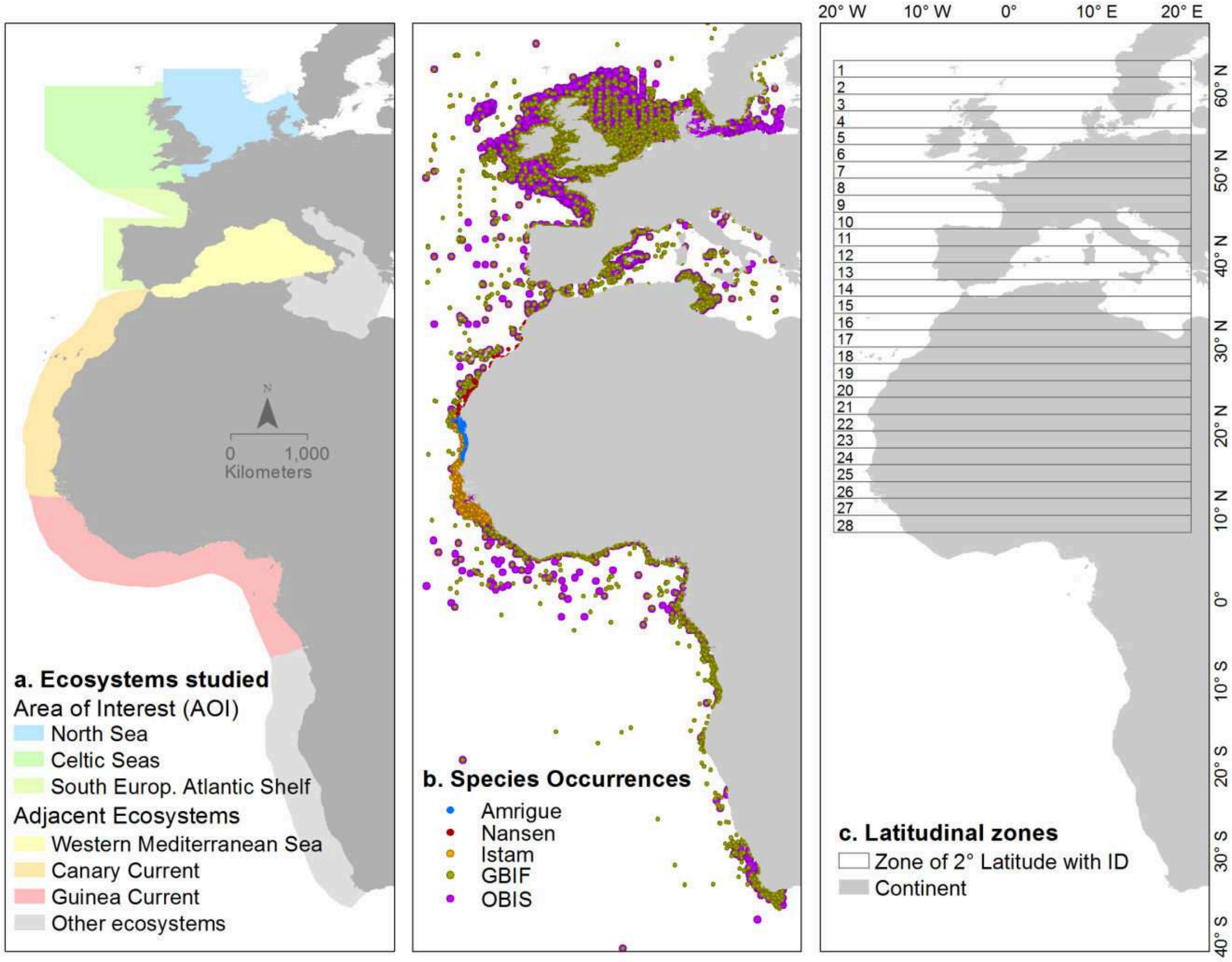


Figure 3-16: (a) Area of study with adjacent ecosystems. (b) Distributions of occurrence records and itsby their data sources. (c) Zone of 2° latitude. Southernmost areas were excluded due to insufficeient occurrence for richness comparison at 2° latitude.

3.4.3.2 Zones of 2° latitude

Chiarucci et al. (2011) suggested that difference scale influences different balance in species diversity. Clarke and Gaston (2006) also suggested that diversity in the sea is influence by both latitudinal and longitudinal gradients. Hence, study design and spatial scales need to be explicitly stated.

In this study, we compared richness by ecosystem and by 2° latitudes. The ecosystems compared have been explained previously. In this section, we explained the process of determination of zone of 2° latitudes.

The value of 2° was chosen considering the scale of the area of study. Zones of 2° were created using *Fishnet tool* of the *ArcGIS*^{TM} software. This tool works by taking the southern and northern limit of the AOI as well as the eastern and western limit of the AOI, which were set as follows: 8°S - 62°N and 22°E - 22°W. The southern limit was set 8°S because the number of occurrence collected in the area below this latitudinal degree was insufficient (Figure 3-16b). Thus, these limits covered both the ecosystems studied and the zones with sufficient data. We determined the number of column and rows of the AOI as one column and 28 rows. The tool devided the AOI as the condition set resulting 28 zones of 2° latitudes. Each zone was given a unique ID that will be used in the next step of computing richness of the studied species by zone/ID (Figure 3-16c).

3.4.4 Calculating areas of continental shelf (0-200 m deep)

Number of species in a given area could be influenced by number of effort conducted in that area and the availability of habitable areas. Our preliminary study revealed that most of species occurrence records were distributed in areas less than 200 m deep.

We calculated the surface area of continental shelf by ecosystem and by 2° latitude to understand the effect of continental shelf area availability on richness of the studied species. Bathymetry data from SRTM30PLUS was used to extract the areas less than 200 m depth (see subchapter 3.2.2). Procedures of continental shelf area extraction are detail stepwise as follow:

- Preparing raster bathymetry data in the AOI (see subchapter 3.2.2).
- Querying areas of 0-200 m depth using *raster calculator tool* of *ArcGIS^{TM}* software. Above or below 0-200 m depth were set to NULL or no-data (Figure 3-17a).
- Converting raster of continental shelf to polygon shapefile.
- Separating polygon by ecosystem and by 2° latitude.
- Re-projecting coordinate system from geographic to a projected coordinate system (Universal Transverse Mercator) in order to calculate geometry. Re-projection accuracy was kept by clipping the world UTM grid/zone shapefile provided by ESRI (Figure 3-17b) using the shapefile of the ecosystems or the zones of 2° latitude.
- Surface areas of each zone were calculated using *Geometry calculation tool* in *ArcGIS^{TM}* with respect to its UTM zone. Figure 3-17c shows the ecosystems studied with its UTM zone used to calculate surface area. Figure 3-17d shows the zones of 2° latitude with its UTM zone also used to calculate surface area.
- Script written in *Python programming language* was used to automate calculation of each zone. All phyton scripts were run under *ArcGIS^{TM}* environment.

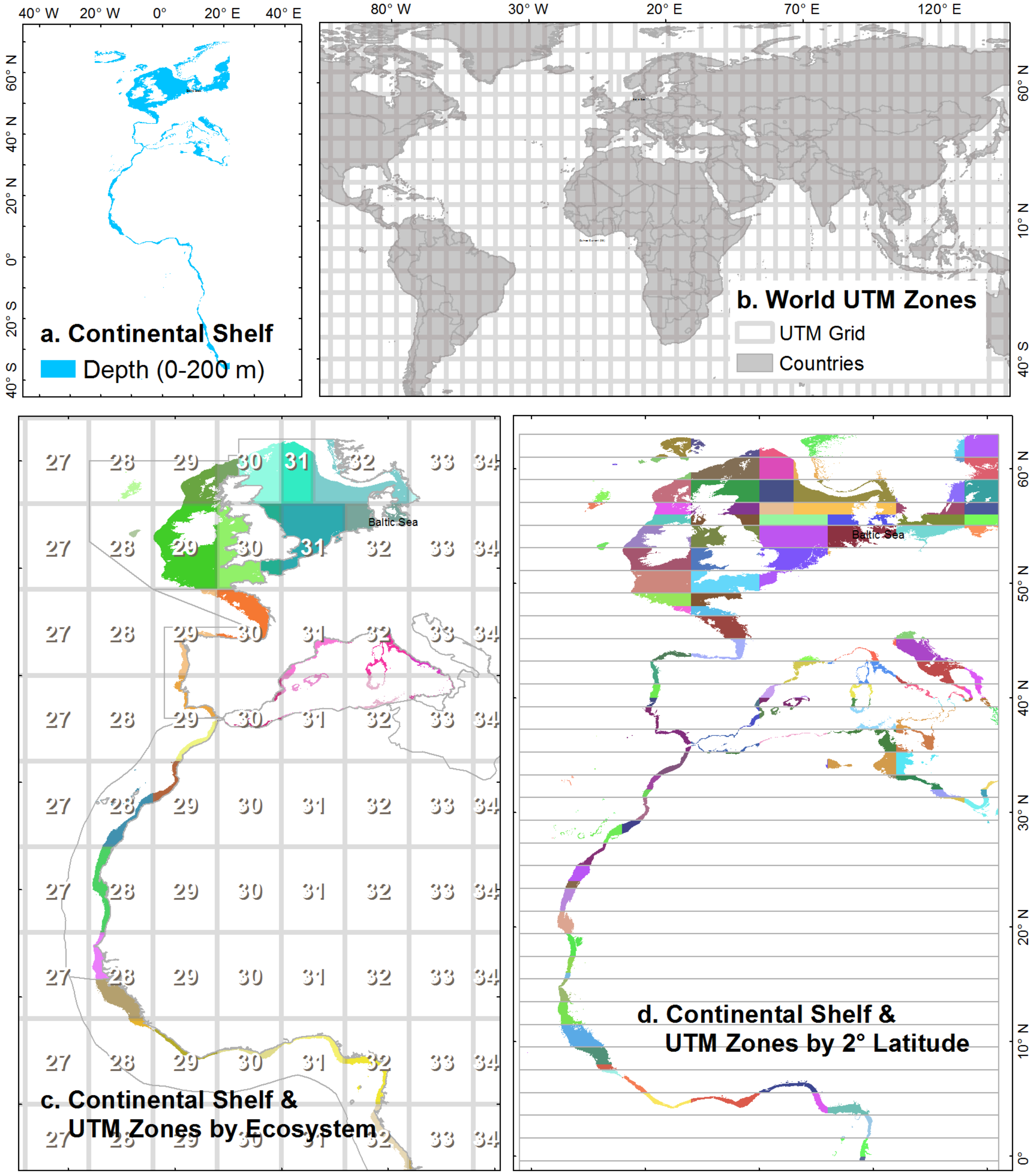


Figure 3-17: (a) Continental Shelf areas; (b) World UTM Zones; Continental shelf and UTM Zone (c) by ecosystem and (d) by 2° latitude in different colors.

3.4.5 Period of study

A preliminary study on the evolution of Sea Surface Temperature (SST) in the AOI indicated a decadal trend of SST rise. Thus, we calculated richness by decadal periods from 1982 to 2012 based on the availability of SST data as mentioned previously and detailed below. Decadal variability of the North Atlantic Oscillation suggests also our view on working with decadal period (Wang et al. 2012):

- Period I = from 1983 to 1992
- Period II = from 1993 to 2002
- Period III = from 2003 to 2012

3.4.6 Calculating richness of the studied species

Neither information on sampling techniques nor sampling effort was uniform in our databases. Considering the complexity of species diversity in its definitions and metrics, especially at the biogeographic scale, we retained only the number of species. Analyses on abundance and biomass therefore could not be conducted. From the variety of biodiversity indices available, only the cumulative richness (S) that can be calculated, S = $\sum_{i=1}^{S} P_i^0$ (Jost 2006). Richness of the studied species is defined here as the number of species of the selected potentially invasive species present in a given specific area or duration. Cumulative richness is the total number of species found in the area at a time period given.

The section of this study used the information of the presence or absence of a species in a large area, and analyses were conducted qualitatively.

3.4.6.1 Number of occurrence

We selected species occurrences observed from 1982 to 2012 before separation into the three decadal periods. The spatial selection process was based on the ecosystem boundaries, with additional inland water polygon to include occurrences in estuarine waters (Figure 3-18). The inland water shapefiles (polygon) were obtained from DIVA-GIS program (http://www.diva-gis.org). Buffer zones of 10 km on the boundaries of the study area were constructed to include occurrences in the vicinity, anticipating the different scales of data sources.

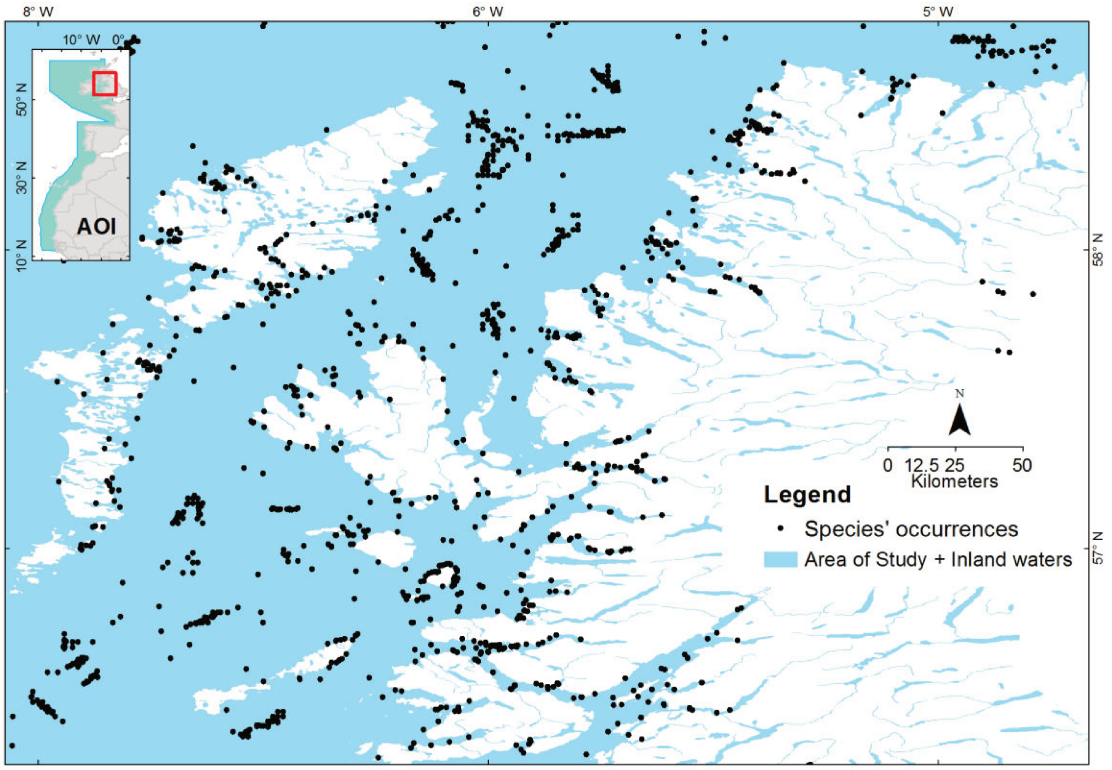


Figure 3-18: Species occurrences of the AOI and inland waters (Buffer zones of 10 km were constructed to include points in the vicinity/estuary).

The number of occurrence in each ecosystem and each 2° latitudinal zone were obtained by simple calculating the occurrences that intersect or fall in each ecosystem or each 2° zone. These processes were conducted by joining occurrence data (point feature) with the ecosystem/2° zone polygons based on spatial location. Polygons of ecosystem/2° zone were set as the target layer to put results. The polygons would have additional fields/columns containing the number of occurrence counted inside or intersect each zone (Table 3-2). Total number of occurrences that intersect the AOI is 622156 (see Table 3-3).

Table 3-2: Number of occurrences per ecosystem.

Database	**World (Global)**	**Ecosystems**					
		North	Celtic	South E.	West Med.	Canary	Guinea
1. OBIS	675735	365449	181346	49708	9963	1431	24685
2. GBIF	116111	11533	16363	958	2494	2608	34750
3. ISTAM	19794	-	-	-	-	11443	7977
4. Amphore	552	-	-	-	-	552	-
5. Nansen	309	-	-	-		308	-
6. AquaMaps	15690	377998	1535	542	1364	1093	3352
Total	828191	377998	199244	51208	13821	17435	70764

Table 3-3: Number of occurrences per period study.

Database	**Period I**	**Period II**	**Period III**	**All Periods**
1. OBIS	91300	215110	266461	572871
2. GBIF	7507	10205	14385	32097
3. ISTAM	10702	5626	-	16328
4. AMPHORE	-	257	295	552
5. Nansen	161	147	-	308
Total	109670	231345	281141	622156

*I = Semester 1/Winter-Spring, II = Semester 2/Summer-Autumn; All Rec. = All Records.

3.4.6.2 Richness in each ecosystem/zone and IDs of species movement

The number of species in each ecosystem was obtained by joining the points of occurrence with the ecosystem polygons based on spatial location. The tool used was the *ArcGIS*^{TM} *Join-Data* tool. Joining data based on spatial location means that the information of each ecosystem (the unique id of the ecosystem/zone 2° latitude) is appended to each point of occurrence based on the location of the occurrence, resulting a new *shapefile* of point feature of occurrence containing the unique ID of each zone (ecosystem/2° latitude). The number of species will then be calculated based on the unique ID using *the Rich package* (Rossi 2011) from *R statistical software*. This calculation will be repeated for the three periods studied and for each ecosystem as well as for each 2° latitudinal zone. Flowchart presenting the process of richness calculation in stepwise is shown in Figure 3-19.

The directions of species movement were symbolized using the following IDs:

- **C=G**: ID for species found both in the Canary Current and the Guinea Current.
- **C=W**: ID for species found both in the Canary Current and the Western Mediterranean Sea. These species are not among the species noted as exotic in the Mediterranean Sea (CIESM 2002).
- **CW**: ID for Atlantic-origin species (the Canary Current) found in the Western Mediterranean Sea in recent years. Most of the occurrences of these species were excluded in this study due to the strict selection criteria applied to occurrence records. These species are noted alien in the Mediterranean Sea by CIESM (2002).

- **CWS**: ID for species found in the Canary Current and the Western Mediterranean Sea; and recently found in the South European Atlantic Shelf.
- **NCS**: ID for species found seasonally in the North Sea, the Celtic Seas and the South European Atlantic Shelf.
- **C=N**: ID for species found in both the Celtic Seas and the North Sea.
- **ALL**: ID for species found in all areas (temperate, subtropical and tropical waters).
- **D** (stands for doubtful): ID for species with low occurrence records.

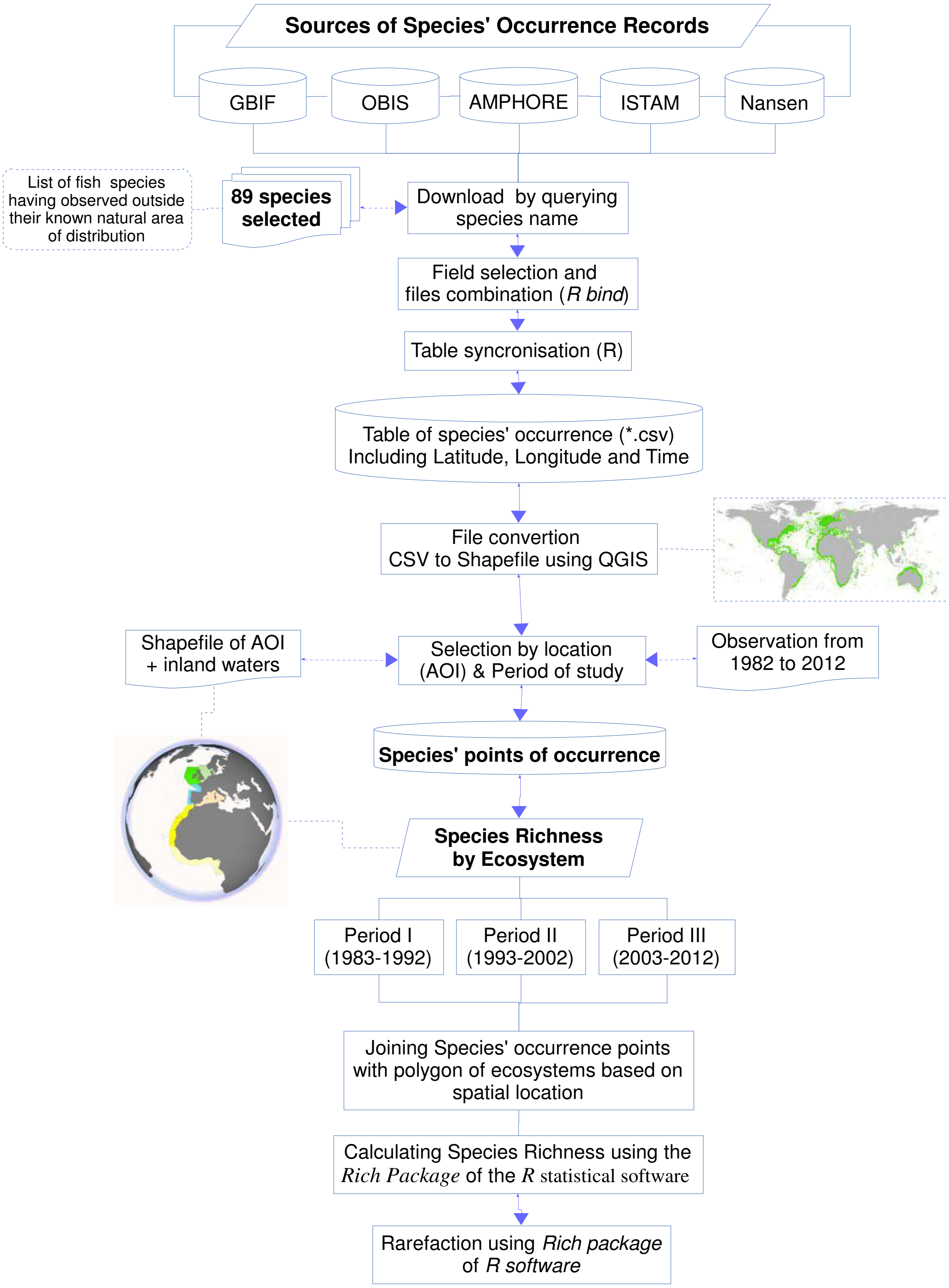


Figure 3-19: Flowchart of occurrence collection and richness computation.

3.4.6.3 Rarefaction

The number of species could be strongly dependent on sampling intensity, both for sample size and individual density. For standardization, a rarefaction procedure was applied to analyse the number of species in each ecosystem and period. This procedure consists in plotting randomized species number against the sampling intensity to estimate the number of species in an ecosystem. Rarefaction curves report the average values of randomized species number derived from re-sampling without replacement (Rossi 2011). These curves were used to determine possible ranges in richness. When the rarefaction curve did not stabilize, the sampled occurrences were considered not representative of true richness, and that curve was excluded from the analysis. The *Rich package* from *R statistical software* was used to perform this analysis. Further details about the rarefaction procedure can be found in Rossi (2011).

3.4.6.4 *Jaccard* similarity

Spatial distribution of species occurrences showed that many species concerned in this study shared their distribution range in the adjacent ecosystems of the AOI. *Jaccard* similarity analysis was performed to obtain initial information of the closeness of the ecosystems. *Jaccard* similarity summarizes the number of species shared between ecosystems divided by the total number of species in both ecosystems. The tool used was *Vegdist function* from the *Vegan package* in *R*.

3.5 Species realised niche

The main idea of species distribution modelling is to project the species' preferential environmental values to the environmental raster data. The species' preferential environmental values in this study also refer to the the species' environmental envelopes, the species' environmental niches or the species' ecological niches.

Hijmans and Elith (2013) stated that the most common strategy for estimating the potential geographic distribution of a species is to characterize the environmental conditions that are suitable for the species. Hence, knowing the species environmental requirements for survival is fundamental (Phillips et al. 2004).

Boitani and Fuller (2000) explained that the process of assessing a species' preferred ranges of values for the environmental variables taken into account is generally called habitat suitability index (HIS) analysis, habitat evaluation procedures (HEP) or more generally, species-environment relationship analysis, referred in this study as the species fundamental niche.

3.5.1 Species selection for representation

We selected three species inhabiting different types of environment to give some examples and demonstrate this work: *Pomatomus saltatrix*, *Balistes capriscus*, and *Solea senegalensis*. The criteria used for the species selection were mainly based on the number of experimental studies that have been conducted with each species, in order to be able to compare results as well as to assess the effectiveness and robustness of the methods presented in this study. Criteria were also based on distribution patterns, number of occurrence, biological characteristics and the commercial value of the species. *Pomatomus saltatrix* has the biggest sampling size among the three species selected, and it has been well studied in terms of experimental as well as observational studies; hence, we will give more detailed results for this species.

3.5.2 Extracting raster environmental values

The niche modelling method associates the environmental variables and species' occurrence records to identify species environmental requirements. These environmental requirements are the ecological niche within which a population can be established. Thus, they control species distribution (Pearson 2007; Phillips et al. 2004).

All of the environmental parameters incorporated in this study are bathymetry, Sea Surface Temperature (SST), chlorophyll-a concentration (CHLOR_a), coloured dissolved organic matter (CDOM_index), diffuse attenuation coefficient at 490nm (KD_490), particulate organic carbon concentration (POC), particulate inorganic carbon concentration (PIC), photo-synthetically available radiation (PAR) and instantaneous photo-synthetically available radiation (IPAR); see Figure 3-20.

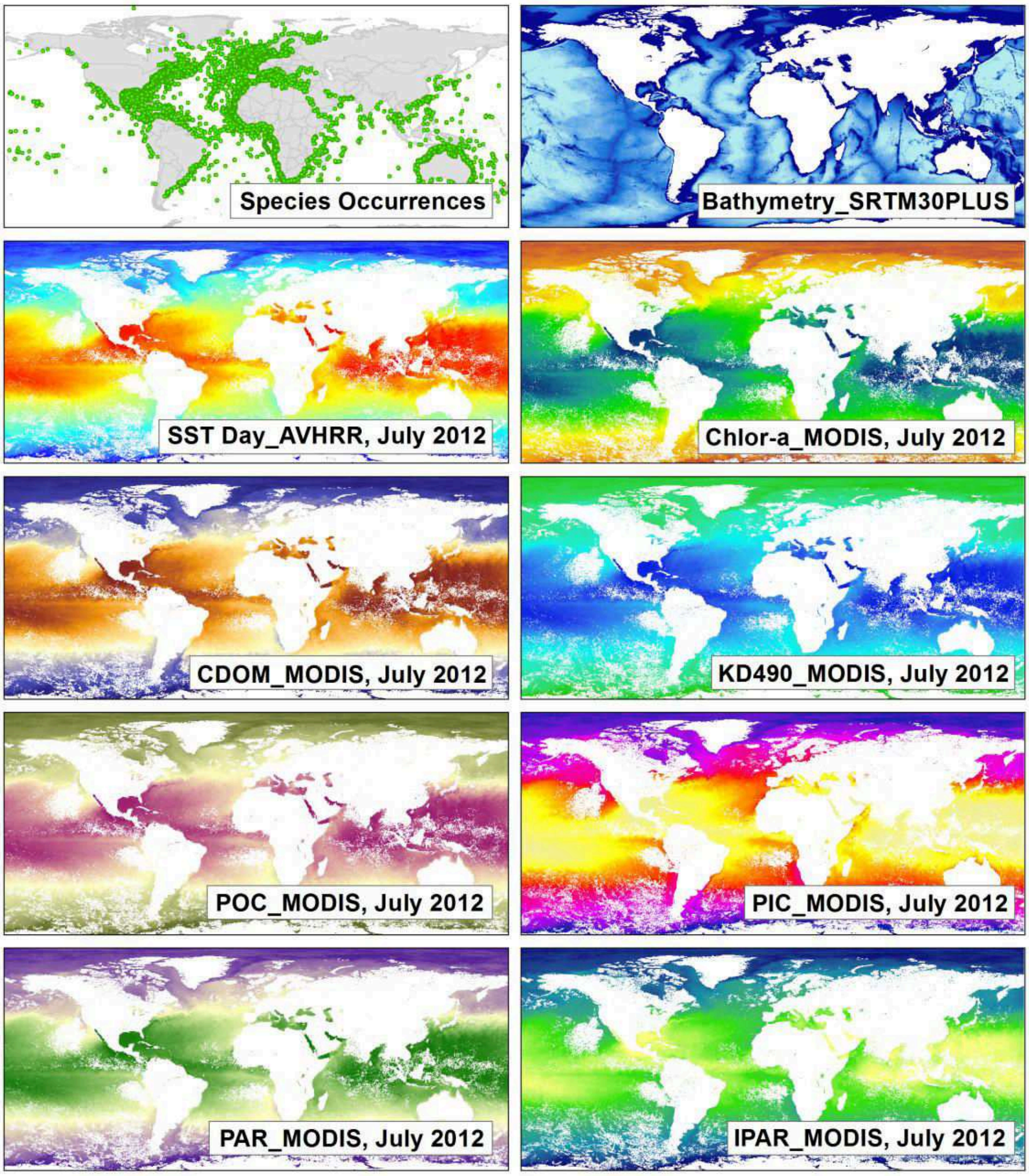


Figure 3-20: Distribution of species occurrence and environmental variables taken into account at global scale. SST = Sea Surface Temperature, CHLOR-a = chlorophyll-a concentration, CDOM = coloured dissolved organic matter, KD490 = diffuse attenuation coefficient at 490nm, POC =

particulate organic carbon concentration. PIC = particulate inorganic carbon concentration, PAR = photo-synthetically available radiation and IPAR = instantaneous photo-synthetically available radiation.

We extracted the environmental values at the location of species' occurrence at the time of observation to get the species environmental requirements. This process was called as *rater-to-point data extraction*. The process used a tool called *raster-to-point* from *the ArcGIS^{TM}* software. The script written in *Python* programming language was incorporated to automate the process. The number of occurrences used to conduct this process is presented in Table 3-4.

Table 3-4: Number of occurrences of each selected species.

Species	**Environment**	**Number of occurrences having information on time of observation used for satellite data extraction**		**Total sample size used for bathymetric data extraction***
		Winter-Spring	Summer-Autumn	
Pomatomus saltatrix	Pelagic	20973	9316	34517
Balistes capriscus	Benthopelagic	1205	1551	7487
Solea senegalensis	Demersal	164	113	356

*Total sample size included occurrences with no time of observation.

The *raster-to-point extraction* process was based on the time of observation of each point of occurrence. *Shapefile* of species occurrence consists of several files including the points and a table containing the attributes of each point. Before performing the extraction process, each point of occurrence was given a unique ID in its attribute table. The attributes that hold the time of observation (Month and Year) of each point were joined in a new field named "Time", containing the values of month and year, i.e., for observation in January 1982 was assigned as "1_1982".

The raster of each environmental parameter taken into account was named according to the time of its acquisition, i.e., a raster acquired on January 1982 was named "1_1982" and assembled in the folder named as the parameter, i.e., the rasters of SST daytime obtained from AVHRR were put in a folder named "SST day AVHRR". In the first process, the *Python* script would go to the first parameter/folder, which was in this case the folder of "SST day AVHRR" and listed all of the rasters inside the folder (raster from January 1982 to December 2012). Through the loop statement in the *Python* codes, the scripts took the first raster (raster whose name was "1_1982") and used the name of the raster as the *key-word* to match for the extraction process. The script would then go to the attribute table of occurrences shapefile in the field "Time" and select all of the points which had the same value of the key-word ("1_1982"). The *raster-to-point data extraction* command was then executed for that first raster using only the selected points of occurrence matched, and the result was then saved in a new *shapefile* containing only the occurrence selected with values of SST day AVHRR for that selected time (see Figure 3-21 and Figure 3-22 for illustration). The script continued to conduct the same process for the second raster to the last raster as well as for the other parameters. At the end, the *shapefiles* resulting from this extraction process were merged based on the unique ID of each point. The flowchart in Figure 3-23 presents this process stepwise.

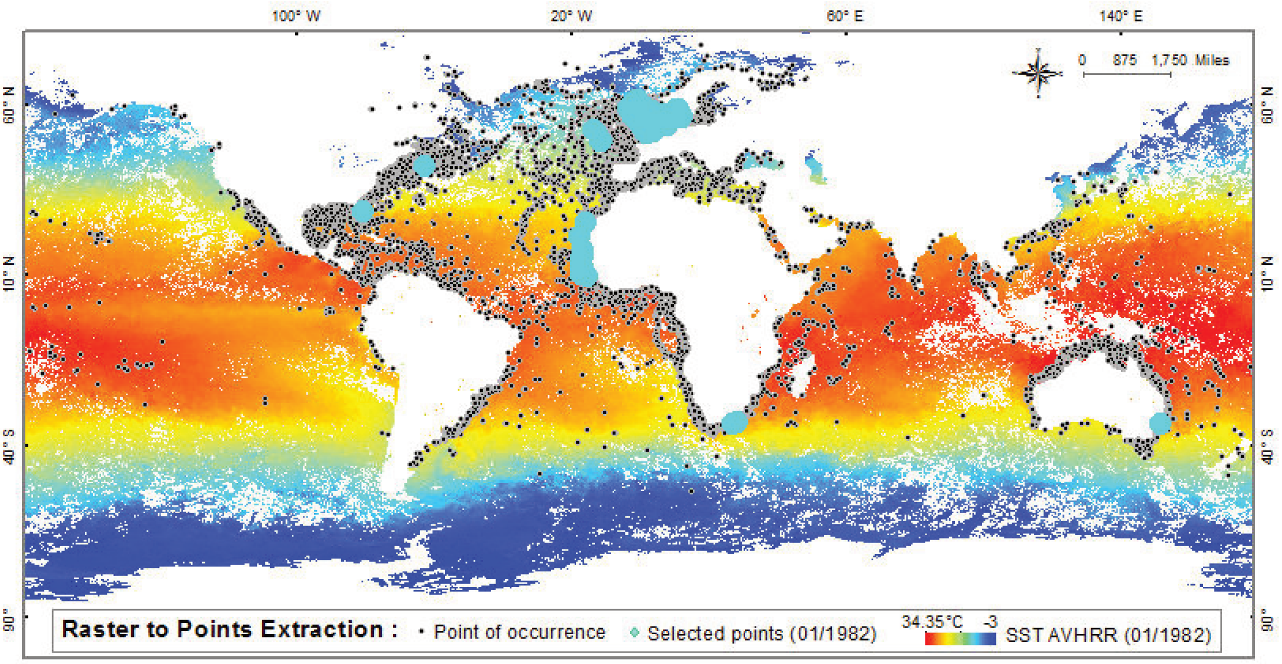
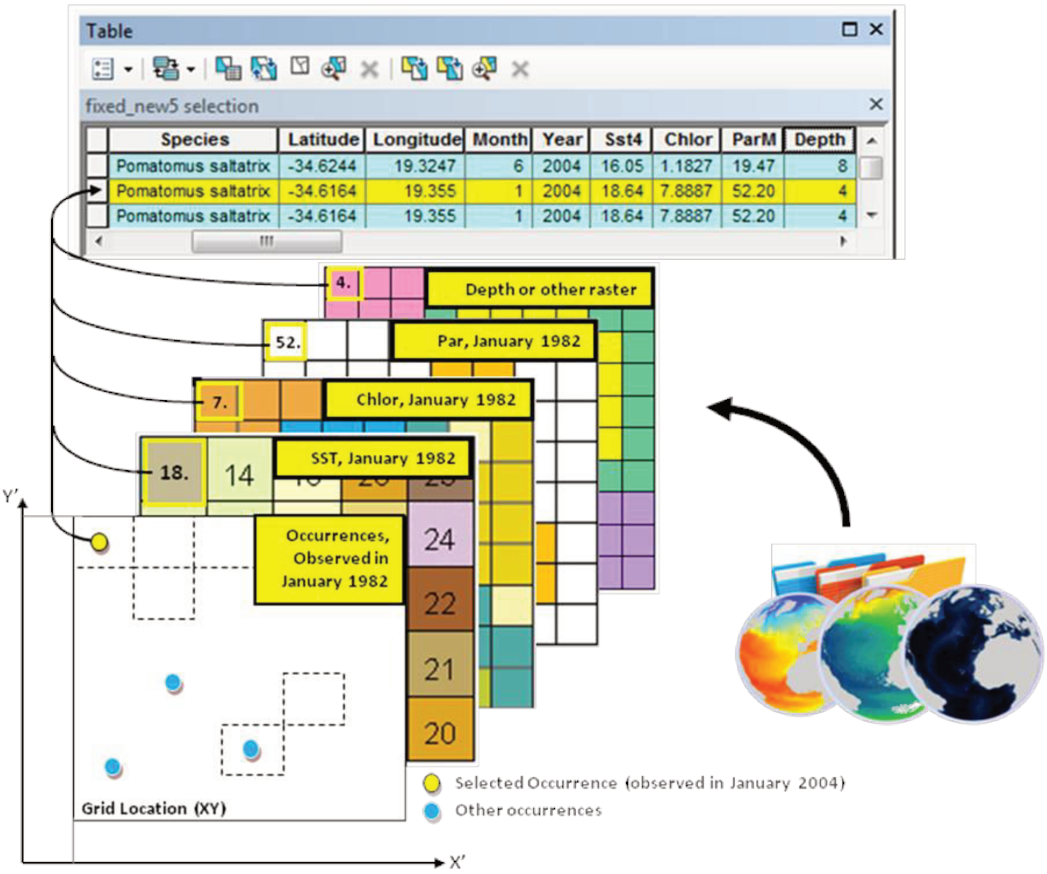


Figure 3-21: This map illustrates the process of extracting environmental raster data by points based on time. The background image in color is a raster of SST AVHRR acquired on January 1982. Black points mark the occurrences of the species. Points in blue are the selected points observed on January 1982 that match the acquisition time of SST and were considered by the extraction process. Land and cloud area are designated as no data (-9999) and represented in white.



Table

fixed_new5 selection

Species	Latitude	Longitude	Month	Year	Sst4	Chlor	ParM	Depth
Pomatomus saltatrix	-34.6244	19.3247	6	2004	16.05	1.1827	19.47	8
Pomatomus saltatrix	-34.6164	19.355	1	2004	18.64	7.8887	52.20	4
Pomatomus saltatrix	-34.6164	19.355	1	2004	18.64	7.8887	52.20	4

Figure 3-22: Another illustration of *raster-to-point data extraction* based on time of observation of the occurrences and time of acquisition of the satellite raster data.

Unlike the *raster-to-point data extraction* for satellite data, the extraction process for bathymetric data and its derivative did not consider the time of observation because these variables are considered as not changing or changing little over time. The process took all of the species occurrences and then extracted the bathymetric raster values at the location of each point (Figure 3-23).

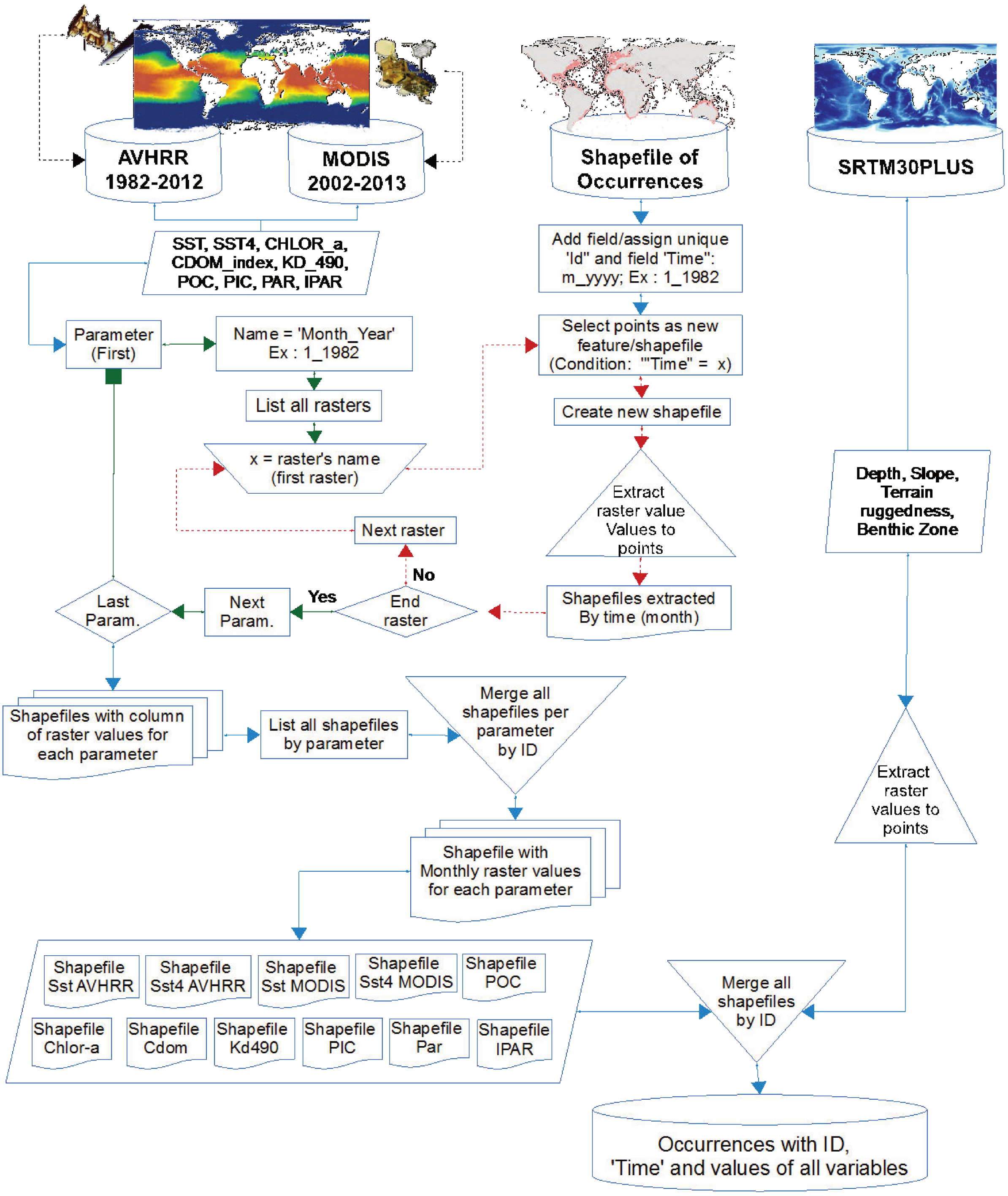


Figure 3-23: Flowchart of the extracting process for environmental raster data to point value.

3.6 Dynamic model of species distribution

This subchapter aims to demonstrate the methodological approach of modelling the potential distribution of fish species using GIS technique. The model used the time series environmental raster data and the species ecological niche.

3.6.1 Selecting environmental data

To be useful, predictive models must accurately represent species requirements (Moore et al. 2011). Thus, selecting accurate environmental predictors is essentials to this process.

We inspected the current information on potentially limiting environmental factors for marine fish distribution. High spatial and temporal resolution datasets of oceanic physical parameters, processed in the previous subchapter, have increased the possibility to base the predictive species distribution map for all targeted species. Adequacy, relevancy and cover capability of information for mapping environmental variability in the AOI were taken into consideration.

Ocean temperature is considered to be the single most important and dominant limiting factor in determining the range of most marine species, especially for the migratory species (Summerson et al., 2007). Sea surface temperature (SST) data is readily available at several spatial and temporal scales, as explained previously, which makes this data a priority source for the species range modelling and mapping.

Chlorophyll-a and other oceanic parameters available from MODIS could also have important roles in limiting species distribution, but unfortunately, the coverage of these data for some location in the AOI, was not consistent for every season, due to the presence of clouds (white areas in Figure 3-24). Incorporation of any of this data into modelling processes would reduce model accuracy and mask the effect of climate change on species distribution, and furthermore lead to false interpretations.

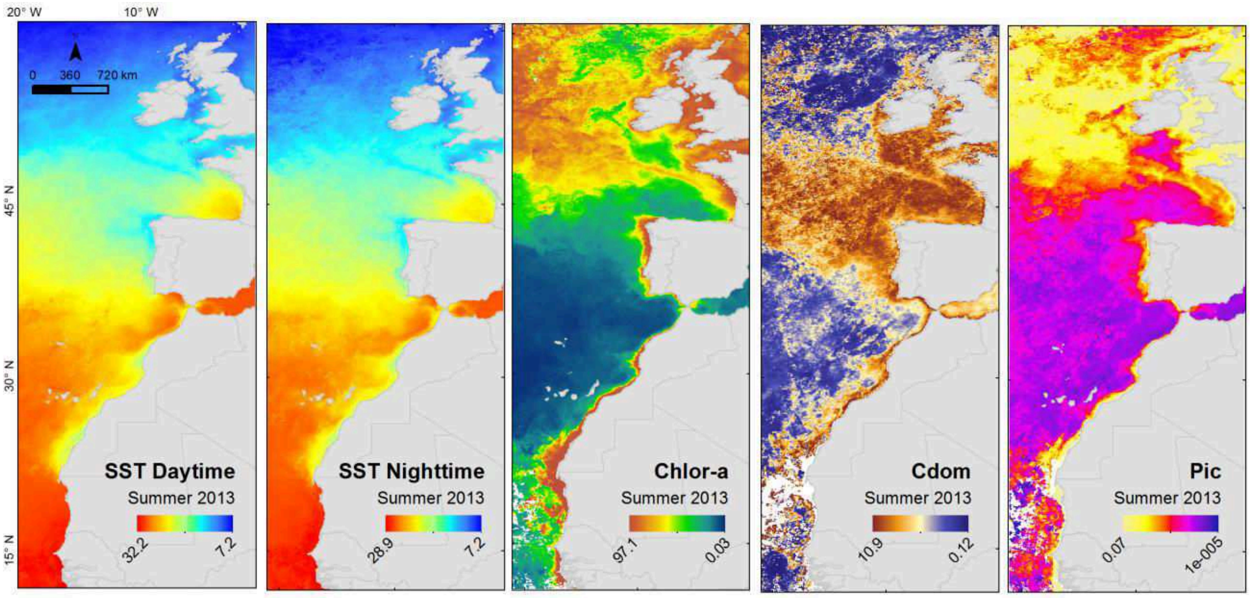


Figure 3-24: Mean seasonal physical parameters in the AOI in summer 2013. White areas on the maps represent the no-data areas. SST = Sea surface temperature; Chlor-a = Chlorophyll-a concentration; Cdom = Colored dissolved organic matter index; Pic = Particulate inorganic carbon.

Bathymetry data and its derivative were considered in this study as the second critical limiting factor for species distribution. Bathymetry data availability at the global scale and in a high spatial resolution (1 km) has made this data a second priority source after SST.

The environmental datasets selected in this study for use in species distribution modelling are presented in Table 3-5. This selection was made to keep the accuracy and relevancy of the species distribution model at the biogeographical scale of the AOI.

Table 3-5. Main environmental raster dataset used for modelling.

Variable	Source	Spatial Resolution	Description
Temperature (SST): Night time	30 years AVHRR and/or MODIS data (1982 – 2013)	1 – 4 km	Vary seasonally and inter-annually
Depth, Slope, Benthic Zone	SRTM30PLUS (GEBCO)	1 km	Little change over time

3.6.2 Species environmental envelopes and preference classes

Kesner-Reyes et al. (2012) defined the species' environmental envelope as a response curve that describes the habitat usage of a species or its preference. In this study, we modified the trapezoidal curve defined by Kesner-Reyes et al. (2012) into four distinct classes symbolized by different colors: Class-1, Class-2, Class-3, and Class-4 (see Figure 3-25 and Table 3-6).

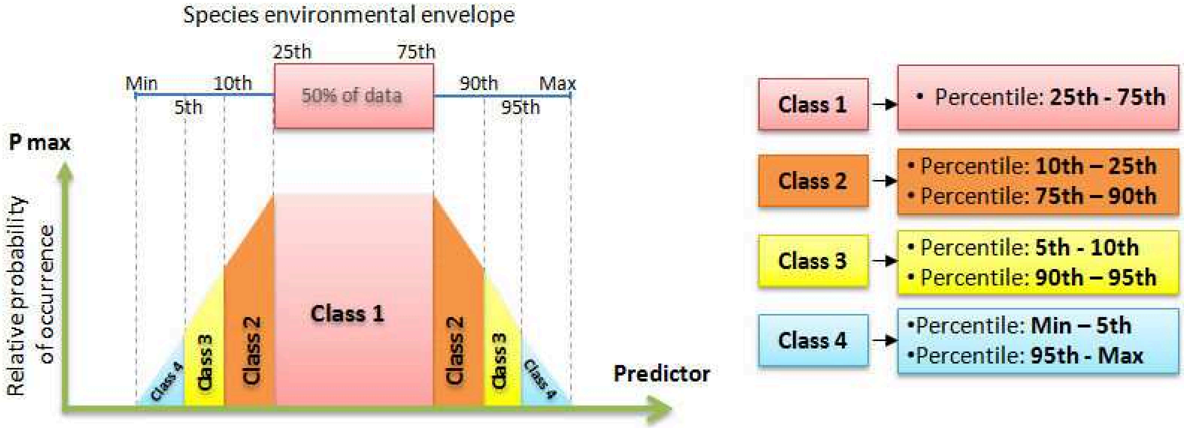


Figure 3-25: Illustration of four distinct classes of species' environmental envelope modified from Kesner-Reyes et al. (2012).

The Class-1 represents the area where the probability of a species occurring is highest or where P=1.00. This is the most preferred class (25th to 75th percentile, i.e., 50% of the occurrences). The spatial zone of this class represented in red color.

The probability of occurrence is assumed to decrease linearly towards the species absolute minimum or maximum parameter thresholds (Kesner-Reyes et al. 2012). These areas were divided into three classes: the Class-2 (the preferred class), the Class-3 (the less preferred class), and the Class-4 (the extreme values class); see Table 3-6 for details. Beyond the absolute threshold values, the probability is set to zero (P=0.00).

Table 3-6: Criteria in determining species' environmental class.

Zone/Class	Color Code	Description	SST (Percentile)	Bathymetry constraint (Percentile)
1	**Red**	Most Preferred	25th – 75th	25th – 75th
2	**Orange**	Preferred	10th – 25th & 75th – 90th	10th – 25th & 75th – 90th
3	**Yellow**	Less Preferred	5th – 10th & 90th – 95th	Min/0 – 10th & 90th – 95th
4	**Blue**	Extreme Values	Min – 5th & 95th - Max	95th – Max

The Class-2 is the preferred class that represents the species environmental range from 10th to 25th percentile and from 75th to 90th percentile (which represents 30% of the occurrences). In spatial representation, orange color was fixed to symbolize this class.

The Class-3 or the less preferred class was defined differently for SST and for bathymetric constraint. The Class-3 for SST is the values that range from the 5th to the 10th percentile and from the 90th to the 95th percentile, while for bathymetric constraint, the values of Class-3 were determined from the minimum value to the 10th percentile and from the 90th to the 95th percentile; see Table 3-6.

The Class-4 or the extreme value class represents the extreme values of the species' environmental envelope. This class was preserved to deal with the possibility of having environmental values resulting from species misidentification and/or false geographical locations. This class was also determined differently for the SST and the bathymetric constraint. The Class-4 for SST is the values found from the minimum to the 5th percentile and from the 95th percentile to the maximum value. As for the bathymetric constraint, the extreme value class was determined by the bathymetric values that range from the 95th percentile to the maximum value (Figure 3-25 and Table 3-6).

These distinct classes allowed us to follow the movements of each class (suitable area) over time. In addition, the weighted analysis method used in this study required a common consistent scale.

3.6.3 Species selection for representation

From 89 species studied, twelve species inhabiting different types of environment and with different origin or affinity were chosen to demonstrate this work: *Anthias anthias, Balistes capriscus, Umbrina canariensis, Arnoglossus thori, Arnoglossus laterna, Arius parkii*, *Solea senegalensis, Diplodus vulgaris, Myctophum punctatum*, *Pomatomus saltatrix, Ammodytes tobianus,* and *Lepidorhombus whiffiagonis* (Table 3-7).

The criteria used in the species selection were based on the species distribution pattern or affinity (subtropical or tropical and temperate waters), number of occurrences used in generating environmental envelope, and biological characteristics.

The environmental envelopes were obtained, as seen in the previous subchapter, by extracting the environmental raster data values at the location of species occurrence at the time of observation at the global scale.

Table 3-7: Species choosen for modelling demonstration.

Species	**Environment**	**Affinity**	**Number of occurrences used for generating environmental envelope**		
			SST		Bathymetry
			Season 1[a]	Season 2[b]	In Total
Anthias anthias	Benthopelagic	Sub/Tropical	128	100	1941
Balistes capriscus	Benthopelagic	All	1205	1551	7487
Umbrina canariensis	Benthopelagic	Sub/Tropical	670	377	2720
Arnoglossus thori	Demersal	All	219	190	605
Arnoglossus laterna	Demersal	Temperate	3175	22645	26808
Arius parkii	Benthopelagic	Tropical	357	423	870
Solea senegalensis	Demersal	Sub/Tropical	164	113	356
Diplodus vulgaris	Benthopelagic	Sub/Tropical	259	264	825
Myctophum punctatum	Bathypelagic	Temperate	182	163	2023
Pomatomus saltatrix	Pelagic	Sub/Tropical	20973	9316	34517
Ammodytes tobianus	Benthopelagic	Temperate	1214	977	2924
Lepidorhombus whiffiagonis	Demersal	Temperate	8852	32920	42575

[a]Season 1 = Winter-Spring; [b]Season 2 = Summer-Autumn.

3.6.4 GIS model: Weighted Overlay

Two formal phases are implemented to model species distribution: (1) assessing the species' preferred ranges for the environmental variables taken into account and (2) projecting these ranges into an environmental raster data by identifying the areas in which these ranges occur (Boitani and Fuller 2000). The second phase of modelling, which involves the true distribution model, has seen its potential greatly enhanced by the increasing use of geographic information systems (GIS). This technique furthermore enables to identify a species potential habitat in large portions of territory, especially in data-poor-areas.

The rationale behind the GIS approach to species distribution modelling is straightforward (Boitani and Fuller 2000), where the database contains layers, generally in a raster format, each of which describes the distribution of each environmental variable.

The GIS weighted overlay model used in this study applies one of the most used approaches for overlay analysis to solve multi-criteria problems including site selection and suitability models (ESRI 2015).

In this study, we adopted the weighted optimization raster model that uses a consistent scale in form of categorical values. The idea behind consistent scale is to integrate analysis of dissimilar input. This scale also represents the class of species suitable areas. Environmental parameters were weighted based on their influence to species distribution (Wright 2011), but in this study, the influence of each parameter was treated equally and set to 0.5 (Figure 3-26).

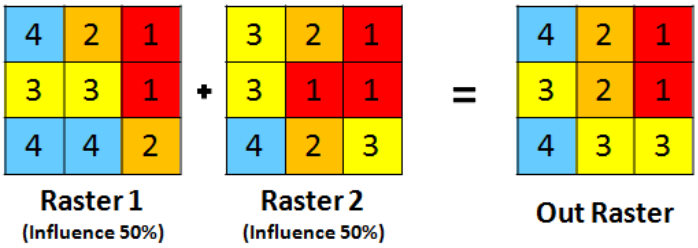


Figure 3-26: Illustration of a weighted model. The first two input rasters have been reclassified to a common measurement scale of 1 to 4 representing the classes of species suitable habitat (see Table

3-6). Each raster was assigned a percentage of influence which is in this study was set to be equally important (50%). Each cell value was multiplied by its percentage of influence and the results were added together to create the output raster. For example, consider the value on the top left cell of each raster. The values for the two inputs (Raster 1 and Raster 2) become 4 * 0.5 = 2 and 3 * 0.5 = 1.5. The sum of 2 and 1.5 is 3.5. The output raster from the Weighted model was integer so that the final value was rounded to 4 (ESRI 2015).

The weighted model compares the biologically important resources using simple mathematical algorithms in the map algebra of the *ArcGIS*^{TM} software. The results show the important areas for the species modelled. These areas could be used to suggest the placement of marine protected areas for marine conservation and to enhance fisheries (Keith 2004). The model can be adjusted to the weighting scenarios, and it can be applied for multiple species or to target specifically species of particular concern.

3.6.5 Species suitable areas: bathymetric constraint and SST constraint

Weighted GIS modelling procedures conducted in this study are detailed stepwise as follows:

- In the first step, we computed the bathymetric constraint of the species modelled. The species bathymetric constraint was obtained using the selected bathymetric data: depth, slope and benthic zone. These derivatives bathymetric data were classed into four classes based on the species' preferences values (Figure 3-27a, Figure 3-27b, and Figure 3-27c).
- A first weighted overlay process was performed for these three raster, resulting in one raster of four classes representing the species' bathymetric constraint (Figure 3-27d). White area on the map in Figure 3-27d is the area that fell outside the species' bathymetric preference range.

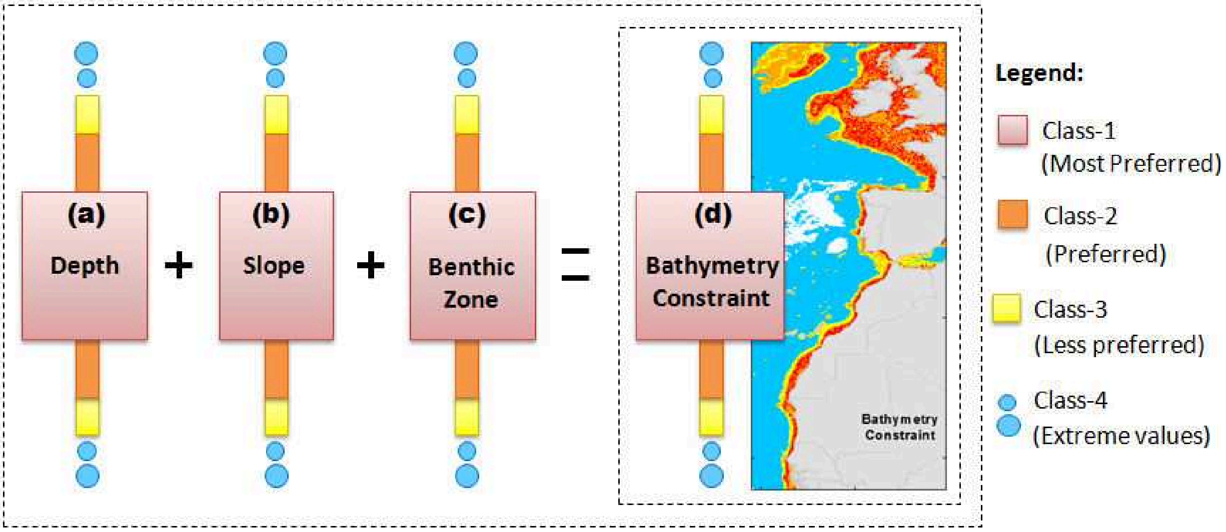


Figure 3-27: Species bathymetric constraint. (a) Depth; (b) Slope and (c) Benthic zone are divided in four classes of different colors. Weighted overlay among these raster resulting in (d) Species' bathymetric constraint. Red color always represents the Class-1, orange the Class-2, yellow the Class-3, and blue the Class-4. White areas on the map represent the areas beyond the species' bathymetric range and were set to Null or No-Data.

- The area in the extreme bathymetric range (the Class 4) was separated from the other three classes (Figure 3-28a). This Class-4 was not incorporated in the further overlay process (with species'

SST classes). This was to ensure that the extreme bathymetric values remain extreme for the final model. It also prevented this extreme class from becoming higher, i.e., if the Class-4 of the bathymetric constraint met the Class-1 of the SST constraint. This would change the extreme class to preferred class, which is not intended.

- The seasonal SST raster was classed into four classes of preference (Class-1 to Class-4) according to the species' SST envelope. SST values that fell beyond the species' SST range were set to NULL or No Data, represented by the white area on the map (Figure 3-28b).
- The second weighted overlay process was performed between the species' SST classes (four classes: the Class1-4) and the species' bathymetric constraint (three classes: the Class 1-3). The result was a raster of three classes (the Class 1-3) of the species suitable areas: the most preferred, preferred and the less preferred (Figure 3-28c).
- In the final step, the raster of Class-4 of the species' bathymetric constraint was collated to the three-class raster of from the previous step, resulting in a raster of potential distribution areas for the species in four classes (Figure 3-28d).

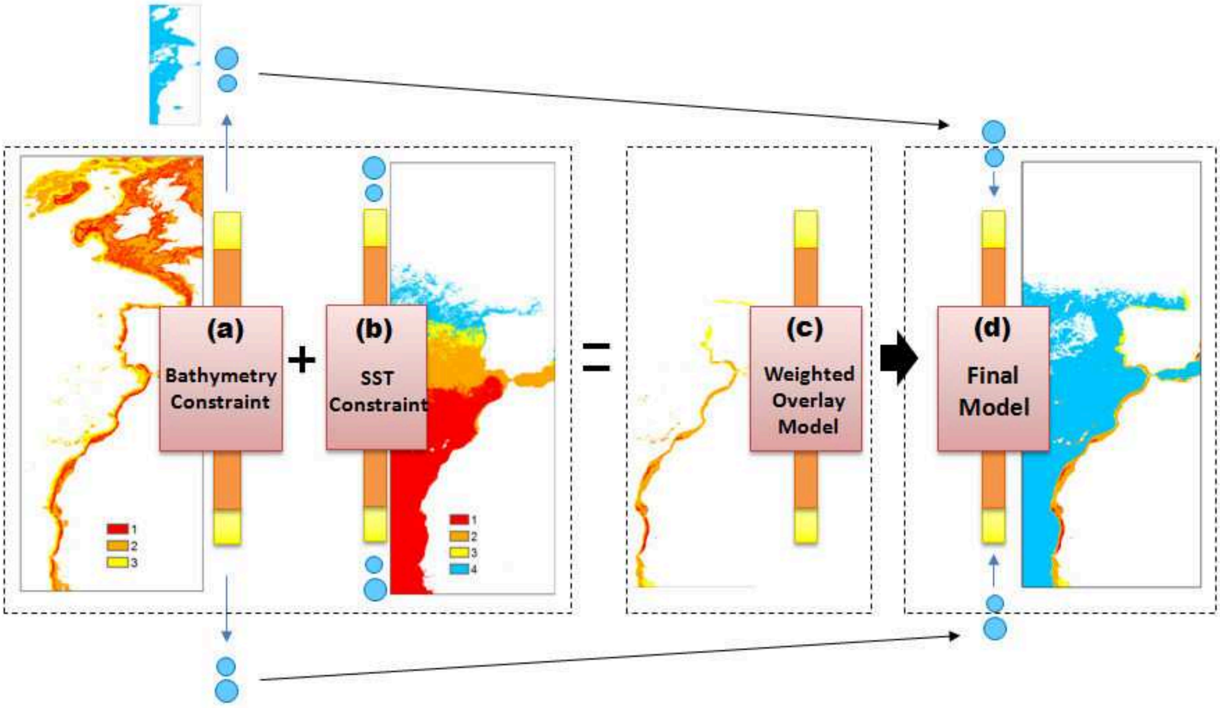


Figure 3-28: Weighted model of *Diplodus vulgaris*. (a) Species' bathymetric constraint (Class 1-3) with separate Class 4; (b) Species' SST constraint in spring; (c) Weighted overlay between three class of bathymetric constraint and four class of SST constraint; (d) Model of *D. Vulgaris* with collated Class-4 of bathymetric extreme class.

The flowchart in Figure 3-29 presents the procedures of GIS-based weighted analysis of species distribution modelling.

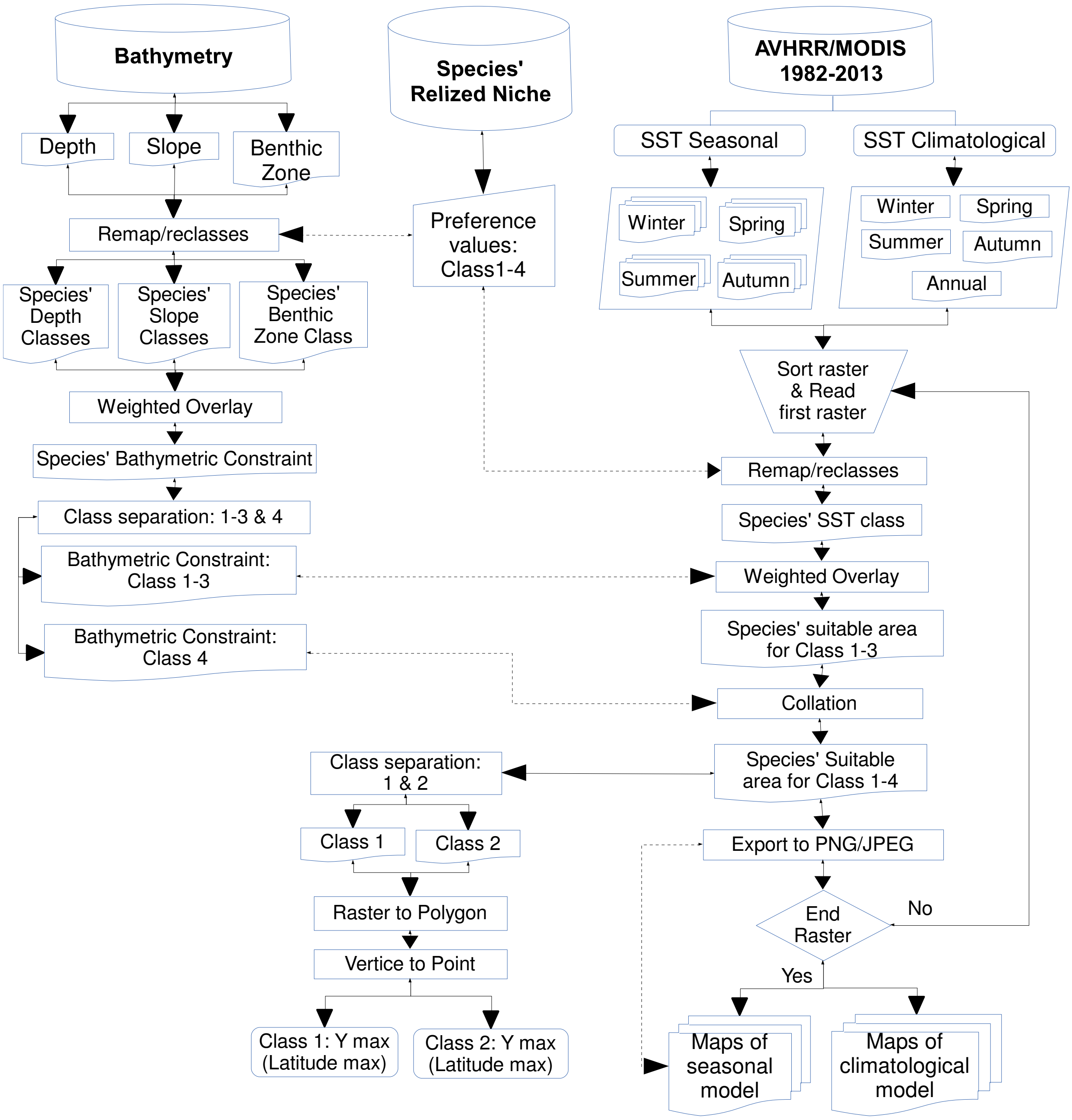
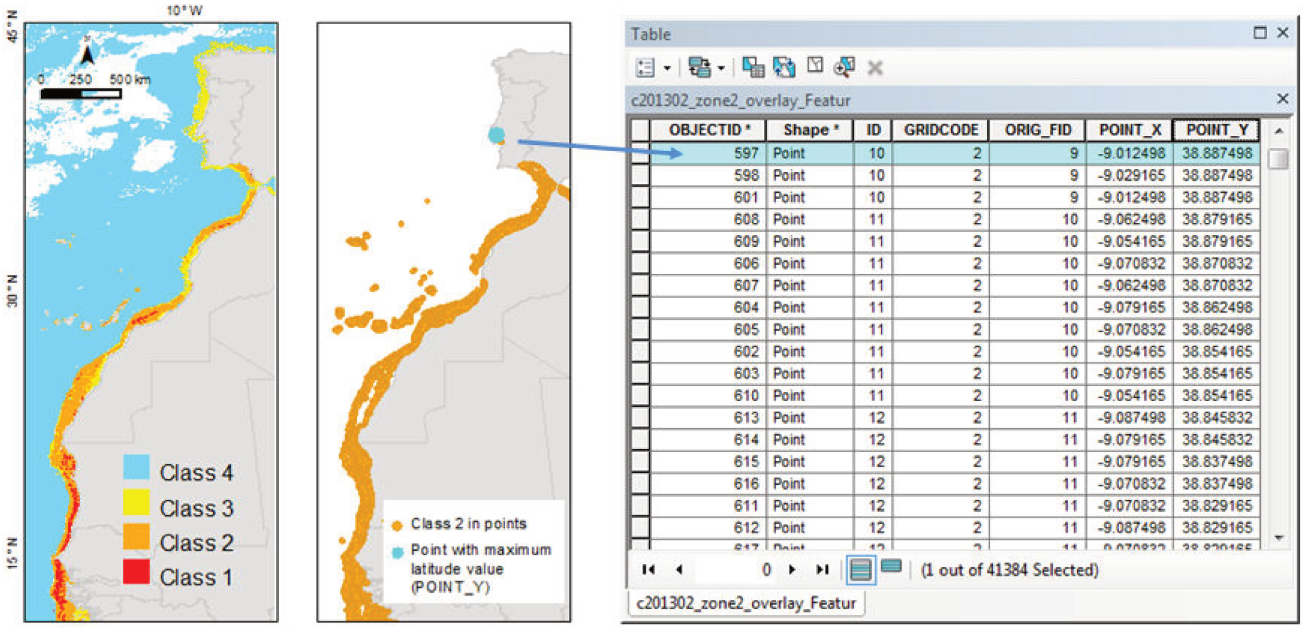


Figure 3-29: Flowchart of modelling species distribution with weighted overlay analysis.

3.6.6 Following the evolution of the northern/southernmost point of the species' suitable areas

The results of weighted overlay analysis were a raster that contained four classes of values of species suitable areas: from Class-1 to Class-4. These classes were separated and converted to the polygon shapefile feature. The polygon feature was constructed by several points or vertices/vertex containing geographic coordinate values of latitude and longitude. These coordinated values were then captured and stored in the form of a table (Figure 3-30). The maximum value of latitude (POINT_Y) is the northernmost point of each class (polygon). Using the entire seasonal model of the species' potential distribution from 1982 to 2013, we were able to follow the evolution of the northernmost point for the upper limit as well as the lower limit of each area/class (see flowchart in Figure 3-29).



OBJECTID *	Shape *	ID	GRIDCODE	ORIG_FID	POINT_X	POINT_Y
597	Point	10	2	9	-9.012498	38.887498
598	Point	10	2	9	-9.029165	38.887498
601	Point	10	2	9	-9.012498	38.887498
608	Point	11	2	10	-9.062498	38.879165
609	Point	11	2	10	-9.054165	38.879165
606	Point	11	2	10	-9.070832	38.870832
607	Point	11	2	10	-9.062498	38.870832
604	Point	11	2	10	-9.079165	38.862498
605	Point	11	2	10	-9.070832	38.862498
602	Point	11	2	10	-9.054165	38.854165
603	Point	11	2	10	-9.079165	38.854165
610	Point	11	2	10	-9.054165	38.854165
613	Point	12	2	11	-9.087498	38.845832
614	Point	12	2	11	-9.079165	38.845832
615	Point	12	2	11	-9.079165	38.837498
616	Point	12	2	11	-9.070832	38.837498
611	Point	12	2	11	-9.070832	38.829165
612	Point	12	2	11	-9.087498	38.829165

Figure 3-30: Capturing the northernmost point (maximum latitude value/POINT_Y) of a class of a species suitable area.

3.7 Dynamic model of richness

The idea of making a richness model of the studied species arose when we were working on the model of individual species. By simply superposing all models of individual species distribution at a given time, we could calculate the potential number of species present in the given area at the given time. This model could bring information on hotspot areas and be used to assess the effectiveness of MPA location in relation to climate change. The basic technique was to put together all individual species models that have the same time information, then to count the number of species in each area (see illustration in Figure 3-31).

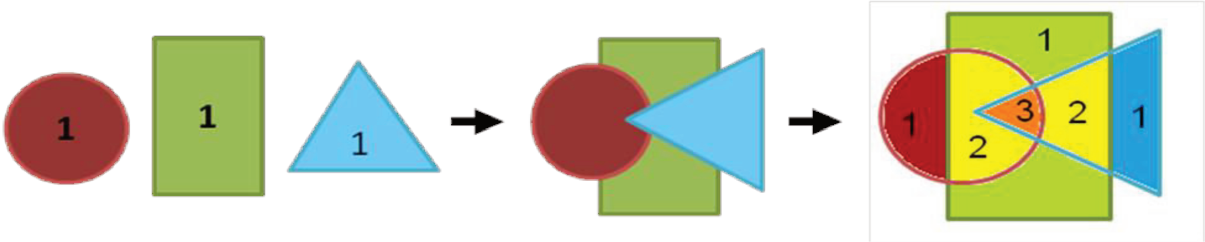


Figure 3-31: Illustration of richness modelling. Each shape represents the distribution area of one species. The number inside the polygon indicates the number of species present in the area.

Figure 3-31 illustrates the principle of making a model of richness. The shapes in the figure represent an illustration of the distribution area of each individual species in the same period of time. The process of superposition takes the spatial location and time as condition. It means that this process takes only the shapes that share the same time. The process superposes all shapes taken into account and then simply calculates the number of shapes intersected as the number of species occurring in the given location.

The individual species distribution model has four classes, representing the species preferential habitat: from the most preferred area/Class-1, to the extreme class/Class-4. In the richness model, we considered only two classes: the Class-1/the most preferred and the Class-2/the preferred. The two classes were joined together to create one class of the most potentially suitable area for a species to occur. The following steps explain the richness modelling procedures in detail:

- The model of a species distribution in raster format was converted to polygon shapefile and separated by its classes. Because each model has four classes, we had then four polygons. In this study we use only Class-1 and class-2.

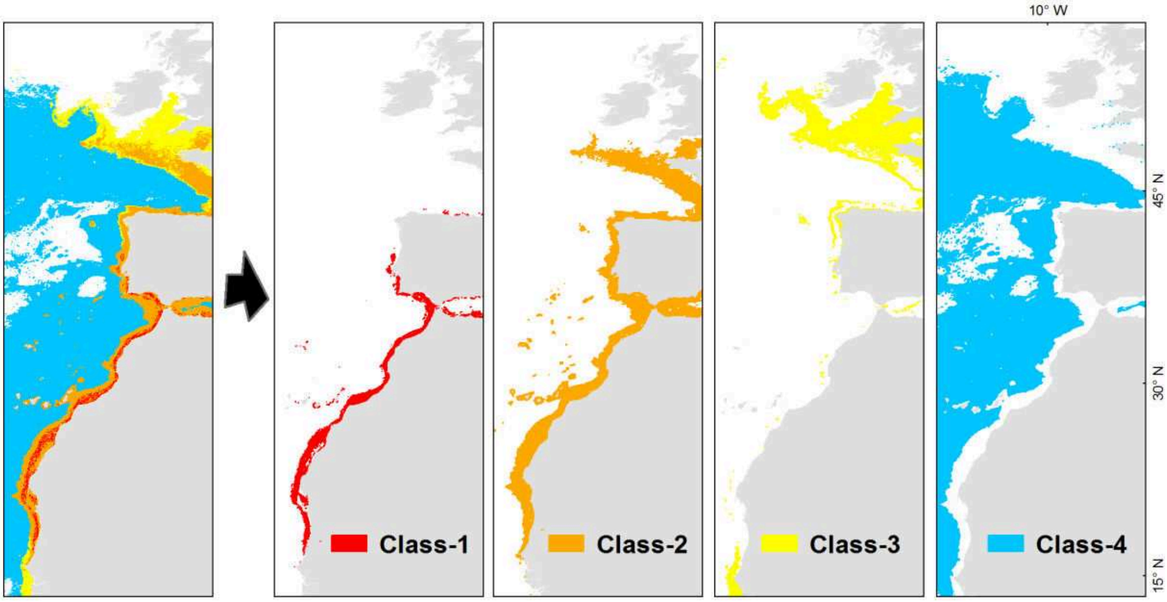


Figure 3-32: Potential distribution of *D. vulgaris* in separate classes (Class-1 to Class-4).

- The two polygons of the Class-1 and the Class-2 were merged together resulting only one polygon. This polygon was assigned with a value of '1' in its attribute table, indicating that this area represented only one species. The area was then considered as the preferred area for the species to occur (Figure 3-33).

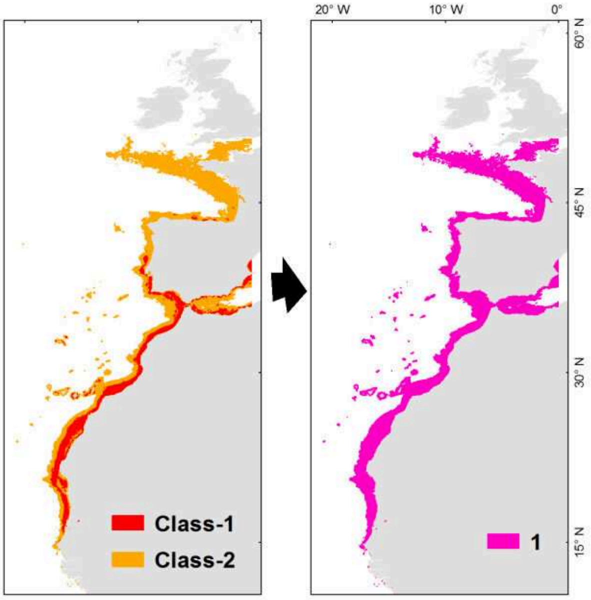


Figure 3-33: Merging the Class 1 and the Class-2 into one class. The resulting class was assigned a value of '1' indicating one individual species.

- The two steps above were applied to all of the species studied (89 selected species). A script written in *Python programming language* was used to automate the process.

- We collected the polygons from all species based on time (season and year) and calculated the number of polygons intersecting other polygons as potential richness (hotspot area). A polygon that overlaped other polygons from other species was assigned a value based on the number of polygon overlaps as illustrated in Figure 3-31. For example, the polygons of all species observed in winter 1982 were collected and superposed. The number of overlapping polygons represents the number of species (Figure 3-31). The tool used to conduct this process is *the Union tool* in the *ArcGIS*^{TM} software.
- The process was repeated for every season from 1982 to 2012.

3.8 Marine Protected Areas (MPAs)

3.8.1 MPA database

We obtained data on Marine Protected Areas (MPAs) from the the World Database on Protected Areas (WDPA), through an online portal of Protected Planet (http://protectedplanet.net). The WDPA contains spatial data and attribute/descriptive information on MPAs. The spatial data are provided electronically in the form of shapefiles as 'polygons'. These files provide information on the location (latitude and longitude) and the size and shape (boundary data) of a specific protected area (Corrigan et al. 2011).

3.8.2 Selecting MPA inside the AOI

MPAs inside the AOI were selected using the *spatial selection tool* of the *ArcGIS*^{TM} software. The tool selected only the MPAs that were present inside the area of study. To ensure all MPAs within the study area were selected, we applied a buffer zones of 5 km surrounding the outer limit of the AOI (Figure 3-34a).

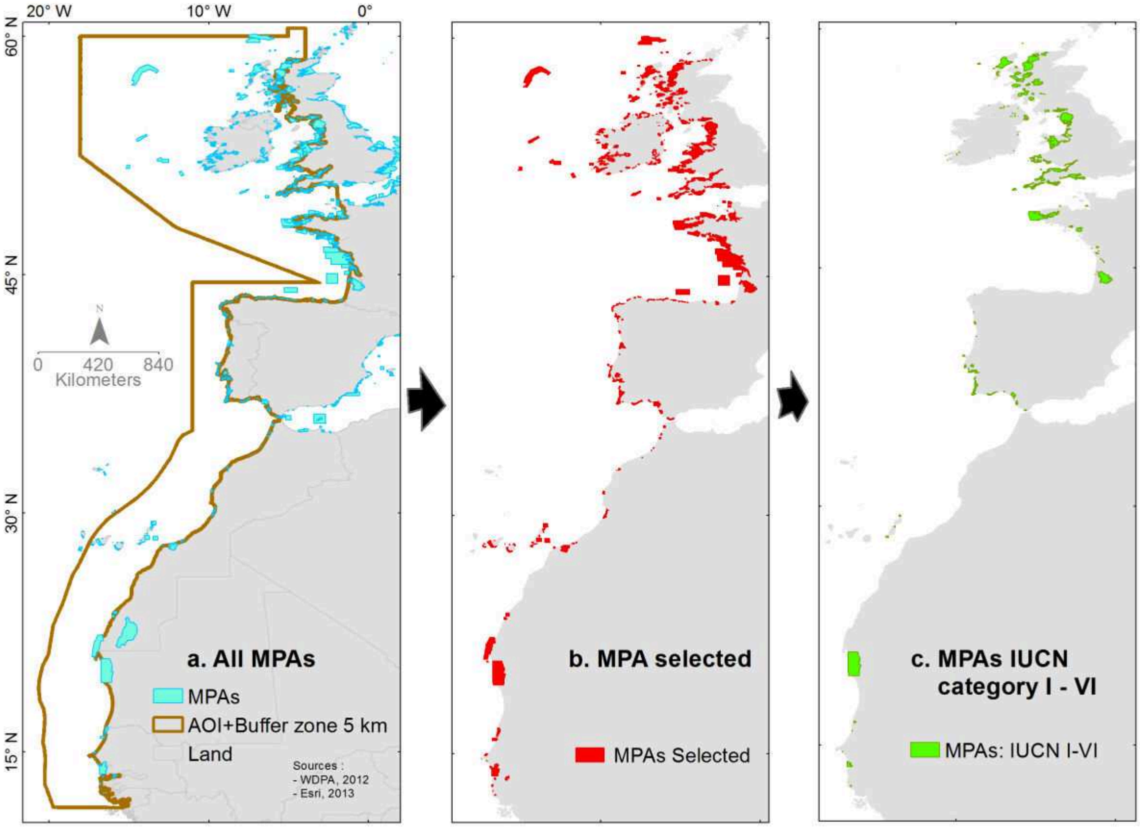


Figure 3-34: (a) MPAs and the boundaries of the AOI with buffer zones of 5 km; (b) Selected MPAs; (c) MPAs selected with IUCN category from I to VI.

3.8.2.1 MPA statistics by country

MPA's polygons need to be reprojected to a *projected coordinate system* in order to perform any geostatistic calculation. The procedures are as follows:

- Defining the coordinate system. A common coordinate system used in georeferenced file is Geographic coordinates (WGS1984). Defining the coordinate system was conducted using the *Define Projection tool* of *the ArcGIS^{TM}* software. The results of this first step were MPA polygons in Geographic Coordinate System WGS1984.
- Converting the geographic coordinate system (GCS) to the projected coordinate system (PCS). Spatial area calculation requires a projected coordinate system, such as *the Universal Transverse Mercator*, because all geometric calculations in *ArcGIS^{TM}* software currently use planimetric algorithms (detailed explanation is available through ESRI website http://resources.esri.com/help/9.3/arcgisengine/dotnet/89b720a5-7339-44b0-8b58-0f5bf2843393.htm). This projected system recognizes areas with number (UTM zones). The AOI consists of several UTM zones. Area calculation on such a biogeographical scale required a particular technique, similar to the technique used to calculate the benthic zone area or the continental shelf area in subchapter 3.2.1.6.

  UTM zones for the countries in the area of study are as follows:

  - Ireland : WGS 1984 UTM Zone 29N
  - United Kingdom : WGS 1984 UTM Zone 30N
  - France : WGS 1984 UTM Zone 30N
  - Spain : WGS 1984 UTM Zone 30N
  - Portugal : WGS 1984 UTM Zone 29N
  - Morocco : WGS 1984 UTM Zone 29N
  - Western Sahara : WGS 1984 UTM Zone 28N
  - Mauritania : WGS 1984 UTM Zone 28N
  - Senegal : WGS 1984 UTM Zone 28N
  - Gambia : WGS 1984 UTM Zone 28N
- MPAs' areas (km^2) were calculated using *ArcGIS' calculate geometry tool.*

3.8.2.2 MPA statistics by 2° latitude

The procedure for calculating MPA areas by 2° latitude was similar to the procedure used for calculating the area of continental shelf explained in the subchapter 3.4.4. We calculated the MPAs' areas per 2° latitude to understand the MPAs distribution by latitude and its proportion in relation to both continental shelf and ecosystem area (Figure 3-34).

At first, we combined all of the MPAs found in the AOI (Figure 3-34a). We re-projected the maps from GCS to PCS. To keep the accuracy of the re-projection map, we clipped the ESRI world UTM polygon in the position of MPAs. It means that instead of having MPA polygons, we used the ESRI UTM world polygon (clipped following the boundaries of MPAs). The ESRI UTM polygon contained the information of UTM zones in its attribute table (Figure 3-34b).

Secondly, we divided the MPAs' UTM polygon by 2° latitude (Figure 3-34c). Area calculation was performed using the *Geometry calculation tool* in *ArcGIS^{TM} software.* The calculation process took into consideration the UTM zone of each latitude/longitude. A script written in *Python programming language* was used to automate the process for all zones.

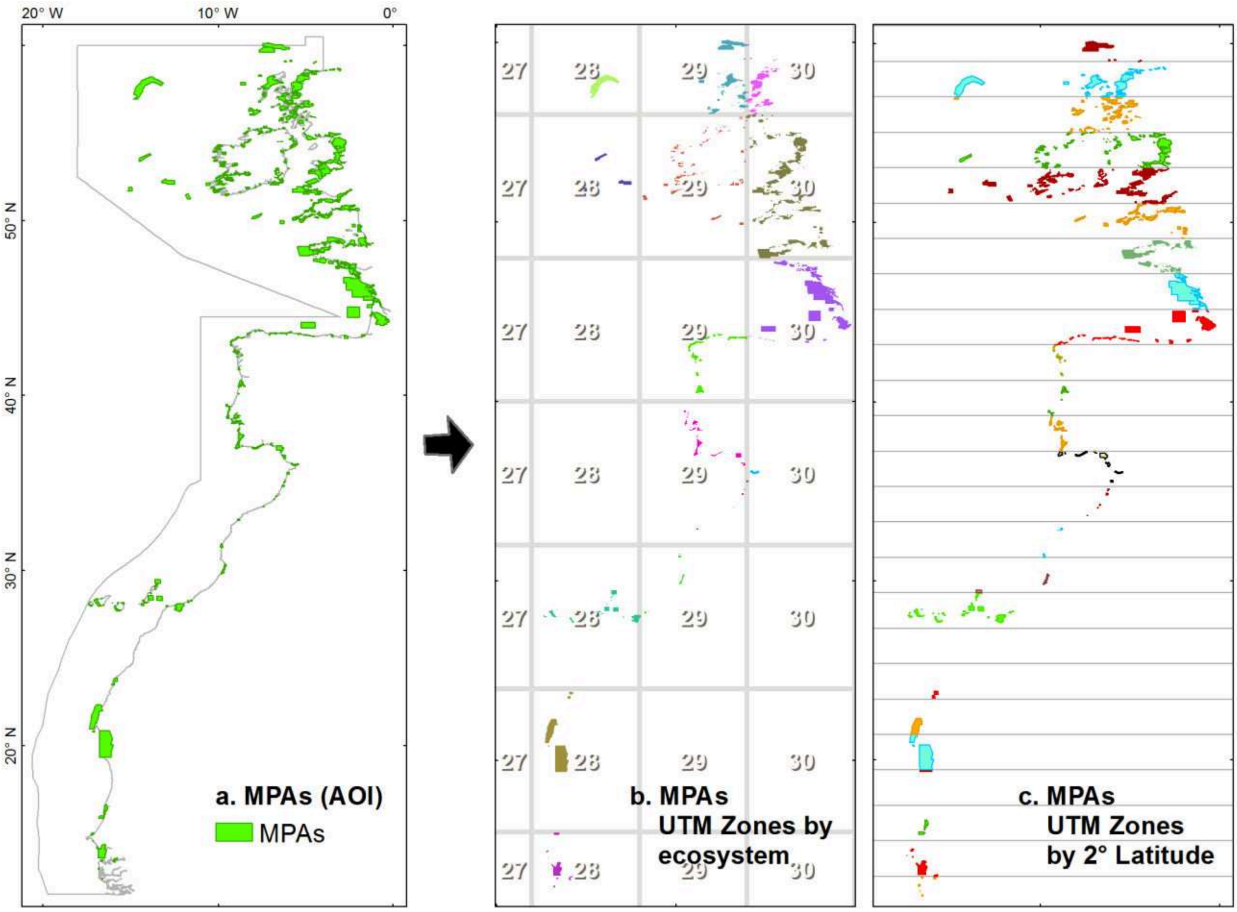


Figure 3-35: (a) MPAs in the AOI; (b) MPAs with their UTM Zones by ecosystem and (c) by 2° latitude.

3.8.3 MPAs areas analysis in relation to richness distribution

The variety of names and uses of MPAs has led to confusion (NOAA's Nat. Marine Protected Areas Center 2013); see Table 2-5 in the section 2.7. The term MPAs could be interpreted as areas established for conservation therefore restricting all human activities. Other types of MPAs allow limited access to human activities such as recreational activities and/or fishing activities. Thus, the term MPAs covers a broad range of purposes, legal authorities and levels of protection (NOAA's Nat. Marine Protected Areas Center 2012).

In this subsection, we selected only MPAs that followed the IUCN management categories, I-IV, as described by Day et al. (2012) as follows:

- Ia = Strict nature reserve. This category ensures the protection of biodiversity and also possibly geological/geomorphological features by strictly controlling human visitation and use.
- Ib = Wilderness area. Usually large unmodified or slightly modified areas, retaining their natural character and influence without permanent or significant human habitation, protected and managed to preserve their natural condition.
- II = Natural park. Large natural or near-natural areas protecting large-scale ecological processes with characteristic species and ecosystems, which also offer environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.
- III = Natural monument or feature. Area set aside to protect a specific natural monument, which can be a landform, sea mount, marine cavern, geological feature such as a cave, or a living feature such as an ancient grove.

- IV = Habitat/species management area. Areas destined to protect particular species or habitats, where management reflects this priority. Many will need regular, active interventions to meet the needs of particular species or habitats, but this is not a requirement of the category.
- V = Protected landscape or seascape. Where the interaction of people and nature over time has produced a distinct character with significant ecological, biological, cultural and/or scenic value; and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and other values.
- VI = Protected areas with sustainable use of natural resources. Areas which conserve ecosystems, together with associated cultural values and traditional natural resource management systems. Generally large, mainly in a natural condition, with a proportion under sustainable natural resource management and where low-level non-industrial natural resource use compatible with nature conservation is seen as one of the main aims.

We followed the seasonal movement richness of the studied species from 1982 to 2013. We selected a zone of hotspot area that was suitable for at least 30 species. We counted the frequency at which this zone intersected or touched the MPAs. We measured the mean intersecting or overlapping area during 32 years of observation.

4 RESULTS AND THEMATIC DISCUSSIONS

4.1 Area of study and bathymetry

4.1.1 Area of Interest (AOI)

The area of interest (AOI) covers three large marine ecosystems/regions in the east Atlantic waters: the Celtic Seas, the South European Atlantic Shelf and the Canary Current (Figure 4-1).

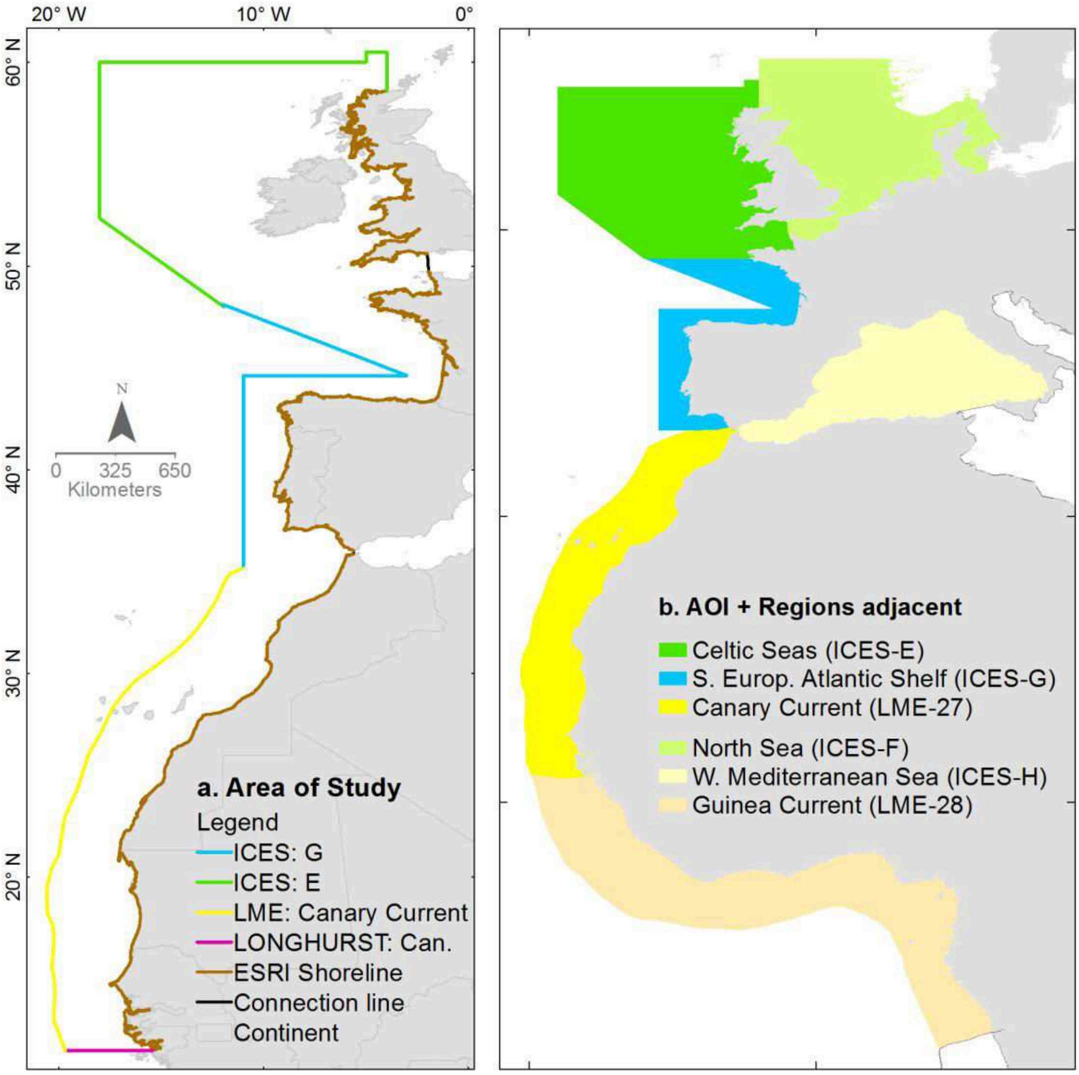


Figure 4-1: (a) Boundaries of the area of interest (AOI); (b) Ecosystems in the AOI (the Celtic Seas, the South European Atlantic Shelf, the Canary Current); and adjacent ecosystems (the North Sea, the West Mediterranean Sea and the Guinea Current).

Figure 4-1a presents the boundaries of the study area covering three marine regions as mentioned previously. Adjacent ecosystems are presented in the Figure 4-1b. Ecosystems in the study area were symbolized with fixed colors according to the color delineating their boundaries. Adjacent ecosystems that limit the study area from the open ocean side, such as the North Atlantic Ocean, are not included in this study. We considered only adjacent ecosystems that limit the study area from the coastal side (the continental shelf) because most of the species occurrences were found in this zone (see Figure 4-16 in the section 4.3.7).

4.1.2 Bathymetry and its derivative

4.1.2.1 Depth and benthic zone

The depth in the study area varies through ecosystems and latitudes (Figure 4-2). Several submarine canyons are found mostly in the middle region of the South European Atlantic Shelf. Several submarine canyons were also found in the northwestern African shelf.

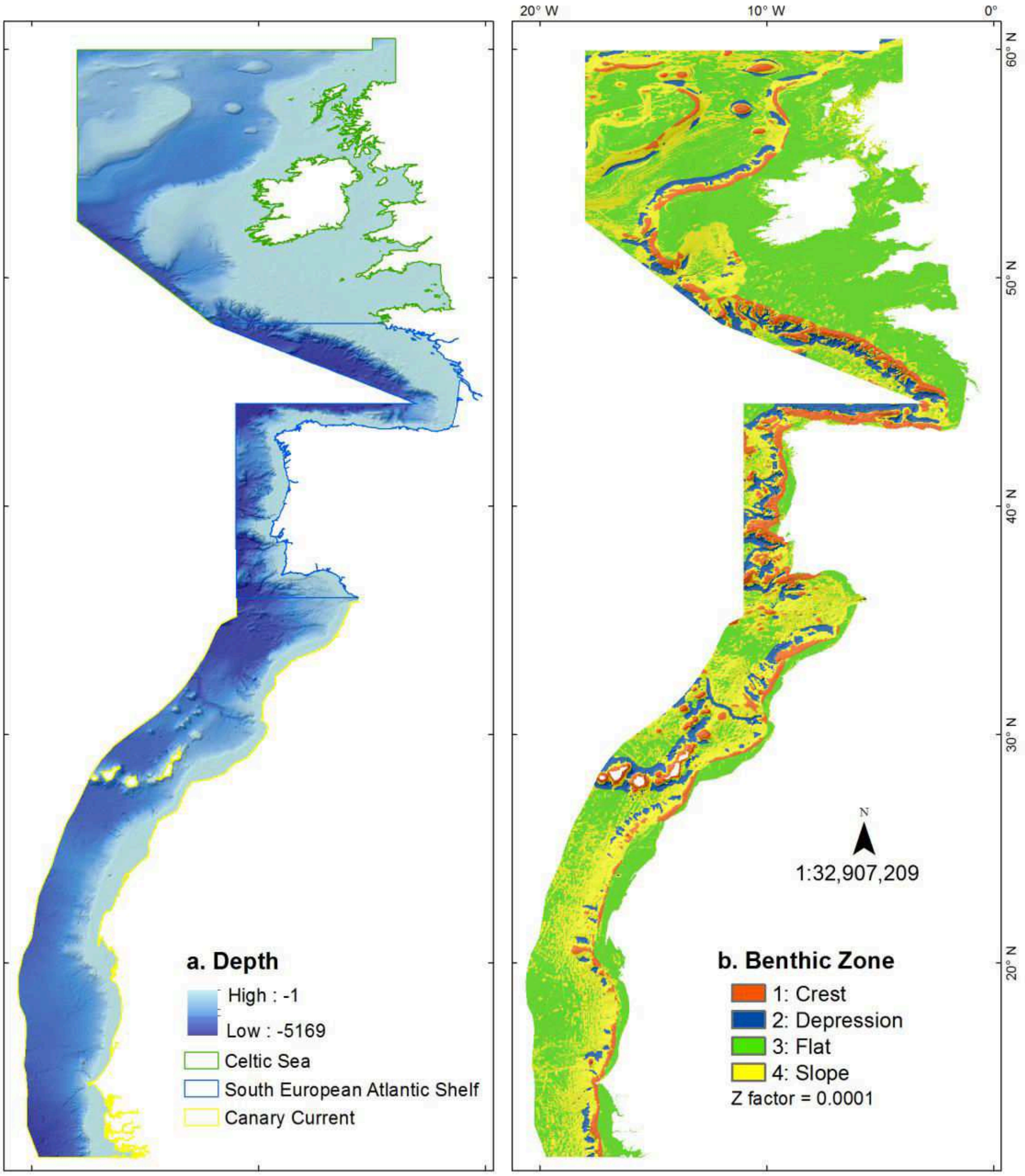


Figure 4-2: (a) Depth distributions and; (b) Benthic zones in the area of interest (AOI). Crests or high points in the terrain are represented by red zones. Depressions or low points in the terrain are represented by blue zones. Flat and slope areas are represented by green and yellow zones respectively. Hillshade applied on the maps produced a 3D effect.

Bathimetric and topographic values outside the AOI in the Figure 4-2 are set to *null* and represented by white colour. For modelling purposes (results presented in the section 4.5), we used bathymetry data that completely cover the AOI (see again subchapter 3.6 in the Materials and Methods section).

The continental shelf in the AOI extends from typically narrow areas (only 10 km wide) in the southern region, to 300-500 km wide areas in the northern region. “Continental shelf” in this study was defined as the areas whose depth range from 0 to 200 meters. This area is usually occupied by many species (see Figure 4-16 in the section 4.3.7). “Other areas” refer to area depper than 200 meters.

Ecosystem boundaries applied in this study allowed comparison of surface areas between the continental shelf and other area among ecosystems (Table 4-1).

Table 4-1: Area of continental shelf (0-200 m) and other area (+200 m) among ecosystems.

No	**Ecosystem**	**Depth area in Km^2 (percentage)**		
		0 – 200 m*	**+ 200 m**	**Total Area**
1	Celtic Seas	861804 (77%)	243933 (22%)	1105737
2	South European Atlantic Shelf	266783 (61%)	165205 (38%)	431988
3	Canary Current	386263 (34%)	736926 (65%)	1123189

*Continental shelf.

Table 4-1 presents the surface areas of continental shelf and other areas in each ecosystem, along with its percentages. The Celtic Seas has the largest continental shelf among ecosystems, 861804 km^2. It is the second largest ecosystem in the AOI and its continental shelf covers 77% of the total area of the ecosystem. The South European Atlantic Shelf has the smallest and narrowest continental shelf (266783 km^2). It is also the smallest ecosystem in the AOI. The Canary Current has 386263 km^2 of continental shelf. It is the largest ecosystem in the AOI. However, most of the area in this ecosystem has more than 200 meters deep (65%).

The Celtic Seas has the largest flat terrain among the studied ecosystems, of 629945 km^2 (Table 4-2). The flat terrain is usually occupied by many species (see Figure 4-24 in the section 4.4.4). This area dominates the area of all ecosystems (73%), and then followed by slope (15%), crest (5%), and depression areas (5%).

Table 4-2: Surface area of benthic zones among ecosystems.

No	**Ecosystem**	**Benthic Zone: Area in Km^2 (percentage)**			
		1. Crest	**2. Depression**	**3. Flat**	**4. Slope**
1	Celtic Seas	51580 (5%)	46901 (5%)	629945 (73%)	133574 (15%)
2	South European Atlantic Shelf	90543 (15%)	87075 (15%)	117944 (20%)	279383 (48%)
3	Canary Current	84201 (7%)	84169 (7%)	454870 (40%)	493268 (44%)

*Crest = high points in the terrain; Depression = low points in the terrain.

The South European Atlantic Shelf is dominated by slope terrain (279383 km^2), nearly half of the total area (48%); see Table 4-2. This ecosystem has also the largest crest and depression terrain (90543 km^2 and 87075 km^2 respectively), nearly in the same proportion (15.7% and 15.1% respectively). Flat area occupies only 20.51% of the total area. Many submarine canyons were found in this ecosystem. Thie terrain condition in this area could become one of the barriers for northward migration from southern species.

In the Canary Current, the flat and slope terrain dominated the area (Table 4-2). However, these physical features were mostly found in the area more than 200 meters deep (see also Table 4-1). The crest and depression terrain occupied small portion of the area, in nearly similar percentage of 7.5%.

4.1.2.2 Slope, aspect and terrain ruggedness

Bathymetry derivative such as slope, aspect (slope direction) and terrain ruggedness might be used to identify areas of high biodiversity, or as input in modelling species distribution and species potential habitats (Figure 4-3).

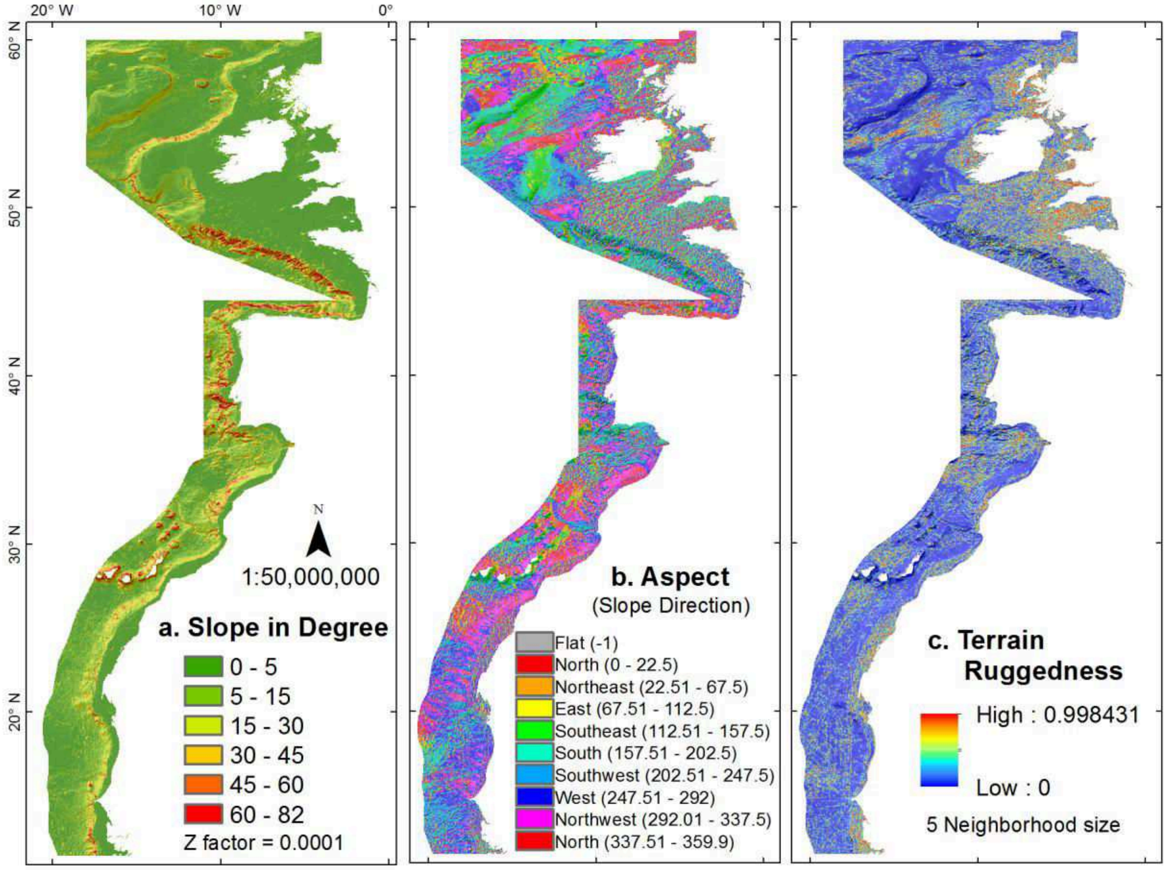


Figure 4-3: (a) Slope in degree; (b) Aspect in degree of direction; and (c) Terrain Ruggedness. The degrees of slope are presented in color graduation, from red (steeper) to green (flat). The lower the slope value the flatter the terrain. The aspect represents slope direction from 0 (north), 180 (south) to 360 (back to north). Terrain ruggedness vary from 0 (no terrain variation) to 1 (complete terrain variation). Hillshade applied on the maps create a 3D Effect.

Slope, aspect and terrain ruggedness in the study area vary among ecosystems. The slope map (Figure 4-3a) presents the variation of slope in each region, from the nearly flat area represented in green color (where the slope values range from 0-5 degree) to the stream slope area in red color (where the slope values range from 60-82 degree).

The Celtic Seas is characterized by a large portion of flat area where the slope values are below 5°, the South European Atlantic Shelf is characterized by the steep slope (above 45°), while the Canary Current is characterized by flat and moderate slopes (less than 3°).

The aspect map (Figure 4-3b) presents the direction of slope. It is the compass direction of slope or where the slope faces. Aspect is utilized by studies as an approach to derive information from sea current direction. The values of the aspect are in degrees that range full circle from 0 (due north) to 360 (due north again). A value of -1 indicates a flat area which has no down-slope direction.

The terrain ruggedness map (Figure 4-3c) indicates how rough or bumpy a surface is. Ruggedness values in the study area range from 0, or no terrain variation (represented in blue color) to

0.99, or nearly complete terrain variation (represented in red color). Higher values indicated areas of high-relief. It could be an indicator of areas with potentially high biodiversity. Wright (2011) and Wright et al. (2013) stated that this feature could be an effective proxy for species habitat.

4.1.2.3 Discussion: Mapping benthic zone

This study produced several maps of bathymetry (derivatives), such as benthic zones, by applying a shallow water classification scheme to larger and deeper areas. The accuracy of the benthic zone attribute produced in this study was not tested because of the broad scale of our area of analysis. Field surveys need to be conducted in future studies to acquire ground truth and to establish a statistically robust assessment of the thematic accuracy of our bathymetry maps.

Benthic terrain classification studies rely primarily on analysis and interpretation of *multibeam bathymetry* beside visual survey data (e.g., transect video, still photos, grab samples, etc.) to make qualitative and/or quantitative inferences (Lundblad et al. 2006). Greene et al. (1999) developed a successful classification scheme for fish habitats offshore of Central California and describes broad classes, such as mega-habitats (based on depth and general physiographic boundaries), meso/macro-habitats (based on scale), seafloor slope, seafloor complexity, and geologic units. Lundblad et al. (2006) added that the scheme can be carried to more detailed habitat characteristics, such as microhabitats (based on observed small-scale seafloor features), seafloor slope (estimated from *in situ* surveys), and seafloor complexity (estimated *rugosity*), by direct observation or through photo or video-interpretation.

Coyne et al. (2003) chose hierarchical classification to define and delineate habitats. This hierarchical classification uses two categories of classes as zones and habitats. Lundblad et al. (2006) explain that “zones” describe a benthic community’s location, while “habitats”, which occur within zones, are based on geomorphologic structure and biological cover type. The structure and cover components are then further divided into major and detailed levels. This approach was first developed by the Caribbean Fishery Management Council (Coyne et al. 2003) and subsequently refined for use in Hawaii and the US Pacific Territories (Lundblad et al. 2006).

This study does not attempt to go further to define more detailed sea floor classes due to lack of field observation, but encourages doing so in future studies. We hope that the use of benthic terrain classification with the integration of marine data into the furtherance of GIS may lead to more efficient management of marine protected areas, simpler decision and advancements in marine and coastal research, and improvements on marine mapping.

Extensive field observations are required to determine habitat types in areas where there is still uncertainty, where gradients exist through habitat types or where habitat diversity is highly heterogeneous (Lundblad et al. 2006).

4.2 Climate change: pattern in SST

4.2.1 Monthly and seasonal SST trend

The mean monthly sea surface temperatures (SST) from 30 years of observation (1982-2012) in three marine ecosystems studied are presented in the time series plots. These plots show considerable variation of SST over time.

In the Celtic Seas, a progressive SST change was observed in the first 10 years of observation (Figure 4-4), followed by ten years of moderately SST changed. In the last ten years of observation, relatively stable of SST was observed. This pattern seems to indicate a decadal variation of SST in this ecosystem. Overall, the temperature seems to increase over time, although in the recent years, the trend of SST seems to going down. The highest mean monthly SST value was observed in August 1995 (16.45 °C) while the lowest was observed in March 1986 (8.08 °C). Detail monthly SST values in the study area are available in Annex 1, Annex 2, and Annex 3.

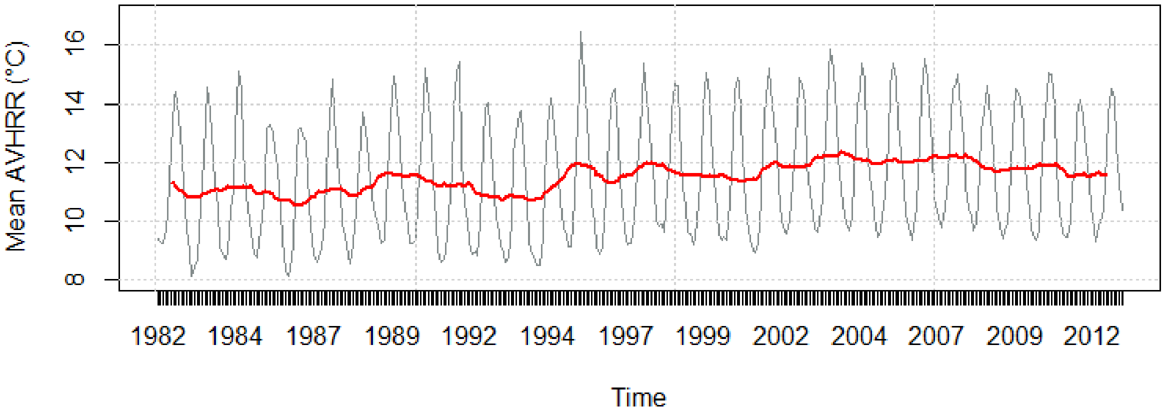


Figure 4-4: Mean monthly SST (°C) in the Celtic Seas observed from 1982 to 2012. The red bold line represents the SST trend.

Seasonal cycles contribute dominantly in the variation of SST in the Celtic Seas region (Figure 4-5). The increasing pattern of SST was observed over time. The orange curves (Figure 4-5a) that represent the SST in early years of observation were mostly found below the blue curves (curves that represent SST in recent years). There may be some orange curves found above the blue curves indicating warmer years, but there is no blue curve found under or below the lowest orange curve. This pattern indicates clearly that the SST in the region is increasing. In general, lower values of SST in the Celtic Seas were observed in winter (January to March), while highest values were observed in summer (July to September) (Figure 4-5b).

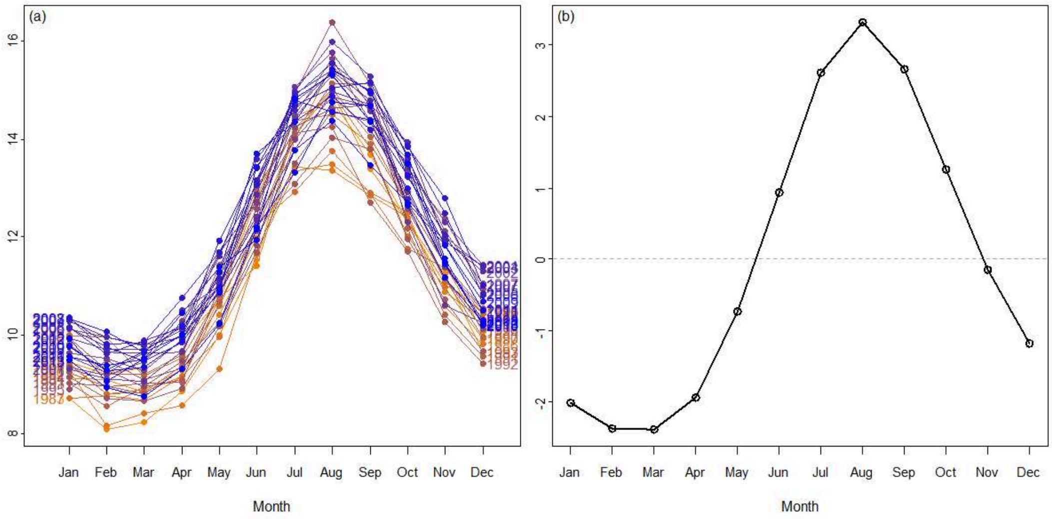


Figure 4-5: Seasonal SST plot in the Celtic Seas. (a) Mean monthly SST (°C) per year. One curve represents one year. The orange curve represents the SST values in earlier years (starting in 1982) and the curve color gradually change to blue as they get near 2012; (b) Estimated Seasonal effect.

In the South European Atlantic Shelf, a decadal variation of SST trend was also observed (Figure 4-6). A stable increasing trend of SST was observed in the first ten years, followed by an aggressively changed of SST trend in the next ten years. In the last ten years of observation, the trend of SST was relatively more stable than the previous two decades. The highest mean SST value was observed in August 2003 (21.11 °C) indicating the hottest period, while the lowest SST was observed in March 1984 (11.65 °C). High peak of SST was observed in summer 2003 after a considerably low SST in the same season of the pevious year.

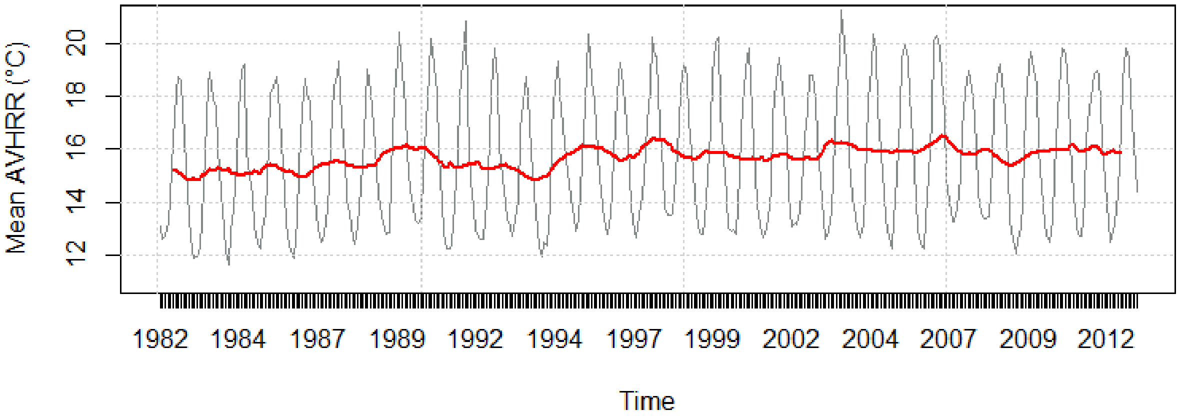


Figure 4-6: Mean monthly SST (°C) in the South European Atlantic Shelf, observed from 1982 to 2012. The red bold line represents the SST trend.

The seasonal variation of SST in the South European Atlantic Shelf presents a similar pattern as in the Celtic Seas (Figure 4-7). It indicates the rising of sea surface temperature in the region. In general, lower values of SST in this ecosystem were found during winter period, while higher values were observed in the summer period. An extreme SST winter value was observed in 1995, with a value higher than other years including the recent years. The SST reached their maximum on August. There were several cases when the maximum summer SST happened on September (e.g., 1982, 1984, 1987 and 1991); see Annex 1 for details.

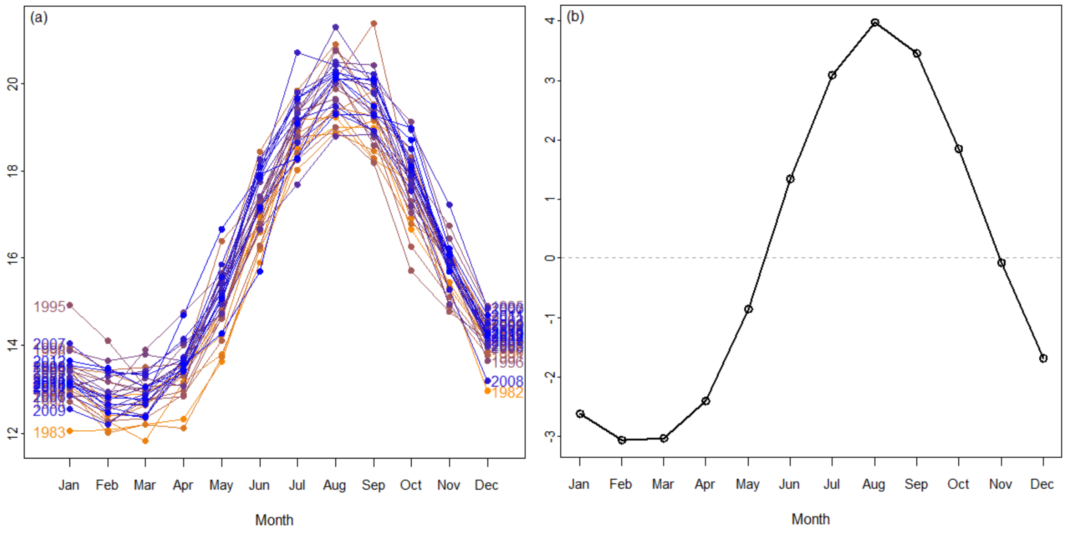


Figure 4-7: Seasonal SST plot in the South European Atlantic Shelf. (a) Mean monthly SST (°C) per year. One curve represents one year. Orange curve represents the SST values in earlier years (starting in 1982) and gradually change to blue as they get near to 2012; (b) Estimated seasonal effect.

In the Canary Current, a consistent increasing SST trend was observed over time (Figure 4-8). The SST values in recent years are higher than those observed in earlier years. The highest mean monthly SST was noted in October 2009 (24.63 °C), while the lowest was observed in February 1984 (17.22 °C). Similarly to the two previous ecosystems, higher values of SST were found in summer, while lower values were observed in winter. Detailed monthly SST values in this ecosystem are available in Annex 1, Annex 2, and Annex 3.

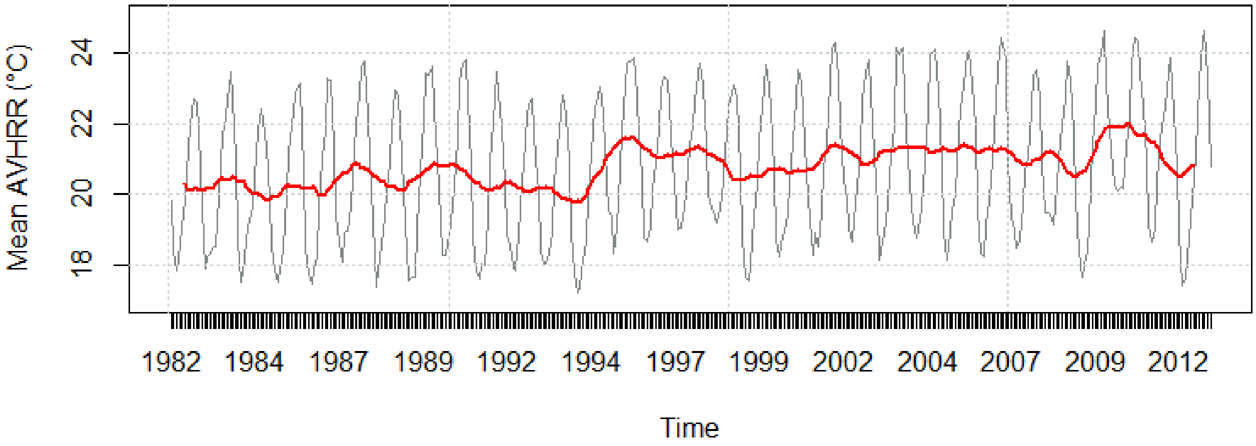


Figure 4-8: Mean monthly SST (°C) in the Canary Current, observed from 1982 to 2012. The red bold line represents the SST trend.

While the SST reaches its peak during summer in the Celtic Seas (Figure 4-5) and the South European Atlantic Shelf (Figure 4-7), the peak of SST arrives later in the Canary Current, from September to October (Figure 4-9), and drops in the same period of winter, January to March. An aggressive increase of SST was observed in winter (January-Mars). In this period, the SST in the recent periods (blue curves) were much higher than those observed in the earlier periods (orange curves). This phenomenon was not observed in the two previous regions.

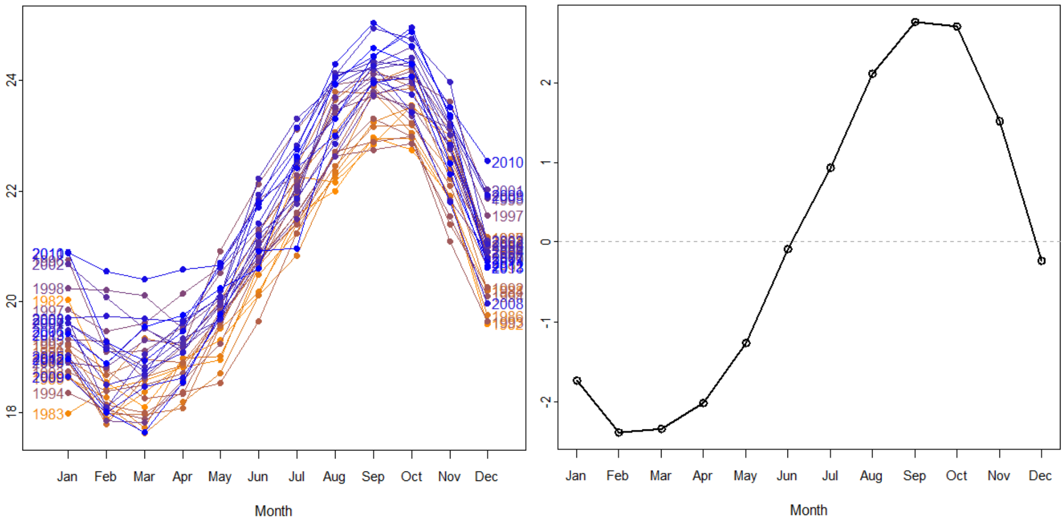
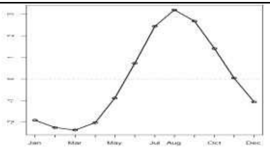
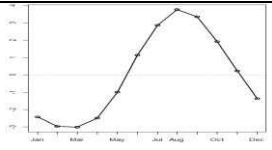
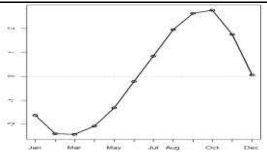
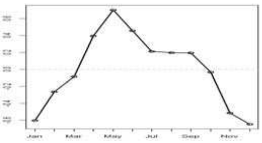
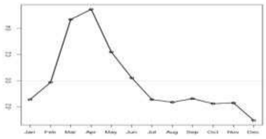
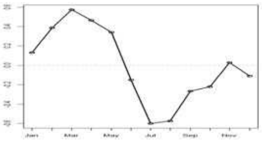
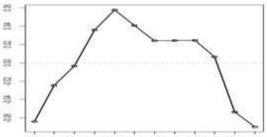
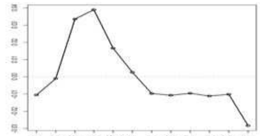
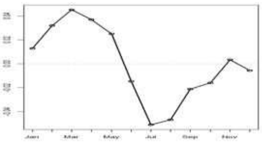
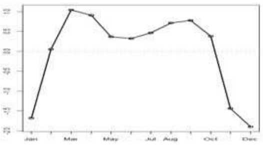
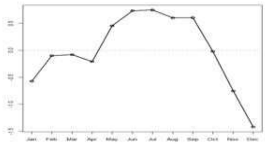
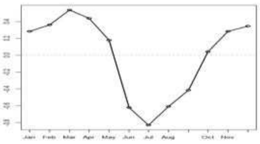
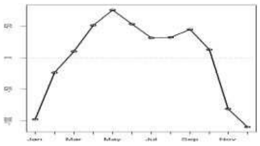
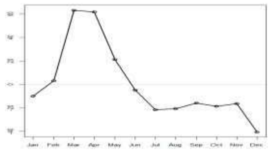
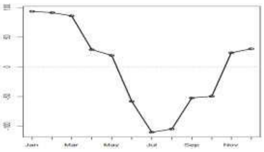
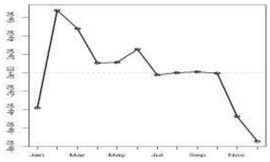
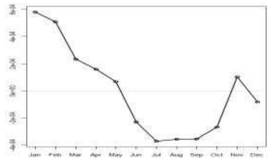
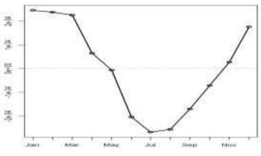
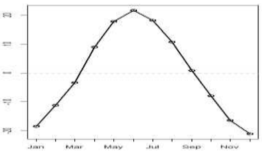
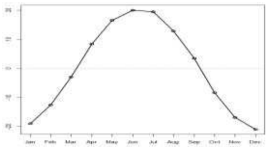
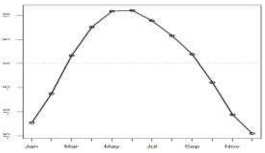
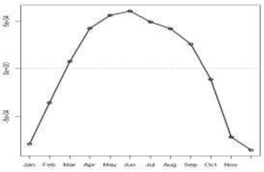
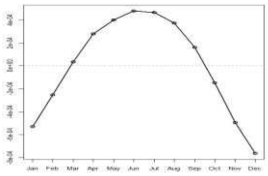
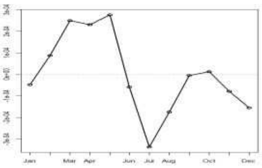


Figure 4-9: Seasonal SST plot in the Canary Current. (a) Mean monthly SST (°C) per year. One curve represents one year. Orange curve represents the SST values in earlier years (starting in 1982) and gradually change to blue as they get near to 2012; (b) Estimated Seasonal Effect.

4.2.2 Chlor-a and other oceanic parameters

Seasonal pattern of Chlor-a and other oceanic parameters obtained from MODIS data in the period of 2002-2013 are presented in Table 4-3. This result shows the variation of oceanic parameters trends among ecosystems. Further analyses of these parameters were not conducted because it beyond the scope of our study. These parameters are also not incorporated in the analyses of species distribution modelling. Hence, it will not be included in discussion.

Table 4-3: Seasonal Component Estimation of all variables.

Parameters	**Celtic Seas**	**South European Atlantic Shelf**	**Canary Current**
SST (Sea Surface Temperature)			
Chlor-a (Chlorophyll-a concentration)			
Kd490 (Diffuse attenuation coefficient at 490nm)			
CDOM (Coloured dissolved organic matter)			
POC (Particulate organic carbon concentration)			
PIC (Particulate inorganic carbon concentration)			
PAR (Photo-synthetically available radiation)			
PAR (Instantaneous photo-synthetically available radiation)			

4.2.3 Disscussion: increasing temperature

In general, the SST values in recent periods are higher than in earlier periods, indicating sea warming. These increasing trends were observed in the three ecosystems studied. It appears clearly in the Celtic Seas (Figure 4-4) and Canary Current (Figure 4-6), while in the South European Atlantic Shelf, the SST values increased slightly over time (Figure 4-8).

Trends of SST patterns indicated a decadal variation of SST increase in the three ecosystems studied (Table 4-4). Table 4-4 shows the maximum, minimum and standard deviation values for daily SST observations in each ecosystem (see Annex 1, Annex 2, and Annex 3 for more detailed information).

Table 4-4: Summary SST statistics in each ecosystem by decadal period.

Period	Celtic Seas # E				South Europe # G				Canary Current # 27			
	Min	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**
I	0.20	21.15	11.10	2.02	4.48	25.30	15.38	2.49	12.31	30.35	20.35	1.97
II	1.00	20.92	11.42	2.10	6.24	25.40	15.67	2.43	13.48	30.59	20.74	1.92
III	2.41	20.88	11.95	1.98	5.00	26.31	15.93	2.59	13.33	30.66	21.22	1.95

* I = 1981-1990; II = 1991-2000; III = 2001-2012; South Europ. = South European Atlantic Shelf.

In the Celtic Seas, the SST changes aggressively in the first two decades (1982-1991 and 1992 to 2001). The mean SST value in the first decade was 11.10 °C, before increasing to 11.42 °C in the following decade (1992-2001), and rised to 11.95 °C in the recent decade (2001-2011) (Table 4-5). Overall, the SST in this ecosystem has increased by 0.85 °C for the past three decades (*P values* < 0.005) (Table 4-5).

In the South European Atlantic Shelf, The mean SST was observed at 15.38 °C in the first decade (1982-1991), 15.67 °C in the second decade (1992-2001) and 15.93 °C in the last decade (2002-2011) (Table 4-5). Overall, the SST in this ecosystem has increased by 0.55 °C for the past three decades (*P values* < 0.005) (Table 4-5).

In the Canary Current, the mean SST was at 20.35 °C in the first decade (1982-1991), 20.74 °C in the following decade (1992-2001), and 21.22 °C in the last decade (2002-2011). Overall, the mean SST in this ecosystem has increased by 0.87 °C for the past three decades (*P values* < 0.005) (Table 4-5).

Table 4-5: Difference between means (*P values*) – Paired Test.

Period	Celtic Seas			South European Atlantic Shelf			Canary Current		
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
I	-	0.32 (5.7e-06)	0.85 (2.2e-16)	-	0.29 (0.0001)	0.55 (1.2e-10)	-	0.39 (7.6e-07)	0.87 (2.2e-16)
II	0.32 (5.7e-06)	-	0.53 (1.3e-12)	0.29 (0.0001)	-	0.26 (0.0006)	0.39 (7.6e-07)	-	0.48 (6.5e-09)
III	0.85 (2.2e-16)	0.53 (1.3e-12)	-	0.55 (1.2e-10)	0.26 (0.0006)	-	0.87 (2.2e-16)	0.48 (6.5e-09)	-

*I = 1981-1990; II = 1991-2000; III = 2001-2012.

4.3 Species studied

The results of this section have been published in Kaimuddin et al. (2016). Please refer to this article for further details.

4.3.1 Selected species

Eighty-nine fish species have been selected from approximately 465 potentially invasive fish species identified in various sources. The selected species were composed by 14 temperate species, 29 subtropical species, 16 temperate-subtropical species, 13 tropical species and 17 species found in all type of affinity mentioned above (see checklist in Annex 4).

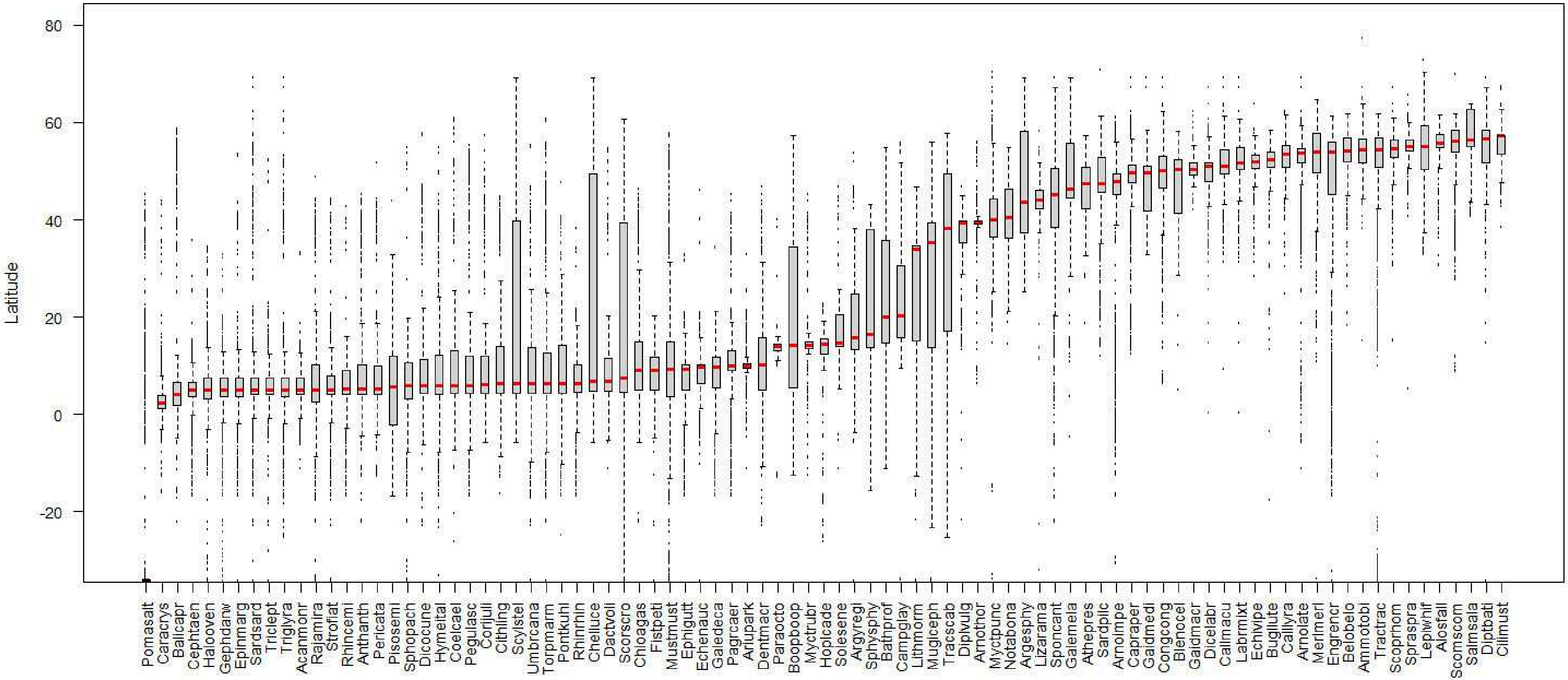


Figure 4-10: Latitudinal Distribution of 89 species studied (ordered by median). Each box-plot represents one species. Lables on abscissa: species' scientific names abbreviated to eight characters using *Cepnames function* of Vegan *package in* R software (Annex 4).

Latitudinal distributions of the 89 selected species for this study are presented using box-plots in Figure 4-10. The box-plot represents the geographic distribution of species occurrences for all seasons including records with no time of observation.

4.3.2 Similarity of ecosystem

Many species of concern in this study share their distribution range with the adjacent ecosystem (Figure 4-11). In the northern part of the study area, the North Sea shares many species with the Celtic Seas. Some of these species, such as *Salmo salar* and *Ammodytes tobianus*, reach the South European Atlantic Shelf. In the southern part of the study area, the Canary Current shares many species with the Western Mediterranean (i.e. *Coris julis* and *Pomatomus saltatrix*). The Canary Current shared also many species with the Guinea Current (i.e. *A. parkii* and *Caranx crysos*).

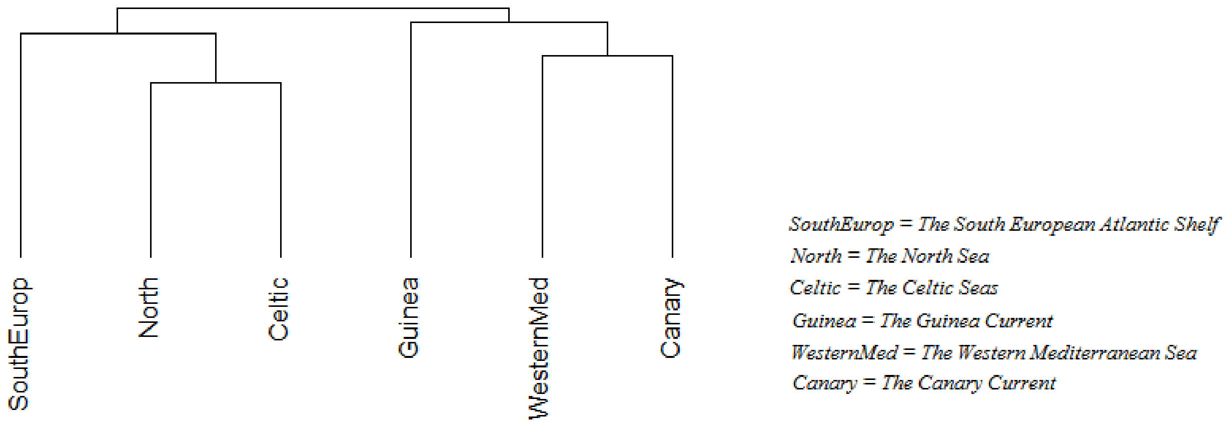


Figure 4-11: Ecosystems clustered by *Jaccard similarity*. Ecosystems with very similar species compositions are grouped together.

4.3.3 Number of species by period by ecosystem

Analyses of richness of the studied species over time in the study area are presented in Figure 4-12.

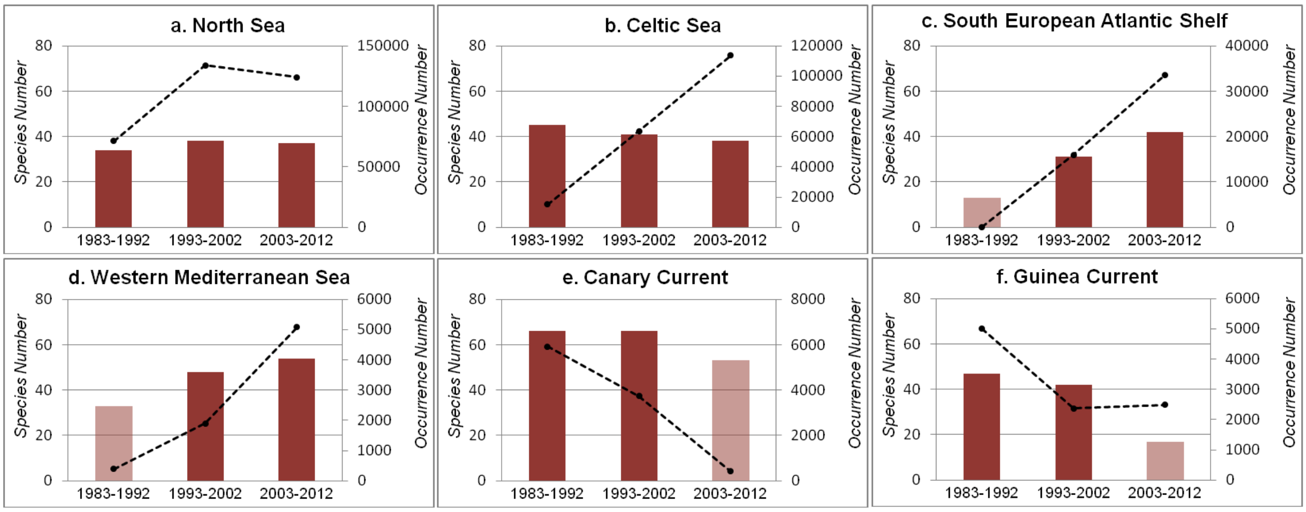


Figure 4-12: Number of species by period in each ecosystem. Transparent bars represent periods with insufficient data (see rarefaction curves in Table 4-7). Dashed lines represent number of occurrence (details are in Table 4-6).

In the North Sea, the number of species increased slightly from the first period to the second period following a significant increase of occurrence records (Figure 4-12a). In the last period: 2003-

2012, the richness in this region decreased slightly following a slight decrease of occurrences (detailed information in Table 4-6). In the Celtic Seas, the number of species decreased over time despite a significant increase in the number of occurrence records (Figure 4-12b).

In the South European Atlantic Shelf, the number of species increased considerably over time following an increasing number of occurrence records (Figure 4-12c). Similarly, in the Western Mediterranean Sea, the number of species increased over time along with the increase of occurrence records (Figure 4-12d). The numbers of occurrences for both ecosystems in the first period were insufficient for rarefaction analysis (see rarefaction curves in Table 4-7).

In the Canary Current, the number of species decreased only slightly over time despite the considerably decreased of occurrence records (Figure 4-12e). A similar pattern was observed in the Guinea Current (Figure 4-12f). The numbers of occurrences for both ecosystems in the third period were insufficient for rarefaction analysis (see rarefaction curves in Table 4-7).

Table 4-6: Number of species and occurrences in each ecosystem by decadal periods.

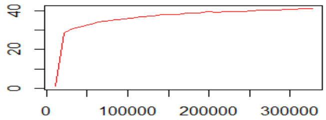
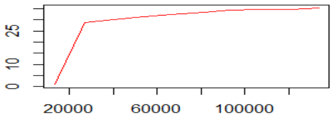
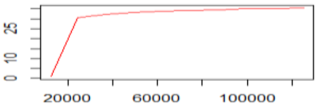
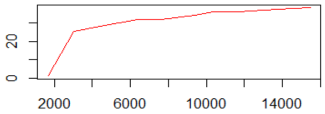
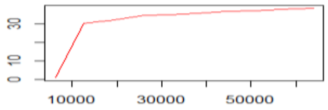
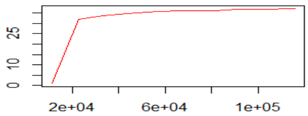
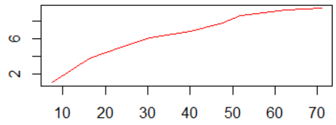
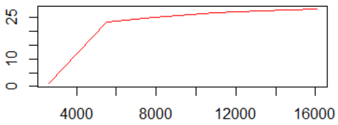
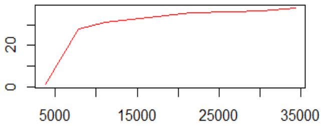
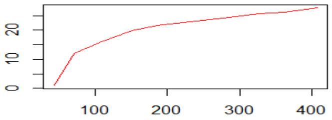
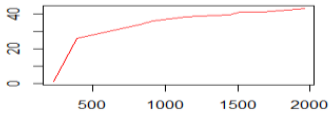
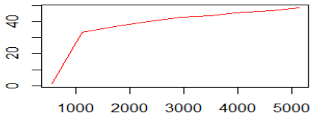
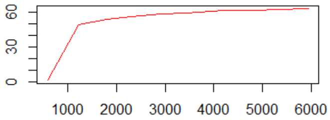
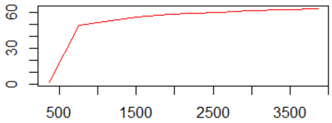
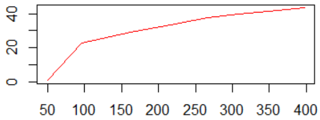
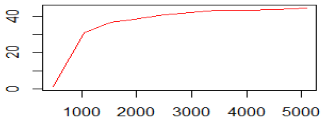
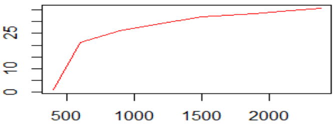
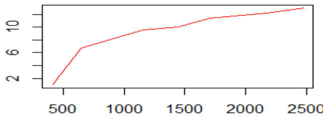
ID	Ecosystem	**Period I (1983-1992)**		**Period II (1993-2002)**		**Period III (2003-2012)**	
		Number of Occ.	Number of Species	Number of Occ.	Number of Species	Number of Occ.	Number of Species
1.	North Sea	71426	34	134036	38	124061	37
2.	Celtic Seas	15222	45	63634	41	113619	38
3.	South Europ.	70	13	15993	31	33584	42
4.	Western Medit.	394	33	1904	48	5087	54
5.	Canary Current	5910	66	3738	66	418	53
6.	Guinea Current	5006	47	2365	42	2489	17

* Number of Occ. = Number of occurrence records.

In the northernmost ecosystems (North Sea and Celtic Seas) species occurrences seem to increase over the time periods and this is accompanied by stable or slightly decreasing numbers of species. The central-most region (South European Atlantic Shelf and Western Mediterranean), on the other hand, appears to be characterized by marked increases in both the number of occurrences and the number of species over time. Finally, the southernmost region (Guinea current and Canary current) exhibits a decrease in both occurrences and the number of species. These results seem to point to an overall enhancement in the biodiversity and biomass in the central region to the detriment of the southernmost region.

The rarefaction curves for richness estimation in each ecosystem are presented in Table 4-7. In all observed ecosystems, the curves are near saturation except in the first period of the South European Atlantic Ecosystem and the Western Mediterranean Sea, and in the third period of the Canary Current and Guinea Current. The stable saturated curves indicate sufficient sample size to allow the comparison of richness among periods, meaning that a larger sample size would not significantly change the estimation of richness.

Table 4-7: Rarefaction curves per period in each ecosystem. The Y-axis represents number of species. The X-axis represents the individual occurrence records.

No.	Ecosystem	Period I	Period II	Period III
1.	North Sea			
2.	Celtic Sea			
3.	South Europ.			
4.	Western Mediterranean Sea			
5.	Canary Current			
6.	Guinea Current			

4.3.4 Number of species by 2° latitude

Analysis of richness by 2° latitude is presented in Figure 4-13. Several zones have been excluded due to insufficient number of occurrence records (see rarefaction analysis by 2° latitude in Annex 5).

Number of studied species varies by latitude. Number of species in the northern region is lower than that in the southern region despite the large continental shelf area. The highest number of species was found in Senegal waters, at latitude of 14°-16° north with 64 species (red bars in Figure 4-13).

Many species from the northern and southern regions have their northern or southern limit of distribution in the central area. Thus, number of species in these middle latitudes is relatively higher than that in the northern latitudes. This region is also known to have several new introduction species from southern zone of tropical waters. This was happended when the sea temperature rise and made the area suitable for tropical species. Detail number of species per 2° latitude along with the occurrence records and area of continental shelf are presented in Table 4-8.

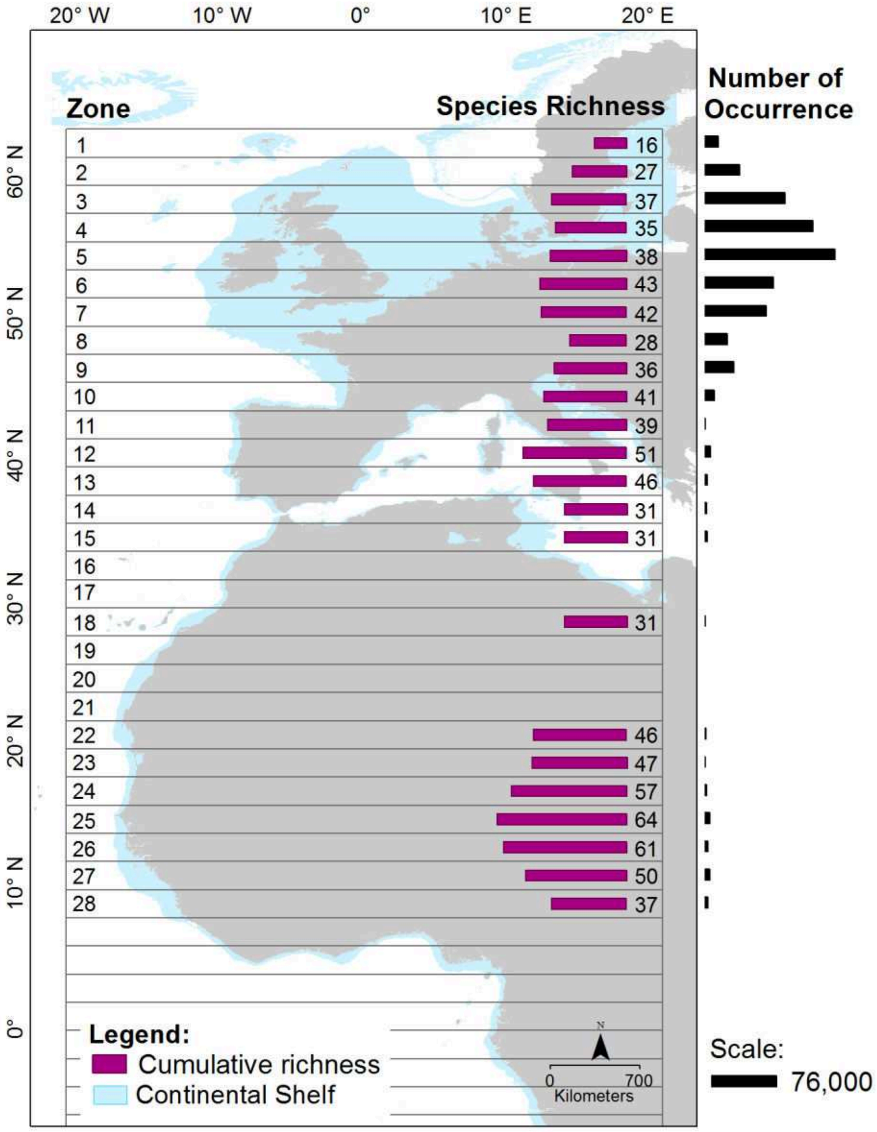


Figure 4-13: Distribution of number of species (bars in dark purple) and number of occurrence records (bars in black) by 2° latitude. Continental shelf area (0-200 m deep) is presented in light blue color.

Table 4-8: Occurrences, Cumulative number of species and Continental Shelf Area (0-200m) per 2° latitude.

Zone	Latitude (°N)	Occurrence Record	Number of Species (Indvidu)	Continental Shelf Area (Km^2)
1	62 - 64	13315	16	89671
2	60 - 62	35309	27	135206
3	58 - 60	82495	37	234857
4	56 - 58	111323	35	303899
5	54 - 56	133786	38	248805
6	52 - 54	70545	43	135686
7	50 - 52	63263	42	163058
8	48 - 50	22764	28	82855
9	46 - 48	29578	36	51267
10	44 - 46	9246	41	87006
11	42 - 44	337	39	82925

Zone	Latitude (°N)	Occurrence Record	Number of Species (Indvidu)	Continental Shelf Area (Km^2)
12	40 - 42	5508	51	63317
13	38 - 40	1746	46	45348
14	36 - 38	1581	31	72663
15	34 - 36	2261	31	77606
16	32 - 34	57*	18	45534
17	30 - 32	13*	11	27395
18	28 - 30	137	31	28438
19	26 - 28	16*	7	11821
20	24 - 26	76*	17	26785
21	22 - 24	54*	15	16205
22	20 - 22	629	46	22786
23	18 - 20	287	47	16036
24	16 - 18	1302	57	10233
25	14 - 16	4874	64	12957
26	12-14	2851	61	25266
27	10-12	5042	50	55564
28	08-10	2422	37	38476

*Zone with insufficient data (see rarefaction analysis by 2° latitude in Annex 5).

4.3.5 Movement route

Out of the 89 selected species, we found 13 species that extended their area of distribution northward. Among these species, approximately 7 species that were initially found in the Canary Current were recently found with marked records in the Western Mediterranean Sea (ID: CW in Figure 4-14a and Table 4-9). Six species that were initially in both the Canary Current and the Western Mediterranean Sea were recently found in the South European Atlantic Shelf (ID: CWS).

Thirty-five species shared their area of distribution with the adjacent ecosystem or moved among ecosystems according to season. Among these species, 10 species were always found in both the Canary Current and the Western Mediterranean Sea (ID: C=W). Twelve species from the Canary Current had ranges that included the Guinea Current (ID: C=G). Thirteen species were present in both the Celtic Seas and the North Sea (ID: C=N), and among those 13 species, 12 also reached the South European Atlantic Shelf (ID: NCS) (Table 4-9).

Regarding the last 41 species studied, it was unclear whether they are moving or not. Among these species, 27 were always present in all ecosystems and at all periods of the study (ID: ALL in Table 4-9), and 14 species were present with very low occurrence records (ID: D in Table 4-9).

The species of Atlantic-origin that have been observed in Mediterranean waters in the last period are among the species listed as exotic for the Mediterranean Sea by the CIESM (2002) (ID: CW in Table 4-9). Six species originated from the Canary Current and the Mediterranean Sea have been recently found in the South European waters: *Chlorophthalmus agassizi*, *Citharus linguatula, Dactylopterus volitans, Diplodus vulgaris, Solea senegalensis, and Sphoeroides pachygaster*. These findings highlighted the importance of the South European Atlantic Shelf as a transition zone and as a target zone for southern species when water temperature rises.

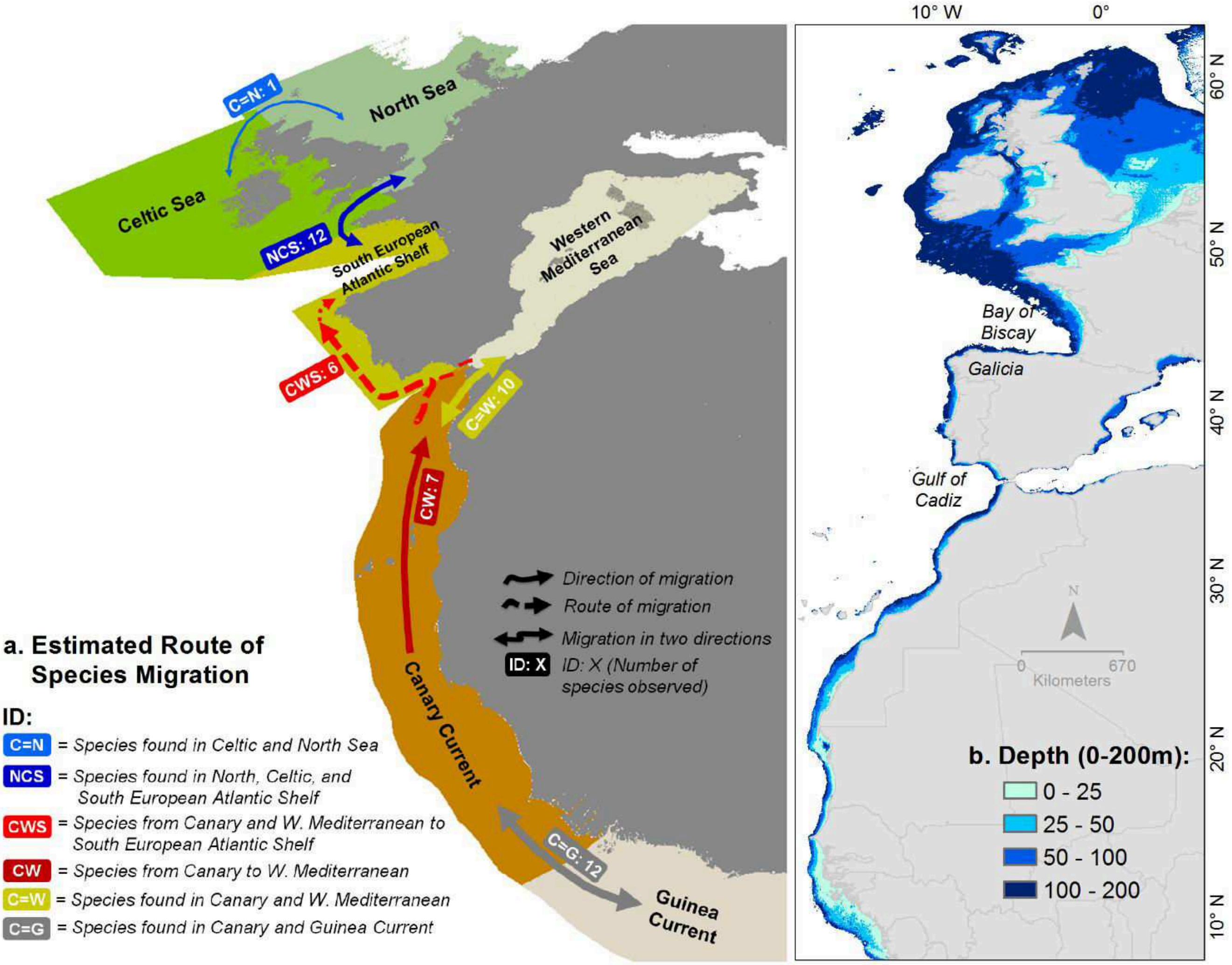


Figure 4-14: (a) Species movement flow in the study area. The arrows indicate the direction(s) of movement. IDs and numbers in rounded rectangles indicate the number of migrating species of that type; see Table 4-9 for details. (b) Depth distribution. Most of the species studied were found in the area with depth less than 200 m (see also Figure 4-16).

Table 4-9: Number of occurrence by ecosystem in each decadal period. Column of CIESM indicates whether a species is noted as exotic/alien (Y) or not (N) by CIESM (2002). South Europ. = the South European Atlantic Shelf; Western Medit. = the Western Mediterranean Sea. P1/Period 1 = 1983-1992; P2/Period 2 = 1993-2002; P3/ Period 3 = 2003-2012. See text and Figure 4-14 for ID definition. Number of species found by ID, C=G: 12 species; C=W: 10 species; CW: 7 species; CWS: 6 species; NCS: 12 species; C=N: 1 species; ALL: 27 species; D (Doubtful): 14 species.

ID	**Species Code***	**CIESM**	**North Sea**			**Celtic Seas**			**South Europ.**			**Western Medit.**			**Canary Current**			**Guinea Current**		
			P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
CW	Acanmonr	Y													71	86	1	31	31	0
CW	Ariupark	Y													50	29	58	540	161	0
CW	Cephtaen	Y													41	23	0	3	3	2
CW	Fistpeti	Y													189	107	0	92	119	0
CW	Gephdarw	Y													47	40	2			
CW	Halooven	Y													87	43	8	0	1	0
CW	Pisosemi	Y													26	6	0	15	4	0
CWS	Chloagas	N							0	2	1	2	59	113	238	139	1	39	3	1
CWS	Cithling	N							2	0	0	1	18	20	328	190	4	64	0	2
CWS	Dactvoli	N				0	4	6				0	6	13	382	245	0	211	189	6
CWS	Diplvulg	N							0	0	3	1	89	295	36	31	4			
CWS	Solesene	Y							0	0	1	0	7	8	95	139	24	2	0	0
CWS	Sphopach	Y							0	0	2				85	121	4	20	40	2
NCS	Alosfall	N	22	166	28	4	14	216	0	0	12	0	0	2						
NCS	Ammotobi	N	441	418	541	47	196	423	0	5	100									
NCS	Calllyra	N	8427	18676	23157	2063	13459	16740	0	1031	2086									

ID	Species Code*	CIE SM	North Sea			Celtic Seas			South Europ.			Western Medit.			Canary Current			Guinea Current		
			P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
NCS	Cilimust	N	1362	1387	485	35	124	96	2	1	0									
NCS	Dicelabr	N	45	119	413	14	112	435	1	51	270	0	1	20						
NCS	Diptbati	N	60	44	65	74	312	543	0	2	0									
NCS	Echivipe	N	41	188	127	4	134	20	0	0	2	1	0	0						
NCS	Gaidmedi	N	1	0	1	8	20	19	0	0	2									
NCS	Labrmixt	N	64	108	368	448	1016	5380	0	0	32	0	0	8						
NCS	Lepiwhif	N	2083	3094	5466	2087	9514	16766	2	683	1838	2	29	141	0	1	0			
NCS	Scoprhom	N	846	1805	2422	31	484	531	0	6	7	0	8	10	0	1	0			
NCS	Spraspra	N	32051	54761	29394	1799	6522	6199	0	46	214	0	0	4						
C=W	Anthanth	N										30	27	84	9	8	2	20	4	4
C=W	Corijuli	N										45	89	67	2	9	1	7	38	0
C=W	Epinmarg	N										1	24	66	26	4	0	3	1	0
C=W	Pericata	N										0	4	20	120	66	2	48	14	4
C=W	Pomasalt	N										0	0	11	62	16	0	15	9	0
C=W	Rajamira	N										0	47	193	1	12	18	1	4	0
C=W	Rhincemi	N										1	0	0	68	0	2	44	10	0
C=W	Sphysphy	N										0	0	16	31	12	0	14	2	0
C=W	Strofiat	N										0	0	8	107	48	2	7	38	0
C=W	Umbrcana	N										0	5	1	234	149	17	35	0	0
C=N	Salmsala	N	38	52	9	8	64	9												
C=G	Campglay	N													24	25	3	2	1	0
C=G	Caracrys	N													33	11	2	103	65	1786
C=G	Dentmacr	N													163	95	6	22	20	0
C=G	Echenauc	N													18	29	0	239	191	0
C=G	Ephigutt	N													45	54	10	981	307	0
C=G	Galedeca	N													377	274	85	1018	261	0
C=G	Hoplcade	N													164	32	4	0	0	2
C=G	Myctrubr	N													96	59	0	6	5	0
C=G	Pagrcaer	N										1	0	0	418	218	1	766	478	4
C=G	Paraocto	N													114	83	1	8	1	1
C=G	Pontkuhl	N													207	122	2	18	4	0
C=G	Rhinrhin	N													118	95	7	205	213	0
ALL	Argesphy	N	8	28	16				0	0	2	0	4	22	0	2	0			
ALL	Arnoimpe	N	0	11	24	0	1363	2142	0	965	1285	1	33	35	69	115	3	27	6	5
ALL	Arnolate	N	1810	5601	10922	12	3129	3150	0	358	661	16	46	109				1	0	0
ALL	Arnothor	N	1	0	0	2	0	25	0	10	0	27	53	284	1	6	0			
ALL	Balicapr	N	0	4	11	16	14	77	0	10	40	0	7	1	0	1	1	0	5	660
ALL	Belobelo	N	40	177	197	6	28	20	0	0	5	0	2	12	0	2	0			
ALL	Blenocel	N	0	0	2	10	30	28	0	0	4	6	4	12	2	0	2			
ALL	Boopboop	N	0	1	0	1	1	3	0	0	3	45	48	199	360	204	5	17	17	2
ALL	Capraper	N	23	25	31	328	2500	6606	0	1147	2018	15	119	276	75	36	5			
ALL	Chelluce	N	5	32	24	2	34	42	0	0	8	0	12	6	7	7	0	0	2	0
ALL	Coelcael	N	2	0	0	2	0	0				0	2	4	169	1	7	0	3	2
ALL	Congcong	N	11	48	132	109	581	1857	7	412	748	9	65	276	2	2	2			
ALL	Dicocune	N	0	2	0				0	29	112				43	31	2	54	11	0
ALL	Engrencr	N	64	1467	4318	1	82	325	4	532	806	61	29	61	52	45	0	38	13	0
ALL	Galemela	N	18	53	45	454	438	790	0	857	2217	2	124	276	41	0	0			
ALL	Lizarama	N	2	0	5	1	4	0	0	35	103	0	2	10	4	3	0	3	0	0
ALL	Merlmerl	N	3634	4508	15839	3687	12728	29770	41	4016	9986	4	345	822	13	11	1	1	0	0
ALL	Mustmust	N	0	1	0	3	2	3				3	1	2	266	81	1	81	41	0
ALL	Pegulasc	N	0	2	0	0	11	0	0	2	2	0	8	1	26	7	1	21	0	0
ALL	Sardsard	N	0	0	1	3	0	0	0	7	15	7	0	3	19	18	1	1	0	0
ALL	Sardpilc	N	294	748	1029	8	234	358	2	961	1718	78	69	175	58	47	2			
ALL	Scomscom	N	12355	20308	14385	2443	4451	10022	0	1180	3092	1	22	30	3	0	0	1	0	0
ALL	Scorscro	N	16	5	0	9	2	0	0	2	5	0	142	569	18	3	3	38	0	0
ALL	Scylstel	N	6	11	21	16	69	223	1	0	0	1	4	1	38	4	0			
ALL	Sponcant	N	70	217	173	21	40	92	2	79	297	1	32	191	91	113	19			
ALL	Torpmarm	N	1	1	1	4	0	4	0	3	16	0	14	31	54	49	11	118	40	0

ID	Species Code*	CIE SM	North Sea			Celtic Seas			South Europ.			Western Medit.			Canary Current			Guinea Current		
			P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
ALL	Tractrac	N	7463	19562	14341	1436	5815	10658	3	3545	5798	6	139	406	89	35	7	0	1	0
D	Argyregi	N							0	7	55				125	57	21	18	0	0
D	Athepres	N	0	2	22	6	4	12	2	0	4				14	0	6			
D	Bathprof	N				2	0	0				0	4	0	2	12	10	0	0	4
D	Bugllute	N	116	362	25	10	72	20				2	0	0				0	2	0
D	Callmacu	N	6	40	19	2	18	8	0	0	2	0	8	5						
D	Gaidmacr	N				2	4	0												
D	Hymeital	N				0	4	0				0	95	136	82	18	3	5	0	2
D	Lithmorm	N							0	7	6	1	17	5	22	42	7			
D	Mugiceph	N	0	2	2							6	4	4	16	19	9	0	1	0
D	Myctpunc	N				2	0	1	1	0	0	11	23	7	1	0	0			
D	Notabona	N										4	2	8	0	0	6			
D	Tracscab	N				2	0	0	0	2	0	0	2	2	0	0	2			
D	Triclept	N				0	1	0							0	103	8			
D	Triglyra	N							0	0	6	2	10	6	36	42	2	3	6	0

*Detailed informations on species name are available in Annex 4.

4.3.6 Evolution of SST

Figure 4-15 presents the movement of mean seasonal SST in all of the ecosystems from 1982 to 2012. The monthly SST values in each ecosystem are available in Annex 1, Annex 2, and Annex 3.

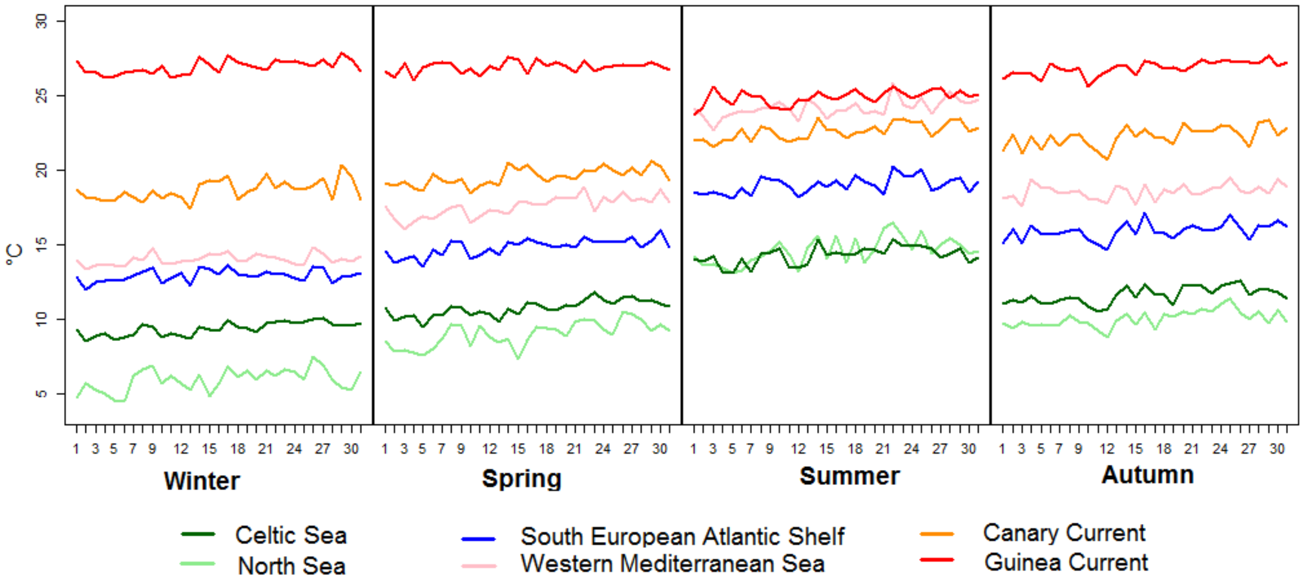


Figure 4-15: Mean seasonal SST in each ecosystem over time (coloured lines). The numbers on the x-axis represent the years from 1982 to 2012. The slope and *P* values are given in Annex 6.

In winter, large differences of mean SST were observed among ecosystems, except between the South European Atlantic Shelf and the Western Mediterranean Sea. These two ecosystems both have mean SSTs that range from 12.9 to 14.01°C (detail in Annex 6).

In spring, the temperature of the North Sea was close to that of the Celtic Seas. The temperature in the South European Atlantic Shelf reached the range of the winter temperature of the Western Mediterranean Sea. The mean SST of the Western Mediterranean Sea during this season was close to that of the Canary Current.

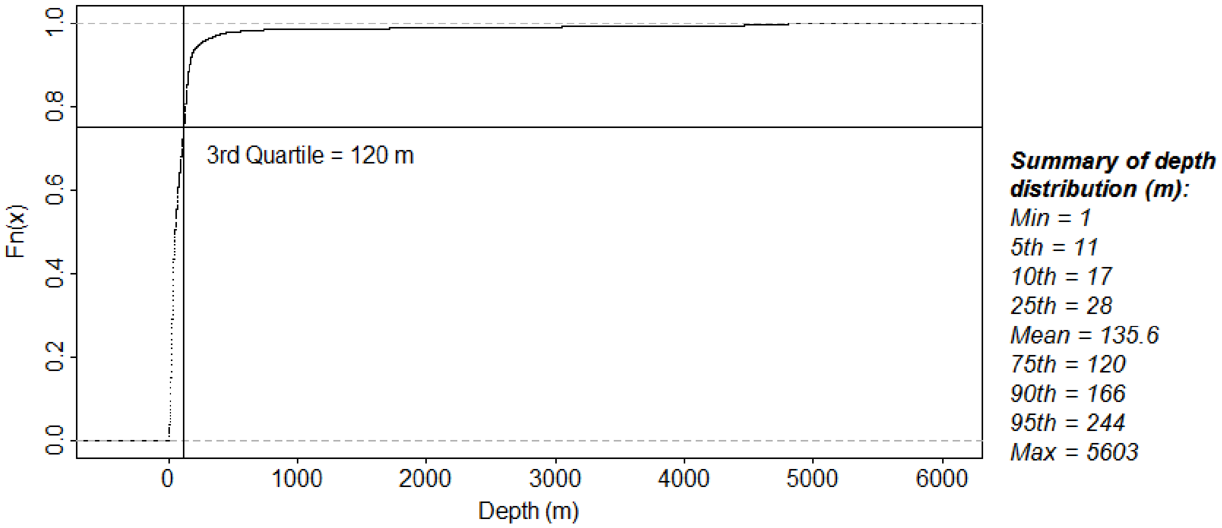
In summer, the temperature increased in all ecosystems except for the Guinea Current, which showed an opposite trend. The mean SST in the South European Atlantic Shelf was in the range of spring temperatures of the Canary Current and of the Western Mediterranean Sea.

In autumn, the mean SST decreased slowly in almost all ecosystems. The temperature in the South European Atlantic Shelf during this season was in the range of summer temperatures of the North Sea and of the Celtic Seas.

4.3.7 Species depth distribution

All of the species studied were mostly found in the area less than 200 m deep (Figure 4-16; see also map on Figure 4-14b). Species movement is thus dependant on the availability of the habitable depth.

The values of depth presented here are the depth of the area where the species was observed. A total of 1801 occurrences with unique depth values were recorded.



Summary of depth distribution (m):
Min = 1
5th = 11
10th = 17
25th = 28
Mean = 135.6
75th = 120
90th = 166
95th = 244
Max = 5603

Figure 4-16: Distribution of depth area of all species studied in all seasons.

4.3.8 Timing of species movement

The cases of *Solea senegalensis*, *Diplodus vulgaris* and *A. tobianus* are presented for further analysis on observational history of species migration. *S. senegalensis* and *D. vulgaris* are presented as examples of species with a northward migration pattern, whilst *A. tobianus* is presented as an example of species with a distribution pattern likely related to seasonal migrations and possibly extending its depth range. In addition, these species have a high commercial value and are therefore well studied.

In the first and the second period of study, *S. senegalensis* and *D. vulgaris* were only observed in the Canary Current and the Western Mediterranean Sea (green and yellow points on maps in Figure 4-17). These species were recently observed in the third period of study in the South European Atlantic Shelf (red points on maps in Figure 4-17).

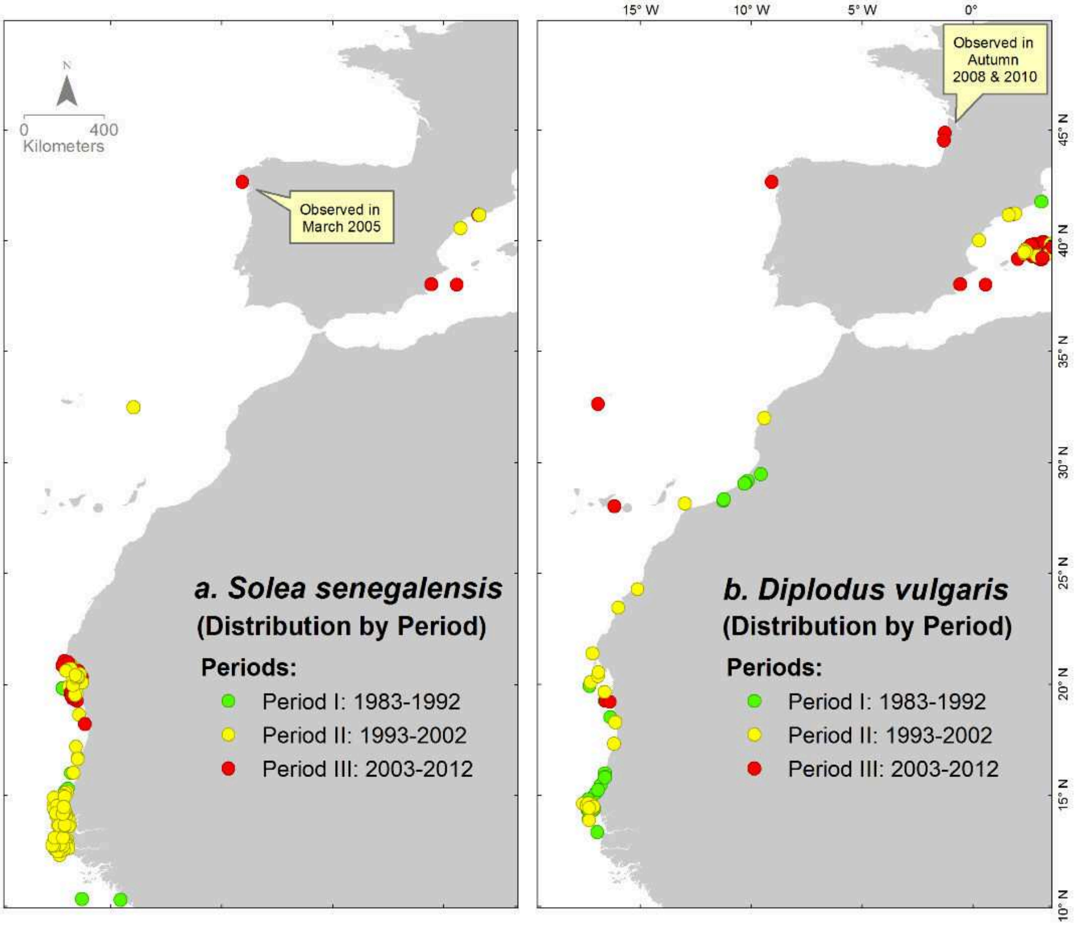


Figure 4-17: Distribution of (a) *S. senegalensis;* and (b) *D. vulgaris* by period of study.

Ammodytes tobianus was mostly found in the North Sea during winter (green points on map in Figure 4-18). In spring and summer, this species could be found in both the Celtic Seas and the North Sea. In autumn, it could be observed in the lower latitude of the Bay of Biscay in the South European Atlantic Shelf (purple points on map in Figure 4-18).

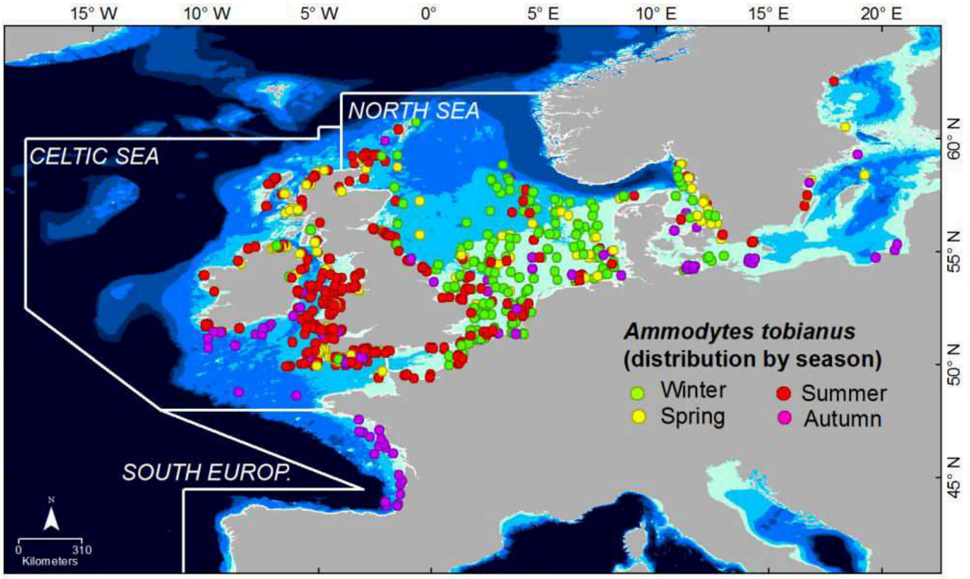


Figure 4-18: Seasonal distribution of *A. tobianus*.

In the first three seasons, *A. tobianus* was generally found in areas between 2 and 100 m deep (Figure 4-19). 50% of its occurrences were found in areas between 20 and 52 m deep, indicating its preferred depth range. In autumn, this species can be found in areas up to 150 m deep.

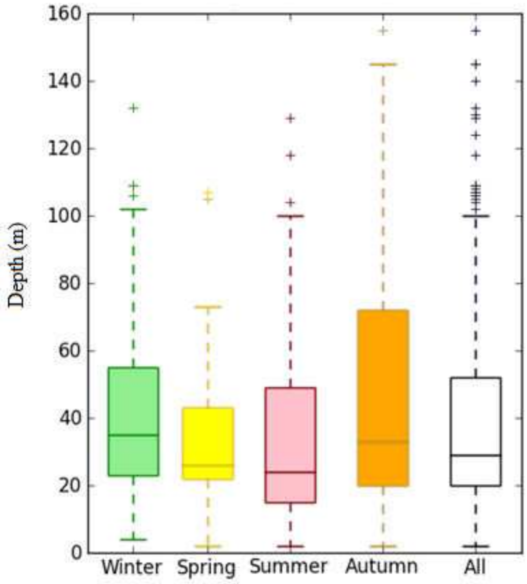


Figure 4-19: Distribution of depth of *A. tobianus* by season.

4.3.9 Discussion: species movement

4.3.9.1 Issue concerning the occurrence records

Bias in species occurrences could lead to a distorted view of the pattern of species distributions (Yang, Ma, and Kreft 2013). Several factors can cause such biases, such as spatial scale, survey location, sampling techniques, misidentification, and species mobility.

The quality issues of some data sources, such as their lack of transparency, have been noted by many authors, and publicly criticized (Soberón, Arriaga, and Lara 2002; Graham et al. 2007; Yesson et al. 2007), especially for records coming from the natural history museums that are rarely collected optimally. In addition, information is sometimes insufficient for political and/or financial reasons in some areas, as in the case for Portugal and Moroccan waters in our study. In contrast, many observed occurrences are available from well-financed, data-sharing countries, even if the real density may be higher elsewhere (Beck et al. 2014). Negotiating access to several biodiversity databases that are not yet publicly available is a near-future task, as stressed by Yesson et al. (2007). Thus, data gap in certain areas could be filled. Nevertheless, many improvements have been achieved and large amounts of good data are already available, are increasingly used and encourage research in many applications.

In this study, we incorporated several data sources including publicly available databases as well as unpublished databases. Using these databases may enable the investigation of patterns of species distributions at large spatial and temporal scales and to better understand how species move in response to environmental change.

We took several measures to minimize the risk of bias, including using recent records (after 1982 only), excluding occurrences without times of observation, performing a strict selection of species studied and occurrence records, and removing suspicious occurrences.

4.3.9.2 Latitudinal variation

Our study covers a wide latitudinal area (tropical, subtropical, and temperate waters) to obtain a complete picture of species distribution. Despite the high number of occurrence (above 100,000 records) coming from numerous scientific expeditions in the temperate regions (the North Sea and the Celtic Seas), species diversity is lower than that observed in the tropical regions, where scientific observations are rare and we consequently have fewer than 7.000 recorded occurrences; see again Figure 4-12. The number of species varies and decreases with increasing latitude, the tropical area being often several times richer in species than temperate ones (Gaston 2000), and the causes being still under debate (Clarke and Gaston 2006).

Latitudinal variability is not the only driver of the species diversity pattern. Other limiting factors are important, such as over-exploitation, habitat loss, seasonal effects, the seafloor profile, and oceanographic force. Nutrient availability, salinity and dispersal rates can also influence the patterns of species distribution and species composition. All of these combined factors can lead to fish migrations, especially of highly tolerant and naturally adaptable invasive species (Hiddink and Hofstede 2008).

4.3.9.3 Fishing effects

Disturbance from fishing activities may influence species distribution by reorganizing the fish assemblage (Summerson, Darbyshire, and Lawrence 2007). Garrison and Jason (2000) stated that the spatial differences in exploitation rates can modify the pattern of species distribution. Fishing activities remove and reduce the regional abundance of predator species, which cascades to lower trophic levels (Martins et al. 2012). If the abundance of the less exploited or less predated species increases, expansion of their distribution as an indirect impact is then possible (Martins et al. 2012).

An FAO statistics report (FIGIS 2016) showed a diminishing trend of catches in European Atlantic regions, whereas an increase of captures was observed in the Eastern Central Atlantic (Annex 7). In the central region of the South European Atlantic Shelf where catch decrease were observed, Teixeira et al. (2014) mentioned that the catch of colder marine species has decreased in recent decades, while the catch for warm marine species has increased considerably.

In this study, although fishing activities could be important in determining species distribution patterns, fishing effects were not considered the major driver.

4.3.9.4 Climate change effects

The recent observations of tropical-Atlantic species, such as *S. senegalensis* and *D. vulgaris* in the central area of our study during autumn suggest that these species' ranges have expanded northwards. Bañón et al. (2010) opined that these phenomena were probably linked to global warming.

Many studies have identified temperature as the dominant environmental factor limiting species distributions. Temperature controls reproduction, growth and the availability of food (Summerson, Darbyshire, and Lawrence 2007). Although temperature is not the only forcing parameter, Cheung et al. (2009) stated that the response of marine species to environmental change, such as ocean warming, is expressed by a shifting of their latitudinal or depth range and changes in the pattern of species richness. Hiddink and Hofstede (2008) also stated that biodiversity at high latitudes in the subtropical and temperate waters seem to be highly sensitive to climate change. Newly recorded tropical species in the South European Atlantic Shelf (ID CWS in Figure 4-14) could confirm the effect of climate change in shifting species distribution. However, the absence of survey data in the earlier period prevents us from definitively attributing this phenomenon to ocean warming. Nevertheless, the steady increase of SST observed in all regions (Annex 8) may promote species emigration, especially in the intermediate regions. Thus, their distribution range is expectedly expanding, as stated also by Kaschner et al. (2011). Furthermore, Bañón et al. (2010) suggested that the presence of tropical species of African origin in the central region of the study area reflects actual natural changes rather than increased sampling effort. Annex 9 presents the distribution of studied species that showed north-bound trend.

4.3.9.5 Physical force effects

The sharp north-to-south temperature gradient in the South European Atlantic Shelf and the bathymetry in this region could restrict the distribution of many species (Bañón et al. 2010); see Figure 4-20. Bakun (2006) mentioned that the success of fish recruitment is strongly influenced by three categories (known as the fundamental triad) of oceanographic processes: *enrichment* (such as upwelling and river run-off), *concentration* (occurs in areas such as fronts and river plumes) and *retention* (such as fronts, currents, and circulation patterns).

Fronts are narrow boundary zones that separate water masses (Mason, Coombs, and Oliveira 2005). Fronts have stronger gradients of many water properties and are more productive, with increased nutrient and plankton concentrations. These environments may benefit adult fish as well as larvae and eggs. Fronts are ubiquitous features of eastern ocean boundaries that act as barriers and reduce the export of particles from coastal waters to the continental shelf (e.g., Bakun 2006). Thus, they act also as potential barriers to planktonic dispersal and adult migration (Figure 4-20e); see Mason, Coombs, and Oliveira (2005) for details.

The upwelling zones with nutrient-rich water increase primary production and in turn food for higher trophic levels, hence supporting high fish production (Aggrey-Fynn 2007). Bañón et al. (2010) explains that upwelling off Cape Finisterre from March to October (Figure 4-20c), is probably the reason for the presence of cool-water species in this area, while they are absent or scarce in the Bay of Biscay. The water in Cape Finisterre is noticeably colder than in the northern Galician coast and the Bay of Biscay. In contrast, warm-water species are present in the Bay of Biscay and absent or scarce off Cape Finisterre.

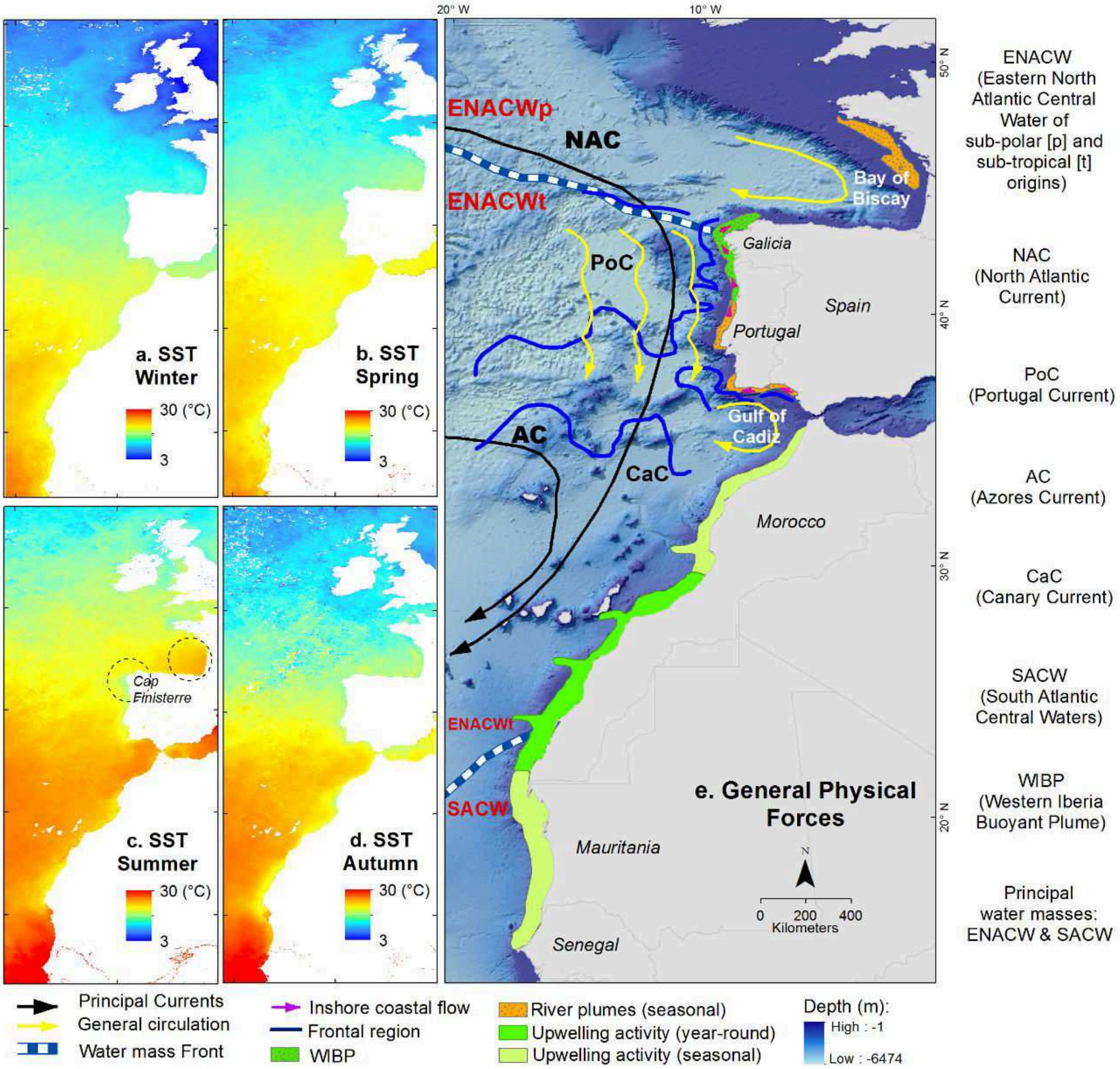


Figure 4-20: SST seasonal climatology of the study aera, 1982-2012: (a) winter; (b) spring; (c) summer; (d) autumn; and (e) main hydrological structures (see again Figure 2-11).

4.3.9.6 Routes and timings

The movements of species distribution, as presented in the results of this study, seem to be strongly correlated with seasonal environmental change. *A. tobianus* is only found in the South European Atlantic Shelf during autumn, while in spring and summer, it can be found in both the North Sea and the Celtic Seas. Although temperature is not the only parameter influencing species distribution, the mean SSTs during this season of these two regions are close to each other (see again Figure 4-15); furthermore, the mean autumnal temperature in the South European Atlantic Shelf is in the same range as summer temperature in the Celtic Seas and the North Sea.

In the Celtic Seas, despite the significant increase of occurrence records over time, richness of the studied species shows a decreasing trend; in contrast, richness is increasing in the North Sea. The studies conducted by Hiddink and Hofstede (2008) in this region, found that the number of species in the northern part of the North Sea was increasing over time. This result was also confirmed by Cheung et al. (2009). However, our study showed that species preferential depth and seasonal variation are important factors. Some species could be observed more in the North Sea in certain seasons, while in the other seasons, they would be more observed in the Celtic Seas or in the South European Atlantic Shelf (see again Figure 4-18). This study shows that 13 species move seasonally in the North Sea, the Celtic Seas and the South European Atlantic Shelf. The northernmost area of the North Sea has deeper waters than the southern area. As a consequence, species with a preferential depth of 100-200 m, such as *Lepidorhombus whiffiagonis*, are more comfortable in the northern part of the region, while species with preferential depth less than 50 m, such as *A. tobianus*, are much more often present in the southern part of the region. Hence, if the winter or spring temperature increases, *L. whiffiagonis* would migrate northwards, while *A. tobianus* can migrate eastwards rather than northwards considering its depth range (Figure 4-18).

In the South European Atlantic Shelf, during warmer periods, six species originating from the Canary Current and the Western Mediterranean Sea extend their distributions to this area (Figure 4-14 and Figure 4-17). Bañón et al. (2010) stated that the arrival of numerous tropical fish in the South European Atlantic Shelf seems to have altered the traditional species distribution pattern in this area, and they have argued that this phenomenon is probably linked to global warming. During warmer seasons, the difference of mean SST between the middle and the southern ecosystems was reduced (range from 15.9 in summer to 22.5°C in winter; see Annex 6). This condition could allow the southern tropical species to migrate to the central region (other limiting factors not considered). However, low records of species occurrences in the earlier period in this region limit our view and prevent our analysis of the effect of global warming. In the earlier period, the low observed richness of the studied species was strongly influenced by the poor availability of observations. Nevertheless, many studies suggested that increasing temperatures were the major cause of the presence of tropical species as mentioned previously. As the SST continues to increase in all regions (Annex 8), the observed ranges of many species expectedly continues to expand.

We are somewhat more confident of the records of tropical-Atlantic species' presence in the Mediterranean Sea than in the South European Atlantic Shelf. In this study, 7 species from the Canary Current tend to be found in the Western Mediterranean Sea. Deidun, Castriota, and Arrigo (2011) noted 33 exotic fish of Atlantic origin present in the Mediterranean Sea. Zenetos et al. (2010) noted the increasing number of alien fish species in this region, with a parallel increase in the number of the Atlantic migrant fish species. Many of these species have already become well established and expanded their distribution into the entire basin, suggesting also an eastward movement (CIESM 2002).

The presence of tropical-Atlantic species in the central region confirms the phenomenon of "tropicalisation" of both pelagic and demersal species (Zenetos et al. 2010), with increasing frequency and biomass (Deidun, Castriota, and Arrigo 2011). This trend is also confirmed by the findings of this study, which suggest a generally nortward route of species movement.

Finally, further study is needed to gain additional insights on species seasonal movement across large spatial extents. Species distribution modeling based on species environmental niches is promising, as results could be used to predict species richness and species ranges. The use of such models could be an alternative or a complementary approach to the limitation in availability of data at the large scale, and would lead to a better understanding of biodiversity changes and enable the identification of present and future high-biodiversity areas.

4.4 Species realised niches

Pomatomus saltatrix, *Balistes capriscus*, and *Solea senegalensis* were chosen among the 89 fish species studied to demonstrate the results of this work. These results will focus on *P. saltatrix*, because it has the biggest sample size. This species has also been well studied in terms of experimental and observational studies. *B. capriscus* and *S. senegalensis* are used to show the effectiveness of this study for species living in different environments and with poor observation data.

4.4.1 Spatial distribution

Bluefish, the preferred common name of *P. saltatrix*, has a wide range of distribution from 160° W to 178.75° E longitude and from 45.28° S to 55.75° N latitude (Figure 4-21). It occurs in most temperate coastal regions and warm temperate waters of all oceans except in the Pacific Ocean, as stated also in many published papers, such as Oliver et al. (1989) and Briggs (1960).

The occurrence distribution of *P. saltatrix* seems to reach north during summer and autumn, as indicated in Wilk (1977). In the East Atlantic European waters, this species was observed at 45.25° N, and it could go further north since it has been recorded at 55.75° N in the north-west Atlantic side. Oliver et al. (1989) and Ballenger (2014) stated that this species is a warm water migratory pelagic species that generally travels northward in spring and summer, and southward in autumn and winter, along the Atlantic seaboard. The most recent observation of this species has been recorded in August 2012 in north-west Atlantic side. Recent observation in some areas, such as European waters, north-east American waters and east Australian waters were probably due to the high number of active campaigns in those areas. The lack of occurrence records in certain areas, such as in Moroccan and Portuguese waters, might be due to the limited access of several biodiversity databases that were not publicly available.

B. capriscus, also known as Grey triggerfish, is distributed in the tropical and temperate zones of the Atlantic (Bernardes 2002). In this study, this species was observed in the tropical and temperate zones along the Eastern Atlantic Ocean and the Western Atlantic Ocean. Using all of our 7,487 occurrence records of this species, the species has been noted from 58.6° N in north Atlantic waters to 38.02° S in the South American coast and from 52.26° E off the east African coasts to 110° W off the west Mexican coast. Ismen et al. (2004) confirmed that this species occurs along the Eastern Atlantic Ocean in the Mediterranean Sea and the Western Atlantic Ocean in the Argentina coast.

S. senegalensis or the Senegalese sole was found from 46.75° N in the Bay of Biscay to 11.25° S in the coast of Angola, and from 13.75° E in Angolan waters to 17.65° W in Senegalese waters. Arjona et al. (2010) confirmed that this species occurs from the Bay of Biscay to the southern Atlantic off Senegal, and in the western basin of the Mediterranean Sea. This species has been noted in an extreme location far north in Norwegian waters, but it could be misidentified with *Solea solea* which in fact occurs in those waters.

Maps of distribution of *B. capriscus* and *S. senegalensis* are presented in Figure 4-21. Further information on these two species can be found in Bernardes (2002), Ismen et al. (2004) and Arjona et al. (2010).

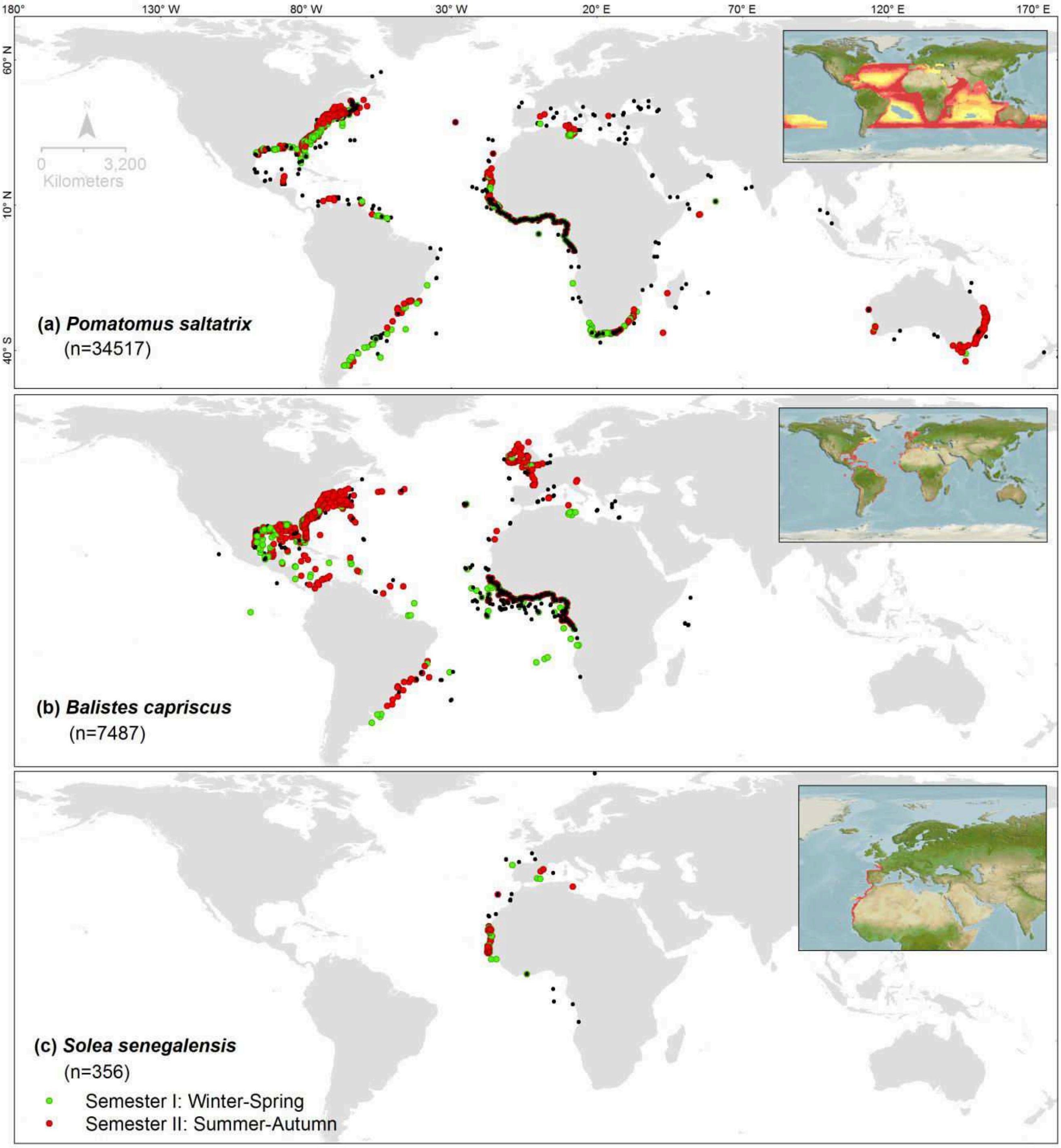
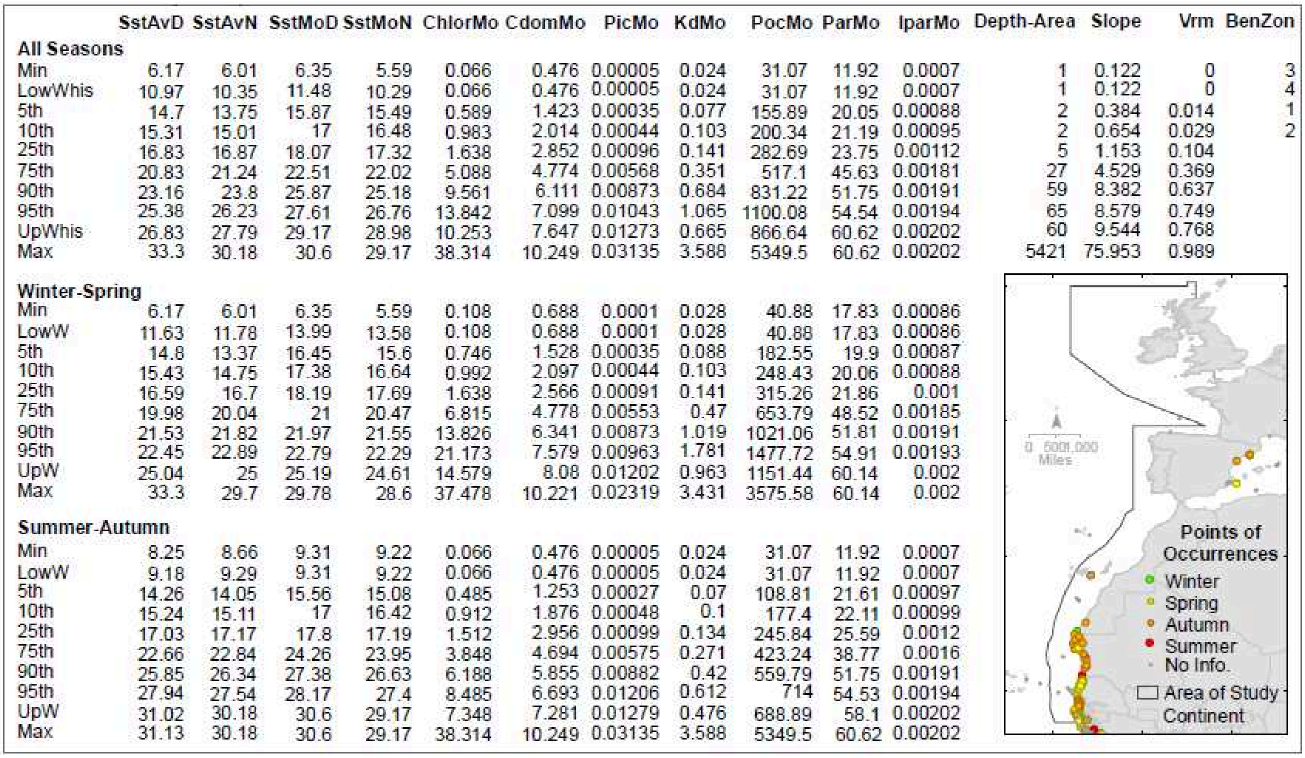


Figure 4-21: Occurrence distribution of (a) *P. saltatrix*; (b) *B. capriscus*, and (c) *S. senegalensis*. Red points represent the occurrences recorded in winter-spring. Green points represent the occurrences observed in summer-autumn. Occurrences without information of time of observation are depicted in smaller black points. Inset pictures are the species' native range model obtained from Kaschner et al. (2013) for supplementary information.

4.4.2 Environmental envelope

The temperature ranges for *P. saltatrix* measured using AVHRR data were slightly different from MODIS data. For the maximum temperature, the values varied from 30-33 °C at daytime and from 29-30 °C at night-time (Table 4-10, Figure 4-22 and Figure 4-23). These values have approximately 2 °C difference with the value from AquaMaps (31.78 °C). Fahay et al. (1999) stated that this species can tolerate water temperatures up to 30.4 °C, while Ballenger (2014) mentioned that the thermal maximum for juveniles of this species is 34 °C which is near the maximum temperature obtained in this study. For the temperature minimum, there is a large difference (of almost 6 °C), between the value found in the study (6.17-6.35 °C at daytime and 5.59-6.01 °C at night-time) and the value used in AquaMaps (0.67 °C). Gilmore et al. (1978), in their research about hypothermal mortality in marine fishes including this species in south-central Florida, revealed that the lethal minimum temperature observed for the species ranged from 6 to 13 °C. This finding corresponds to the minimum temperature obtained in our study.



	SstAvD	SstAvN	SstMoD	SstMoN	ChlorMo	CdomMo	PicMo	KdMo	PocMo	ParMo	IparMo	Depth-Area	Slope	Vrm	BenZon
All Seasons															
Min	6.17	6.01	6.35	5.59	0.066	0.476	0.00005	0.024	31.07	11.92	0.0007	1	0.122	0	3
LowWhis	10.97	10.35	11.48	10.29	0.066	0.476	0.00005	0.024	31.07	11.92	0.0007	1	0.122	0	4
5th	14.7	13.75	15.87	15.49	0.589	1.423	0.00035	0.077	155.89	20.05	0.00088	2	0.384	0.014	1
10th	15.31	15.01	17	16.48	0.983	2.014	0.00044	0.103	200.34	21.19	0.00095	2	0.654	0.029	2
25th	16.83	16.87	18.07	17.32	1.638	2.852	0.00096	0.141	282.69	23.75	0.00112	5	1.153	0.104	
75th	20.83	21.24	22.51	22.02	5.088	4.774	0.00568	0.351	517.1	45.63	0.00181	27	4.529	0.369	
90th	23.16	23.8	25.87	25.18	9.561	6.111	0.00873	0.684	831.22	51.75	0.00191	59	8.382	0.637	
95th	25.38	26.23	27.61	26.76	13.842	7.099	0.01043	1.065	1100.08	54.54	0.00194	65	8.579	0.749	
UpWhis	26.83	27.79	29.17	28.98	10.253	7.647	0.01273	0.665	866.64	60.62	0.00202	60	9.544	0.768	
Max	33.3	30.18	30.6	29.17	38.314	10.249	0.03135	3.588	5349.5	60.62	0.00202	5421	75.953	0.989	
Winter-Spring															
Min	6.17	6.01	6.35	5.59	0.108	0.688	0.0001	0.028	40.88	17.83	0.00086				
LowW	11.63	11.78	13.99	13.58	0.108	0.688	0.0001	0.028	40.88	17.83	0.00086				
5th	14.8	13.37	16.45	15.6	0.746	1.528	0.00035	0.088	182.55	19.9	0.00087				
10th	15.43	14.75	17.38	16.64	0.992	2.097	0.00044	0.103	248.43	20.06	0.00088				
25th	16.59	16.7	18.19	17.69	1.638	2.566	0.00091	0.141	315.26	21.86	0.001				
75th	19.98	20.04	21	20.47	6.815	4.778	0.00553	0.47	653.79	48.52	0.00185				
90th	21.53	21.82	21.97	21.55	13.826	6.341	0.00873	1.019	1021.06	51.81	0.00191				
95th	22.45	22.89	22.79	22.29	21.173	7.579	0.00963	1.781	1477.72	54.91	0.00193				
UpW	25.04	25	25.19	24.61	14.579	8.08	0.01202	0.963	1151.44	60.14	0.002				
Max	33.3	29.7	29.78	28.6	37.478	10.221	0.02319	3.431	3575.58	60.14	0.002				
Summer-Autumn															
Min	8.25	8.66	9.31	9.22	0.066	0.476	0.00005	0.024	31.07	11.92	0.0007				
LowW	9.18	9.29	9.31	9.22	0.066	0.476	0.00005	0.024	31.07	11.92	0.0007				
5th	14.26	14.05	15.56	15.08	0.485	1.253	0.00027	0.07	108.81	21.61	0.00097				
10th	15.24	15.11	17	16.42	0.912	1.876	0.00048	0.1	177.4	22.11	0.00099				
25th	17.03	17.17	17.8	17.19	1.512	2.956	0.00099	0.134	245.84	25.59	0.0012				
75th	22.66	22.84	24.26	23.95	3.848	4.694	0.00575	0.271	423.24	38.77	0.0016				
90th	25.85	26.34	27.38	26.63	6.188	5.855	0.00882	0.42	559.79	51.75	0.00191				
95th	27.94	27.54	28.17	27.4	8.485	6.693	0.01206	0.612	714	54.53	0.00194				
UpW	31.02	30.18	30.6	29.17	7.348	7.281	0.01279	0.476	688.89	58.1	0.00202				
Max	31.13	30.18	30.6	29.17	38.314	10.249	0.03135	3.588	5349.5	60.62	0.00202				

Figure 4-22: Environmental values for *P. saltatrix*. *SstAvD* = SST AVHRR at day time. *SstAvN* = SST AVHRR at night time. *SstMoD* = SST MODIS at day time. *SstMoN* = SST MODIS at night time. *ChlorMo* = Chlorophyll concentration. *Cdom* = the Colored dissolved organic matter. *KdMo* = Diffuse attenuation coefficient at 490 nm. *PocMo* = Particulate organic carbon concentration. *PicMo* = Particulate inorganic carbon concentration. *ParMo* = Photo-synthetically available radiation. *IparMo* = Instantaneous photo-synthetically available radiation. *Depth-Area* = Depth. *Slope* = Slope. *Vrm* = Terrain ruggedness. *BenZon* = Benthic zone in categorical values: first row for the zone most occupied by the species, second row for the zone second most occupied, third row for the zone third most occupied, and the last row for the zone less occupied. *Winter-Spring* = envelopes in the period of January to June. *Summer-Autumn* = July to December. *Min* = minimum. *LowW* = the lower whiskers. *5th* = the 5th percentile. *10th* = the 10th percentile. *25th* = the first quartile. *75th* = the third quartile. *90th* = the 90th percentile. *95th* = the 95th percentile. *UpW* = the upper whisker. *Max* = maximum.

The temperature minimum and maximum for *B. capriscus* range from 7 to 31 °C (Table 4-10, Figure 4-23 and Annex 10). The minimum temperature determined in AquaMaps for this species is -0.74 °C, but some studies, i.e., Aggrey-Fynn (2007), have suggested that this species is sensitive to low temperatures. Furthermore, Johnston et al. (1998) stated that the range of temperatures from -1.86

to +2 °C is for Antarctic fish and that it would be lethal for temperate and tropical species. Our study methods showed then a robust and reliable result as it agrees with the results from observational studies.

S. senegalensis is also showed a thermal niche that agreed with observation. The temperature minimum and maximum for this species in our study ranged from 10.64 to 30.27 °C, whereas AquaMaps used the range of 1.97 to 30.6° C (Table 4-10, Figure 4-23 and Annex 11). *S. senegalensis* occurs mainly in tropical waters, and the northernmost point where this species has been recorded is in the Bay of Biscay, which has a minimum temperature that range from 8.0-9.5 °C (Puillat et al. 2004), near the minimum value obtained in this study.

Figure 4-22 contains the environmental envelopes of *P. saltatrix* for each parameter originating from satellite data measurement and derivative of bathymetric data. These values are presented in box-plot parameters to easily display the distribution of the extracted environmental values based on ten numbers summary, such as minimum, lower whiskers, fifth percentile, tenth percentile, first quartile, third quartile, ninetieth percentile, ninety fifth percentile, upper whiskers, and maximum. The envelopes for *B. capriscus* and *S. senegalensis* are available in Annex 10 and Annex 11 respectivelly.

The ten first lines in Figure 4-22 are the species environmental values obtained during all seasons. The next ten lines are the values obtained during the periods of winter-spring. The last ten lines are the values observed in summer- autumn. Inset map on the Figure 4-22 shows the distribution occurrences in the focused study area, with period of observation indicated by different color (green for January-March, yellow for April-June, red for July-September, and orange for Oktober-December.

Table 4-10: Species thermal niche.

	P. saltatrix				***B. capriscus***				***S. senegalensis***			
	SST*	**SST4****	**SST**	**SST4**	**SST**	**SST4**	**SST**	**SST4**	**SST**	**SST4**	**SST**	**SST4**
	Avhrr	Avhrr	Modis	Modis	Avhrr	Avhrr	Modis	Modis	Avhrr	Avhrr	Modis	Modis
All Seasons												
Min	6.17	6.01	6.35	5.59	10.16	9.58	8.51	7.43	12.31	12.5	11.63	10.64
25th	16.83	16.87	18.07	17.32	24.66	24.01	26.01	24.41	18.96	18.81	19.77	19.18
75th	20.83	21.24	22.51	22.02	28.19	27.6	28.58	28.09	25.93	25.24	24.62	24.35
Max	33.3	30.18	30.6	29.17	31.57	30.09	30.6	29	30.27	28.16	26.59	26.48
Semester I: winter-spring												
Min	6.17	6.01	6.35	5.59	10.86	10.12	8.62	7.99	12.31	12.5	11.63	10.64
25th	16.59	16.7	18.19	17.69	23.76	23.42	26.79	27.02	18.12	17.68	18.7	17.04
75th	19.98	20.04	21	20.47	27.22	26.89	28.23	28.09	22	22.54	22.52	21.99
Max	33.3	29.7	29.78	28.6	30.54	29.09	29.79	29	26.99	26.73	24.07	23.48
Semester II: summer-autumn												
Min	8.25	8.66	9.31	9.22	10.16	9.58	8.51	7.43	20.13	18.31	20.98	21.48
25th	17.03	17.17	17.8	17.19	26.18	25.79	18.03	17.66	25.12	24.92	22.65	23.09
75th	22.66	22.84	24.26	23.95	28.74	27.98	28.58	28.01	27.75	27.36	25.96	25.47
Max	31.13	30.18	30.6	29.17	31.57	30.09	30.6	28.87	30.27	28.16	26.59	26.48

*SST refers to the sea surface temperature at daytime; **SST4 refer to the sea surface temperature at night-time. *Min* = minimum; *25th* = first quartile; *75th* = third quartile; *Max* = maximum.

Table 4-10 presents the distribution of sea surface temperature values for the three species selected, extracted from satellite data that form their fundamental thermal niche on the four-number summary: minimum, first quartile, third quartile, and maximum. The first four lines in the table are the distribution of the SST values obtained in all seasons followed by the values obtained during Semester I (winter-spring) and Semester II (summer-autumn) respectively. Detailed informations on the species' environmental values distribution for all of the parameters taken into account are shown in Figure 4-22, Annex 10, and Annex 11.

Figure 4-23: SST distribution at daytime and night-time from the AVHRR and MODIS data. (a) *P. saltatrix*, (b) *B. capriscus* and (c) *S. senegalensis*. *Sem I* = SST in winter-spring. *Sem II* = SST in summer-autumn. The grey area = the species' maximum and minimum temperature from AquaMaps.

4.4.3 Other oceanic parameters

MODIS data provides more oceanic parameters beside SST, such as chlorophyll-a concentration (CHLOR_a), coloured dissolved organic matter (CDOM_index), diffuse attenuation coefficient at 490nm (KD_490), particulate organic carbon concentration (POC), particulate inorganic carbon concentration (PIC), photo-synthetically available radiation (PAR) and instantaneous photo-synthetically available radiation (IPAR). The realised niches of these parameters for *P. saltatrix* are presented in Table 4-11. The realised niches of the same parameters for *B. capriscus* and *S. senegalensis* are provided in Annex 10 and Annex 11.

Table 4-11: Environmental envelope of *P. saltatrix* for MODIS' oceanic parameters.

	CHLOR_a	**CDOM_index**	**KD_490**	**PIC**	**POC**	**PAR**	**IPAR**
All Seasons							
Min	0.066	0.476	0.024	0.00005	31.07	11.92	0.0007
25th	1.638	2.852	0.141	0.00096	282.69	23.75	0.00112
75th	5.088	4.774	0.351	0.00568	517.1	45.63	0.00181
Max	38.314	10.249	3.588	0.03135	5349.5	60.62	0.00202
Semester I: winter-spring							
Min	0.108	0.688	0.028	0.0001	40.88	17.83	0.00086
25th	1.638	2.566	0.141	0.00091	315.26	21.86	0.001
75th	6.815	4.778	0.47	0.00553	653.79	48.52	0.00185
Max	37.478	10.221	3.431	0.02319	3575.58	60.41	0.002
Semester II: summer-autumn							
Min	0.066	0.476	0.024	0.00005	31.07	11.92	0.0007
25th	1.512	2.956	0.134	0.00099	245.84	25.59	0.0012
75th	3.848	4.694	0.271	0.00575	423.24	38.77	0.0016
Max	38.314	10.249	3.588	0.03135	5349.5	60.62	0.00202

We could not find an experimental or observational study with which to compare the results of these parameters; however, because the number of occurrence used to generate these values is much higher (i.e., the number of occurrence used for *P. saltatrix* is approximately 2000 to 3000 records) than the numbers used in several studies, our results should be usable as base information for other studies.

4.4.4 Bathymetric niche (depth and its derivative)

The range of depth for *P. saltatrix* is 1 to 5421 m (Table 4-12). 90% of the data showed that this species was found in the area below 60 m. The occurrences above the 95th percetile were found in the extreme depth and they are recorded as outliers (Figure 4-24). Aquamaps determined that the range of depth for this species was from 0 to 200 m. The depth in our study is the depth of the area where the species observed. Thus, it is possible for a species to occur in open ocean with depth above 200 m, and not necessarily in the water column.

In the case of *B. capriscus*, in our study, the species has been found in areas from 2 m to 5913 m, while Aquamaps determined the maximum depth for this species was 100 m, but Aggrey-Fynn (2007) mentioned that this species has been catched in the ranges of 50 m, 200 m and 1000 m depth offshore.

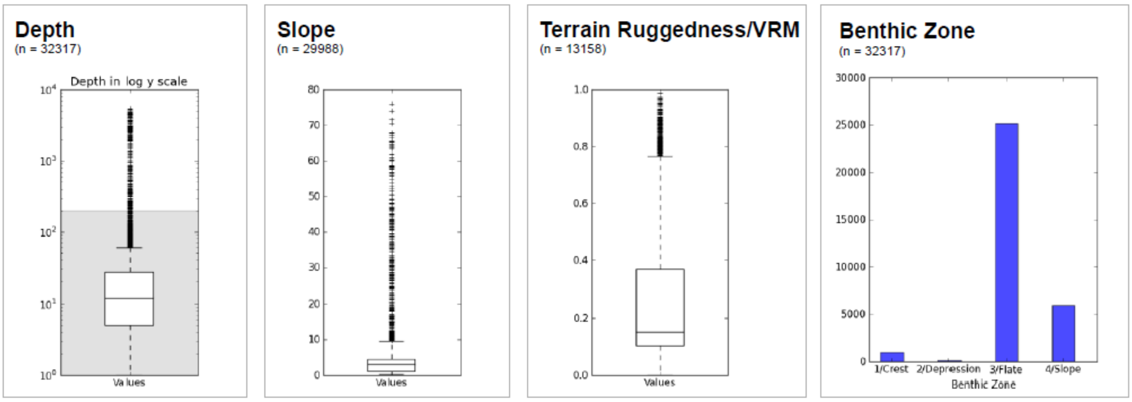
Table 4-12 presents the distribution of Depth, Slope and Terrain ruggedness of the species selected. The values of "Benthic Zone" are presented in Figure 4-24, Annex 10 and Annex 11.

Table 4-12: Distribution of bathymetric niche values of *P.* saltatrix, *B. capriscus* and *S. senegalensis*. .

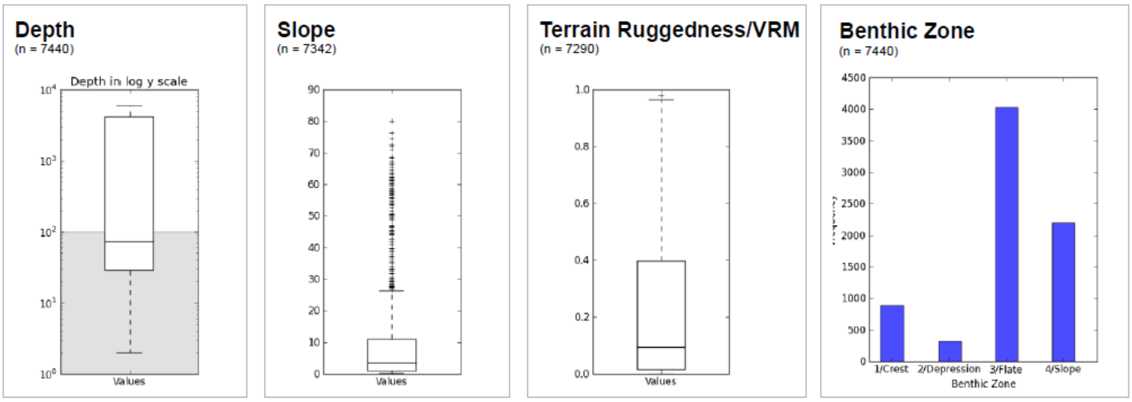
	P. saltatrix			***B. capriscus***			***S. senegalensis***		
	Depth (m)	Slope (°)	Terrain ruggedness	Depth (m)	Slope (°)	Terrain ruggedness	Depth (m)	Slope (°)	Terrain ruggedness
Min	1	0.122	0	2	0.122	0	2	0.122	0.002
10th	2	0.654	0.029	17	0.384	0.005	5	0.486	0.013
25th	5	1.153	0.104	29	0.926	0.016	13	0.876	0.055
75th	27	4.529	0.369	4191	11.15	0.397	48.5	3.262	0.452
90th	59	8.382	0.637	4981	22.554	0.61	87	6.944	0.673
Max	5421	75.953	0.989	5913	80.01	0.979	4874	39.788	0.947

Box-plot of slope for *P. saltatrix* shows that 90% occurrences were found in areas of slope lower than 10 degrees (Table 4-12), as presented also by the graph of benthic zone in Figure 4-24 where the species were observed mostly in the zone-3 or flat area. The distribution of the terrain ruggedness shows that the species was found in every type of ruggedness but 50% of the occurrences were found in areas with a ruggedness value lower than 0.4 (Figure 4-24). Typical values for natural terrains range between 0 and about 0.4, however it is important to understand that the number is unit-less and not directly comparable between study sites. Ruggedness values in the output raster can range from 0 (no terrain variation) to 1 (complete terrain variation) (Wright et al. 2013).

a. Pomatomus saltatrix



b. Balistes capriscus



c. Solea senegalensis

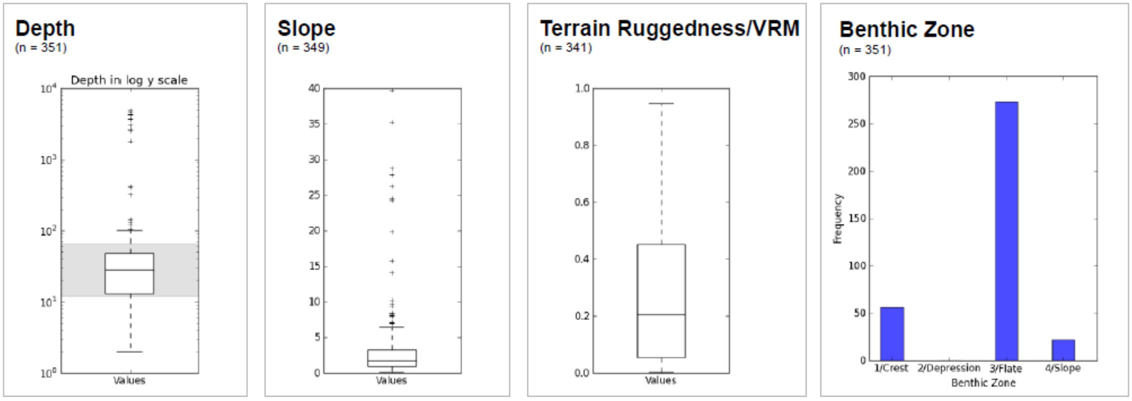


Figure 4-24: Box-plot of depth values (in logarithmic scale), slope in degree, terrain ruggedness, and benthic zone for (a) *P. saltatrix*, (b) *B. capriscus* and (c) *S. senegalensis*. The grey area in the box-plot of depth = the minimum and maximum depth values obtained from AquaMaps.

Thermal niche and bathymetric niche of all of the species studied are summarised in Table 4-13. Detailed informations on fundamental niche of all of the species studied are available in the supplementary materials.

Table 4-13: Thermal and depth niches of the species studied.

No	Species	SST						Depth					
		Min	10	25	75	90	Max	Min	10	25	75	90	Max
1	*Acanthurus monroviae*	15.8	17.2	19.6	25.7	27.2	29.3	2	11	17	40	76	5287
2	*Alosa fallax*	1.7	1.9	5.0	9.6	17.8	28.4	2	6	11	84	141	4842
3	*Ammodytes tobianus*	0.2	4.4	5.8	14.8	16.5	19.5	2	10	20	61	79	4842
4	*Anthias anthias*	13.0	15.7	19.1	25.0	26.3	29.0	2	12	17	99	449	5134
5	*Argentina sphyraena*	2.5	4.4	5.3	22.9	24.9	26.1	5	52	94	477	2990	6029
6	*Argyrosomus regius*	15.9	17.1	18.9	23.6	27.2	29.1	2	7	11	35	57	4349
7	*Arius parkii*	18.6	24.8	25.6	27.4	28.2	29.9	2	3	6	14	21	3683
8	*Arnoglossus imperialis*	3.2	12.1	13.0	15.7	17.8	28.5	2	22	68	158	195	3771
9	*Arnoglossus laterna*	0.0	6.9	14.9	17.6	18.6	27.0	2	13	21	42	68	4842
10	*Arnoglossus thori*	9.2	13.5	17.6	23.9	25.4	27.1	2	44	57	139	1453	4802
11	*Atherina presbyter*	9.6	11.7	16.8	20.3	21.4	22.9	2	2	9	105	615	4842
12	*Balistes capriscus*	9.6	21.5	24.0	27.6	28.1	30.1	2	17	29	4191	4981	5913
13	*Bathysolea profundicola*	15.1	17.4	21.5	26.3	27.3	27.6	2	25	78	622	1954	4842
14	*Belone belone*	4.1	9.2	14.0	18.2	19.0	26.9	2	6	15	45	131	4842
15	*Blennius ocellaris*	8.4	9.5	10.8	18.4	23.2	24.8	2	15	29	133	2176	4842
16	*Boops boops*	10.4	16.6	18.1	24.0	26.6	29.7	2	16	21	73	126	4842
17	*Buglossidium luteum*	0.7	5.2	10.7	16.6	17.1	25.3	2	10	15	37	52	4842
18	*Callionymus lyra*	0.0	6.6	12.0	17.0	18.1	26.8	1	13	22	66	113	6029
19	*Callionymus maculatus*	3.8	4.0	4.3	15.3	18.7	23.5	2	18	33	156	1016	4842
20	*Campogramma glaycos*	16.2	17.7	18.7	23.1	25.7	28.1	2	7	17	72	153	4443
21	*Capros aper*	5.9	11.2	12.3	14.2	17.2	28.5	3	10	122	174	231	6029
22	*Caranx crysos*	14.3	22.7	23.9	27.5	28.3	31.3	2	11	18	4664	4880	5540
23	*Cephalopholis taeniops*	15.9	17.0	18.9	24.7	26.4	28.1	2	11	17	40	99	5380
24	*Chelidonichthys lucerna*	1.6	12.0	13.9	17.3	23.8	28.4	2	10	16	47	99	4842
25	*Chlorophthalmus*	0.3	8.3	14.8	24.9	26.8	29.9	2	17	73	442	721	5605
26	*Ciliata mustela*	0.1	3.8	5.5	10.9	17.0	26.8	2	3	3	30	50	4842
27	*Citharus linguatula*	12.8	17.1	18.8	25.4	27.0	29.2	2	14	18	79	161	4472
28	*Coelorinchus*	1.2	18.1	20.3	26.6	27.9	30.5	2	14	19	402	603	5196
29	*Conger conger*	5.1	10.8	12.5	16.2	18.4	28.1	2	18	43	221	594	5603
30	*Coris julis*	9.1	16.8	20.6	25.1	25.8	28.3	2	12	17	71	449	4951
31	*Dactylopterus volitans*	10.9	17.9	21.1	26.8	27.5	29.5	2	13	18	72	1530	8018
32	*Dentex macrophthalmus*	16.5	17.5	19.0	24.2	27.1	28.7	2	15	21	127	348	4842
33	*Dicentrarchus labrax*	0.8	6.4	12.7	17.1	18.0	26.3	2	8	15	59	87	4951
34	*Dicologlossa cuneata*	2.9	16.2	17.4	22.4	25.6	28.5	2	10	17	43	99	4802
35	*Diplodus vulgaris*	12.6	14.1	16.5	24.7	25.6	27.5	2	16	30	77	599	4951
36	*Dipturus batis*	0.8	7.3	8.3	12.5	13.3	17.9	2	57	93	147	181	4842
37	*Echeneis naucrates*	15.0	22.8	23.8	27.2	28.6	31.2	2	8	16	52	127	6922
38	*Echiichthys vipera*	3.4	8.4	13.3	17.3	18.1	19.1	2	9	16	49	104	4454
39	*Engraulis encrasicolus*	0.0	5.3	6.9	15.3	18.0	29.9	2	18	27	79	113	5380
40	*Ephippion guttifer*	17.1	24.0	25.1	27.0	27.9	29.1	2	6	10	26	71	5380
41	*Epinephelus marginatus*	13.1	19.1	20.4	23.8	25.0	28.4	2	8	14	28	50	6169
42	*Fistularia petimba*	15.8	22.3	23.6	26.3	28.9	31.5	2	17	32	88	148	5683
43	*Gaidropsarus*	8.1	9.5	10.2	12.1	13.3	13.3	5	73	112	778	1141	4770
44	*Gaidropsarus*	6.2	7.5	8.8	14.7	15.8	16.4	2	8	26	489	2973	4842
45	*Galeoides decadactylus*	16.6	20.5	23.9	27.0	28.1	29.9	2	5	9	24	57	5395
46	*Galeus melastomus*	5.9	9.0	13.0	18.0	19.1	28.9	4	13	181	498	616	4931
47	*Gephyroberyx darwinii*	5.9	17.7	19.5	26.2	27.6	29.7	2	12	17	157	797	7864
48	*Halosaurus ovenii*	16.0	18.9	20.6	27.2	28.1	29.7	2	12	17	401	816	4472
49	*HoplosteThus, cadenati*	17.7	19.0	20.7	26.6	27.6	29.1	5	13	343	661	873	3989
50	*Hymenocephalus*	13.2	15.3	18.1	25.6	27.2	29.9	2	14	19	496	994	7265
51	*Labrus mixtus*	1.6	10.3	11.7	15.5	16.5	24.8	2	9	17	44	61	4951
52	*Lepidorhombus*	0.0	8.1	10.8	13.5	14.5	27.0	4	99	122	173	232	4842
53	*LithognaThus,*	14.0	16.4	18.2	24.7	27.0	29.7	2	12	21	65	658	6020

No	Species	SST						Depth					
		Min	10	25	75	90	Max	Min	10	25	75	90	Max
54	*Liza ramada*	5.2	12.5	15.6	19.3	22.9	25.5	2	8	16	76	1328	4842
55	*Merluccius merluccius*	0.0	7.5	10.8	14.6	17.3	29.0	1	57	95	152	211	4842
56	*Mugil cephalus*	3.0	16.1	19.4	25.2	27.9	31.2	1	2	2	100	1679	5431
57	*Mustelus mustelus*	10.6	15.8	16.7	23.3	26.5	29.3	2	16	25	91	167	4775
58	*Mycteroperca rubra*	16.1	17.1	18.3	23.3	26.4	28.1	2	19	36	97	3181	4770
59	*Myctophum punctatum*	1.8	9.4	14.3	18.8	20.2	26.4	5	29	909	3726	4697	5603
60	*NotacanThus,*	11.4	13.8	13.8	22.4	24.5	24.6	60	34	637	1821	2707	4774
61	*Pagrus caeruleostictus*	14.6	19.0	23.1	26.8	27.6	29.7	2	9	14	36	66	5380
62	*Parapristipoma*	16.1	17.1	18.4	24.7	26.8	28.2	10	23	36	81	1954	3316
63	*Pegusa lascaris*	10.5	14.8	17.7	25.8	27.0	28.1	2	11	17	55	361	5380
64	*Peristedion*	13.3	18.3	20.1	26.0	27.5	29.5	2	12	17	99	334	4842
65	*Pisodonophis*	17.7	20.2	22.0	23.3	27.5	29.1	2	10	18	1954	4598	5380
66	*Pomatomus saltatrix*	6.0	15.0	16.9	21.2	23.8	30.2	1	2	5	27	59	5421
67	*Pontinus kuhlii*	16.6	17.9	19.6	26.0	27.1	28.4	2	14	18	141	354	5380
68	*Raja miraletus*	13.0	15.5	16.0	19.0	22.1	28.8	2	15	20	76	142	5999
69	*Rhinobatos cemiculus*	18.6	20.3	23.6	27.4	27.9	28.8	2	10	16	39	99	5380
70	*Rhinobatos rhinobatos*	14.5	19.5	23.7	26.7	27.4	29.3	2	10	16	35	73	5380
71	*Salmo salar*	0.7	1.8	3.6	13.7	16.8	27.7	2	15	23	119	119	4842
72	*Sarda sarda*	12.7	17.5	21.2	27.1	28.9	30.3	2	11	17	76	1926	5999
73	*Sardina pilchardus*	0.5	7.5	12.4	17.6	18.9	28.3	2	23	37	117	163	4893
74	*Scomber scombrus*	0.1	7.1	8.9	15.3	17.4	29.6	1	27	43	131	160	4842
75	*Scophthalmus rhombus*	0.0	3.8	10.8	17.2	18.5	25.6	1	13	18	37	55	4842
76	*Scorpaena scrofa*	4.8	14.1	16.2	23.7	25.4	29.0	2	14	19	83	257	5999
77	*Scyliorhinus stellaris*	5.0	9.8	12.4	16.6	19.1	28.5	2	11	17	56	138	5104
78	*Solea senegalensis*	12.5	17.4	18.8	25.2	27.4	28.2	2	5	13	49	87	4874
79	*Sphoeroides*	9.0	16.4	17.4	22.8	26.5	30.0	2	17	28	156	424	8694
80	*Sphyraena sphyraena*	18.1	19.1	21.4	26.4	27.4	29.2	2	14	23	92	2990	5380
81	*Spondyliosoma*	2.7	14.7	16.3	19.3	23.3	27.8	2	9	17	55	98	4842
82	*Sprattus sprattus*	0.0	2.8	4.9	10.3	15.3	27.8	1	21	28	57	83	4842
83	*Stromateus fiatola*	14.2	15.6	15.9	24.8	26.5	29.1	2	11	17	49	99	5999
84	*Torpedo marmorata*	11.0	17.4	21.0	26.7	27.6	29.1	2	10	16	76	1009	5380
85	*Trachurus trachurus*	0.0	7.7	10.7	16.5	18.3	29.2	1	20	31	129	166	4842
86	*Trachyrincus scabrus*	9.9	10.6	14.1	21.5	26.0	27.6	42	35	509	1039	2279	5297
87	*Trichiurus lepturus*	5.9	18.0	20.5	26.7	28.2	31.1	2	7	10	78	226	5375
88	*Trigla lyra*	16.0	17.4	19.4	25.6	27.4	28.9	2	11	17	71	334	5445
89	*Umbrina canariensis*	12.3	15.8	16.5	20.7	23.5	28.5	2	13	19	81	201	5999

4.4.5 Discussion: ecological niche

4.4.5.1 Thermal niche and lethal temperature

The maximum SST values for *P. saltatrix* measured using AVHRR and MODIS data varied with an approximately 2 °C difference with the value determined in AquaMaps. According to Fahay et al. (1999) and Ballenger (2014), this species can tolerate water temperatures from 30-34 °C, which is near the maximum temperature obtained in this study. This species begins to lose its equilibrium at 35 °C and cannot survive at a temperature above it (Olla and Studholme 1975; and Olla et al. 1975). At the minimum SST, there is a large difference, of almost 6 °C, between the value found in our study (about 6 °C) and the value used in AquaMaps (0.67 °C). This species was noted among the species killed in south-central Florida when the temperature range from 6 to 13 °C (Gilmore et al. 1978). Thus our result corresponds to the minimum temperature from the observational study.

The minimum temperature for *B. capriscus* was also determined by AquaMaps at -0.74 °C, but some studies, i.e., Aggrey-Fynn (2007), have suggested that this species is sensitive to low temperatures, which is possibly the reason for their movement. Gilmore et al. (1978) also found that this species was among noted to be killed by cold in Florida during the January 1977 freeze, when the temperature was recorded as 6 °C. In additions, Johnston et al. (1998) stated that the range of temperatures from -1.86 to +2 °C is for Antarctic fish and that it would be lethal for temperate and tropical species. Our study methods showed then a robust and reliable result as it agrees with the results from observational studies.

P. saltatrix and *B. capriscus* were found in nearly the same range of temperatures for both seasons, winter-spring and summer-autumn (Table 4-10 and Figure 4-23). This result reflects the migratory nature of these species, to find their preferred range of temperatures when the season changes. For the case of *B. capriscus*, Aggrey-Fynn (2007) stated that this species migrates during cold season from coastal waters to warmer waters further offshore, usually between 25-26 °C off the Ghanaian coast. This seems to correspond with the finding in our study that 50% of the occurrences of this species were found in the temperature ranged from 24.66 to 28.91 °C. Fry (1947) explained that the ability of fish species to avoid or select environmental temperature is one of the critical components of their behavioural repertoire, because the vast majority of fish species do not have the capability to regulate their body temperature.

In the case of *Solea senegalensis*, the minimum and maximum temperature of this species in our study ranged from 10 to 30 °C, whereas AquaMaps used the range from 1 to 30 °C (Table 4-10, Figure 4-23 and Annex 11). This species occurs mainly in tropical waters, and the northernmost occurrence where this species has been recorded is in the Bay of Biscay, which has a minimum temperature that range from 8-10 °C (Puillat et al. 2004), near the minimum temperature obtained in this study. Between winter-spring and summer-autumn, this species was found in different range of temperature (Table 4-10 and Figure 4-23). Fifty percent of our data in all seasons showed that this species was found in the range of 18.8 to 25.9 °C. This finding is correspond to the optimal temperature of this species mentioned by Imsland et al. (2003) that range from 16 to 25 °C.

MODIS data showed a slightly higher minimum values than AVHRR data (Figure 4-22 and Table 4-10), which is coherent with the lethal temperature minimum obtained from observational studies. However, the number of occurrence used to determine niche using MODIS data was much lower than that when using AVHRR data. Even though the niche resulting from MODIS matched the values obtained from literature, the values from AVHRR cannot be neglected since they were generated using sample sizes three times bigger. In general, the niche obtained from these two instruments showed a consistency with the results obtained from observational or experimental studies despite the facts that the species lived in different water column and that the data used was satellite data that measured only the surface of the sea water. NonethelessThe niches generated in this study came from the occurrence obtained from the area occupied by the species around the world, while the values from observational studies came mainly from observation in a particular area.

MODIS instruments began acquiring data in July 2002, while AVHRR had started its acquisition earlier, in November 1981. Because the method took into account only the occurrences whose time of observation matched the satellite raster data, the number of occurrence that matched with MODIS data was lower than that with AVHRR data. Nevertheless, the number of occurrence of MODIS data used in this study is much higher than the number of occurrence used to generate niches in other studies, i.e. in Aquamaps: 577 records were used to generate *P. saltatrix* niche, while in this study we used 3,037 records for MODIS and 11,386 records for AVHRR; see supplementary materials).

For certain migratory species such as *P. saltatrix*, it seems that the species occurred at higher latitudes in autumn when the sea water was still warm after summer. Sea water is known to warm or cool slowly due its thermal capacity.

P. saltatrix was observed mostly in the southern areas during winter. Oliver et al. (1989) and Ballenger (2014) mentioned that this species is a warm water migratory pelagic species that generally travels northward in spring and summer, and southward in fall and winter along the Atlantic seaboard. Olla and Studholme, (1971) whit their studies using adult and juvenile bluefish have suggested that this species was also capable of behavioral thermoregulation. This capability had been suggested since both juveniles and adults exhibited increases in activity when exposed to changes in temperature under homeo-thermal conditions.

Temperature plays a crucial role in almost all aspects of fish biochemistry, physiology and behavior. This parameter is one of the main drivers and a good proxy of the ecological niche for its crucial role in almost all aspect of the of a fish (Fry, 1947). The parameter correlates well with other factors, such as oxygen and nutrient concentration and to a lesser extent chlorophyll concentration (Helaouët and Beaugrand 2009). The vast majority of fish species do not have the capability to regulate their body temperature, and because there exists a range of temperature below or above which a given species cannot survive, their capability to avoid or select environmental temperature is one of the more critical components of their behavioral repertoire (Fry 1947). Temperature is also the oceanic parameter observed for a long period using satellite sensors. It is also the most accessible data.

Gilmore et al. (1978) mentioned that the species most sensitive to low temperatures are principally tropical species. Fishes with limited mobility were greatly affected. They could not escape the rapidly cooling shallow waters as readily as other species. The tropical species are also assumed to be temperature sensitive at most stages of development. Graham (1972) observed the range of lethal temperatures of various tropical fishes from Panamanian waters, in controlled laboratory experiments. He found the fish range lower lethal temperature between 8-13 °C. These observations demonstrate that some tropical fishes are more eurythermic than others.

A number of other factors, both biotic and abiotic, play also important role on thermal distribution. These include season, time of day, food availability, salinity, habitat requirements, nutritional state, competition and/or predation, age, social factors and pathological condition (Olla et al. 1985).

Temperate and sub-temperate estuarine fishes are generally regarded as eurythermic when compared to offshore fish populations and subtropical or tropical fishes. However, occasionally environmental extremes may produce extensive mortality in temperate estuarine fishes (Southward 1958).

Gilmore et al. (1978), in their study in south-central Florida estuaries during winter 1977, showed that many stenothermic tropical and subtropical fishes suffered mortality. These species were almost entirely typical estuarine and shallow coastal zone inhabitants. In this season, these species reach their northern breeding limits in Florida waters and become vulnerable to low temperature stress. A combination of physical conditions produced the extensive fish mortality in the areas: 1) the passage of the cold front was sudden, 2) water temperature minima were very low (to 6 °C) and 3) water temperatures remained low for five to six days.

4.4.5.2 Pelagic species versus demersal species

Data acquired using satellite instruments is assumed to be not representative to measured the living conditions of demersal species, except perhaps for SST measured at night time. According to GHRSST Science Team (2010), the SST measured at night time shows little difference with the sea surface foundation temperature (temperature below 10 m deep, see section 2.2.1.1). Thus, we used SST night as temperature niche in the future analysis.

Using SST as a predictor for distribution models of deep-water species raised many questions on their correlation. Whitehead et al. (2010) stated that diversity, from an ecological perspective, is a function of niche overlap. They assumed that SST and water depth are prominent factors distinguished habitats of different species. They mentioned that species physiology of energetic and thermal regulation, and species' anatomy for diving related to the two environmental parameters above. The deep-water species diversity and SST may have structures similar to diversity patterns of prey species, including zooplankton and fish.

Bathymetric data is more useful for studies of demersal species than pelagic species. Despite this, for shallow waters, bathymetric conditions could also influence the water column above the bottom, where the pelagic species live.

The stratification of the sea temperature varies seasonally (Figure 4-25). In the winter period, the differences of temperature between the surface and the water column were small. These differences increased as the seasons changed to spring, autumn and reached their maximum in summer. Figure 4-26 shows another example of sea surface temperature and seafloor temperature in the Mediterranean Sea.

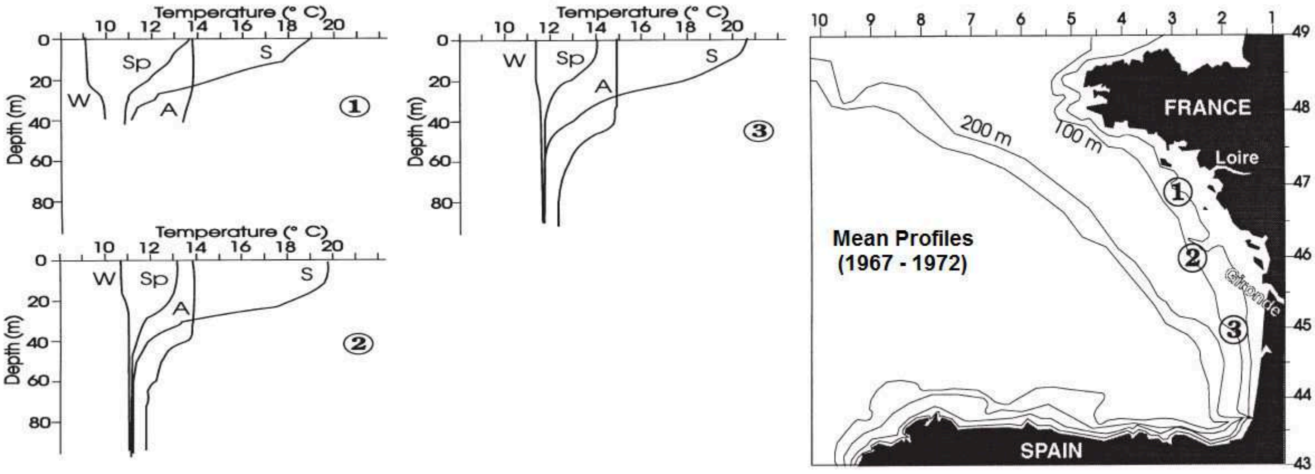


Figure 4-25: Mean vertical temperature profiles according to Koutsikopoulos and Le Cann (1996) in the Bay of Biscay, in three locations indicating by numbers 1, 2 and 3. W = winter, Sp = spring, S = summer, A = autumn.

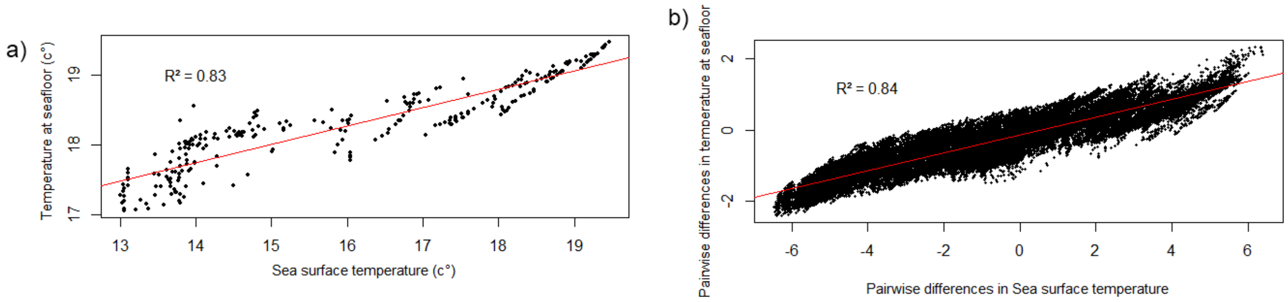


Figure 4-26: Spatial distribution and temporal variation between sea surface temperature and seafloor temperature in Mediterranean waters (Lasram et al. 2015).

4.4.5.3 Bias in occurrence data

The maximum and minimum environmental values of niches generated in this study are often outliers. Extreme values could be due to biases in species coordinate positions or species misidentification. Nontheless, for certain species inhabiting open ocean in some stage of their life, the maximum value (i.e. depth) cannot be neglected.

A species could occur in the area having depth higher than 200 m, but the species is actually present near the surface water. Aquamaps determined that the range of depth for *P. saltatrix* was from 0 to 200 m maximum, while in this study, the extreme maximum depth observed was 5421 m. The value of depth represents in our study was the depth of the area where the species occurred, not necessarily in the 5421 meters of the water column. This species, as mentioned previously, is a migratory pelagic species whose movements vary with size. Small bluefish are found along the shore and in bays, whereas larger fish tend to be found offshore, in deeper water (Hayden et al. 1978). Fahay et al. (1999) mentioned that the eggs of Blue fish were found in the open ocean. Kendall and Walford (1979) further mentioned that the larvae of this species occured in open oceanic waters near the edge of the Continental Shelf in the southern Mid-Atlantic Bight and over mid-shelf depth farther north. The adults of this species are generally oceanic and distributed from near-shore to well offshore over the continental shelf (Bigelow and Schroeder 1953; Olla and Studholme 1971).

The extreme maximum depth area observed in this study was probably for the juvenile stage. In the case of Triggerfish, Aggrey-Fynn (2007) stated that *B. capriscus* is more planktivorous at juvenile stage, so that this species has a wider and deeper habitat range and its foraging might be more independent of light and temperature.

Terrain ruggedness is often an important variable in wildlife habitat models. Quantitative analysis shows that this parameter appears to be important in understanding the behavior and distribution of a species (Sappington et al. 2007). Since bluefish use a diverse array of habitats according to their life stage, almost all of the estuarine and near-shore waters serve as an important habitat for some or the other of these life stages. For example, juveniles are found in many habitats, though they do not use the marsh surface (Ballenger 2014).

In the study of distribution modelling processes that mostly used 2D environmental raster data, it could be better to use environmental values of the area rather than the values where the species was captured. For example, if we used 200 m as maximum depth value (i.e used in Aquamaps), we will then look for areas with a 200 meter maximum depth and exclude other areas beyond that limit, while the species could be present in near surface of waters deeper than 200 m, such as in the open ocean, although they can be present only in the first 200 m of the water column. However, incorporating the values defined in Aquamaps could enhance the model of species distribution.

Bias in species occurrence have been discussed, i.e., Beck et al. (2014). Several factors, such as survey location, spatial scale, misidentification, and mobilization can cause such biases. This could lead to a potential strong distortion of our view on large-scale biodiversity patterns (Yang et al. 2013).

Some data sources used in this study have quality issues, and the lack of transparency on data quality has been noted by many authors and publicly criticized (Graham et al. 2007; Soberón et al. 2002; Yesson et al. 2007). To address this issue, we increased the number of sample records by assembling and cross-checking data from at least five data sources. The total number of occurrence records collected for *P. saltatrix* used to generate its actual niche in this study was 34517 points. In generating thermal niche, we used approximately 13784 occurrence records for AVHRR data and approximately 3037 points for MODIS data. The number of occurrence used in generating bathymetric niche is much higher, approximately 32317 points, as these parameters are considered stable in a small period of time. This number is much higher than that used in AquaMaps (577 points).

Yañez-Arenas et al. (2014) stated that to ensure an adequate representation of a species niche, the sample size must be large enough. Some studies failed to predict species distribution using a small number of occurrence records. Pearson et al. (2006) showed in their study that the success rate of these models was poor and suggested that the models were greatly influenced by the sample size. Therefore, our results could enhance the model prediction as well as provide useful biogeographical information for niche-based distribution modelling.

Another issue with regard to small sample size is data clustering. Many species occurrence records are available from well-financed, data-sharing countries, even if the real density of occurrences of the species may be higher elsewhere (Beck et al. 2014). For this reason, we collected species occurrence records observed from all around the world, and thus, the quality of prediction was not reduced.

An in-depth study on how the occurrences distributed needs to be conducted. Occurrences of *P. saltatrix* were mostly found in areas less than 300 m deep (Figure 4-27a). The frequency of occurrences in deeper (more than 500 m) was very low. Likewise for *S. Senegalensis*, this species was mostly found in areas less than 100 m deep. The occurrences of these species observed in areas deeper than 1000 m is questionable and require further study, although they were not negligible, as shown in the case of *B. capriscus*.

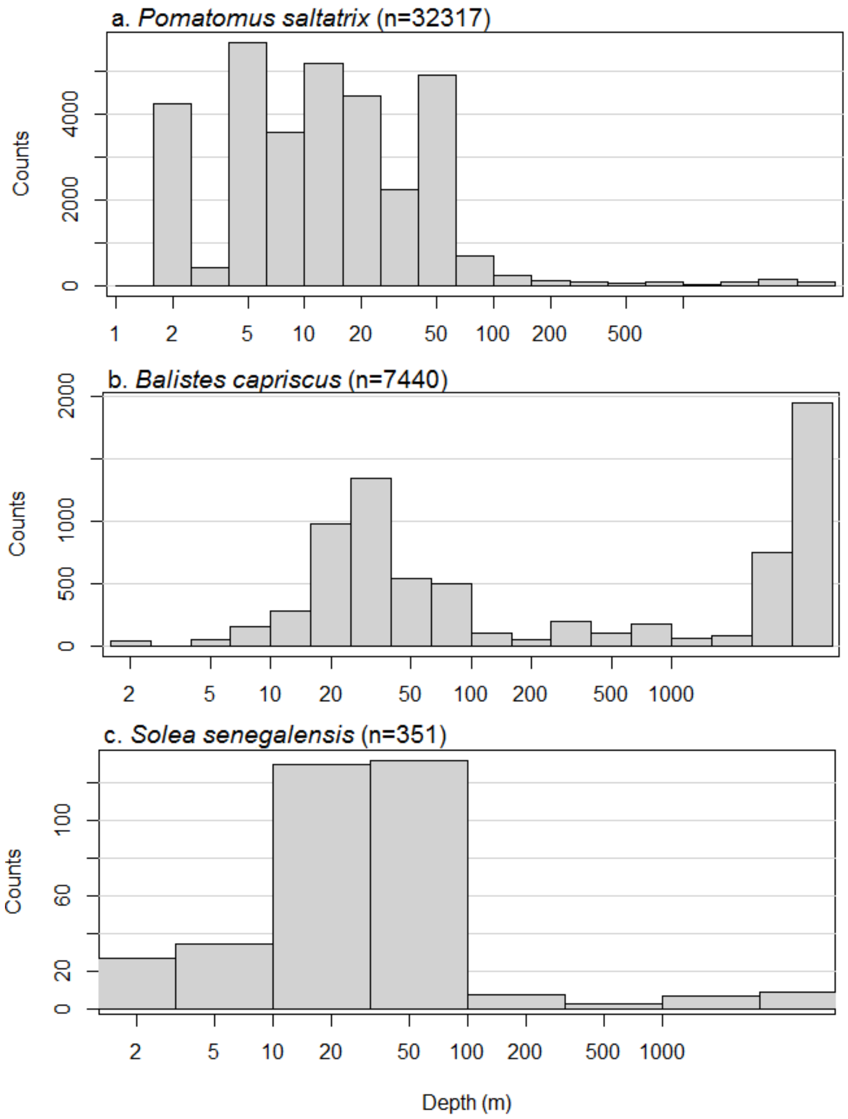


Figure 4-27: Distribution of depth areas where the species were observed. (a) *P. saltatrix*; (b) *B. capriscus*; (c) *S. senegalensis*.

The concept of niche is multidimensional (Helaouët and Beaugrand 2009). It has evolved over time and has several interpretations (Chase and Leibold 2003). Hutchinson (1987), in a now-classic reference (Franklin 2009), defined the niche as "…the hyper-volume defined by the environmental dimensions within which that species can survive and reproduce". Hutchinson further distinguished the fundamental (physiological or potential) niche, defined as the response of species to environment (resources) in absence of biotic interactions (competition, predation, facilitation), from the realized (ecological, actual) niche – the environmental dimensions in which species can survive and reproduce, including the effects of biotic interactions. The species fundamental niche represents its range of physiological tolerance in the absence of interactions with other species (competition, predation). The realized niche is the environmental space where a species actually occurs, accounting both for the availability of suitable environmental conditions and for any biotic interactions affecting a species distribution. The fundamental niche represents the response of all physiological processes of a species to the synergistic effects of environmental factors (Helaouët and Beaugrand 2009). The realized niche is often depicted as a subset of the fundamental niche, although it is not necessarily so. Hutchinson defined the "biotope" as the realized environment in the sense used above, and the realized niche as the intersection of the biotope and species fundamental niche (Franklin 2009).

Pulliam (2000) assessed the differences between fundamental and realized niche and, as stated by Hutchinson (1957), his study indicates that the realized niche is smaller when factors reducing survival, such as competition predominate. However, he also provides evidence that the realized niche can be greater than the fundamental one when dispersal is high.

Pulliam (2000) also emphasizes the importance of measuring fitness, specifically population growth rate, in order to identify a species niche (where growth rate is positive). He proposes that Hutchinson's niche concept, meta-population theory, and source-sink theory (Pulliam 1988) together can help explain the relationship between the distribution of species and suitable habitat.

The approach that we have presented here illustrated the capabilities of GIS technique for generating species realised niches using only occurrences localities enormously available online, along with the use of satellite data and other environmental raster data. The method showed effective, robust and reliable results since they were in agreement with the results from observational or experimental studies. Therefore, these results can provide valuable biogeographic information for use in species distribution modelling. With the establishment of ecological niches, in terms of niche modelling, our study opens a way for predicting species distribution. The availability of global, daily, systematic, high resolution images obtained from satellites has been a major data source for elucidating the relationships between exploited marine organisms and their habitat (Chassot et al. 2011). The results can now be used to improve modelling as well as projections for guiding future model or surveys.

The utilization of large, mixed-origin databases shows promising strong results but, as stated by Soberón et al. (2002), without proper quality control of those mixed-origin databases, their use is fraught with potential errors. However, the existence of such large amounts of good-quality, on-line data will encourage a multiplicity of users. Developing tools or procedures to spot and correct problems in the type of data will have to become a priority for the near future. In addition, a major challenge in the immediate future is to negotiate access to the several substantial biodiversity databases that are not yet publicly and freely available to the global scientific community, as stressed by Yesson et al. (2007), and to encourage more data providers to digitize and supply their records, especially to fill the gap of data in occurrence records for certain areas, such as in Portuguese and Moroccan waters. Further research is also required to investigate the impact of misgeolocation bias or data resolution and to determinate species environmental preferences.

4.5 Species distribution models

In this subchapter, we present the model of species distribution over time. Eight species inhabiting different types of environment have been selected to demonstrate this work: *Anthias anthias, Arius parkii, Arnoglossus laterna, Arnoglossus thori, Balistes capriscus*, *Diplodus vulgaris, Solea senegalensis* and *Umbrina canariensis*. These species have different affinities or origin, from sub/tropical waters to temperate waters. The environmental envelopes of these species obtained from the previous study of the chapter 4.4, and used to build the model are presented in Table 4-14.

Table 4-14: Environmental envelopes of the eight selected species.

No	Species	Class[a]	SST (°C)	Bathymetry constraint		
				Depth (m)	Slope (°)	B. Z.[b]
1.	*Anthias anthias*	1	19.1-25.03	17-99	1.2-7.8	3
		2	15.7-19.1 & 25.03-26.2	12-17 & 99-449	0.7-1.2 & 7.8-23.6	1
		3	14.5-15.7 & 26.2-27.08	9-12 & 449-2286	0.3-0.7 & 23.6-35.3	4
		4	12.9-14.5 & 27.08-29.02	2-9 & 2286.05-5134	0.1-0.4 & 35.3-75.9	2
2.	*Arius parkii*	1	25.5-27.4	6-14	0.4-1.4	3
		2	24.7-25.5 & 27.4-28.2	3-6 & 14-21	0.3-0.4 & 1.4-2.5	1
		3	22.3-24.7 & 28.2-28.5	2-3 & 21-34	0.2-0.3 & 2.5-3.7	4
		4	18.5-22.3 & 28.5-29.8	2-2 & 34-3683	0.1-0.2 & 3.7-61.8	2
3.	*Arnoglossus laterna*	1	14.9-17.5	21-42	0.3-1.3	3
		2	6.9-14.9 & 17.5-18.5	13-21 & 42-68	0.2-0.3 & 1.3-2.5	4
		3	5.2-14.9 & 18.5-19.2	10-13 & 68-113	0.1-0.2 & 2.5-4.1	1
		4	0.01-5.2 & 19.2-2	2-10 & 113-4842	0.1-0.1 & 4.1-69.6	2
4.	*Arnoglossus thori*	1	17.5-23.8	57-139.2	1.9-8.8	1
		2	13.4-17.5 & 23.8-25.4	44-57 & 139.2-1453	0.8-1.9 & 8.8-21.02	3
		3	11.9-13.4 & 25.4-25.6	26-44 & 1453-3439.8	0.5-0.8 & 21.02-37.7	4
		4	9.1-11.5 & 25.6-27.08	2-26 & 3439.8-4802	0.1-0.5 & 37.7-78.2	2
5.	*Balistes capriscus*	1	24.01-27.6	29-4191	0.92-11.15	3
		2	21.4-24.01 & 27.06-28.1	17-29 & 4191-4981	0.8-0.2 & 11.5-22.5	4
		3	18.3-21.4 & 28.1-28.3	12-17 & 4981-5113	0.7-0.8 & 22.5-37.08	1
		4	9.5-18.3 & 28.3-30.09	2-12 & 5113-5913	0.2-0.7 & 37.08-80.01	2
6.	*Diplodus vulgaris*	1	16.5-24.7	29.75-77	1.7-6.7	3
		2	14.1-16.5 & 24.7-25.5	16-29.75 & 77-599	1-1.7 & 6.7-24.5	1
		3	13.5-14.1 & 25.5-26.4	7-16 & 599-1411.7	0.6-1 & 24.5-36.1	4
		4	12.5-13.5 & 26.4-27.5	2-7 & 1411.75-4951	0.1-0.6 & 36.1-72.7	2
7.	*Solea senegalensis*	1	18.8-25.2	13-48.5	0.88-3.26	3
		2	17.4-18.8 & 25.2-27.3	5-13 & 48.5-87	0.4-0.8 & 3.2-6.9	1
		3	16.9-17.4 & 27.3-27.6	3-5 & 87-363.5	0.3-0.4 & 6.9-8.3	4
		4	12.5-16.9 & 27.6-28.1	363.5-4874	8.3-39.7	2
8.	*Umbrina canariensis*	1	16.4-20.7	18.75-81	1.14-5.3	3
		2	15.7-16.4 & 20.7-23.4	13-18.7 & 81-201.1	0.5-1.4 & 5.3-11.3	1
		3	15.4-15.7 & 23.4-25.5	10-13 & 201.1-3043.1	0.3-0.5 &11.3-19.4	4
		4	12.3-15.4 & 25.5-28.5	2-10 & 3043.1-5999	0.2-0.3 &19.4-63.4	2

[a] Class: 1 = Most Preferred, 2 = Preferred, 3 = Less Preferred, 4 = Extreme Values/Areas.

[b] B. Z. = Benthic Zone (1 = Crest, 2 = Depression, 3 = Flat, 4 = Slope).

4.5.1 *Anthias anthias*

Anthias anthias (Figure 4-28) has several common names such as *Swallowtail seaperch*, *Anthias* or *Barbier* (in french) (Aquabase 2008; Froese and Pauly 2011). It is a commercial species whose status in the IUCN Red List is Not Evaluated/NE (IUCN 2013). This species has a common length of 15 cm, and a maximum length of 27 cm (Froese and Pauly 2011). Table 4-15 presents the taxonomic hierarchy of this species.

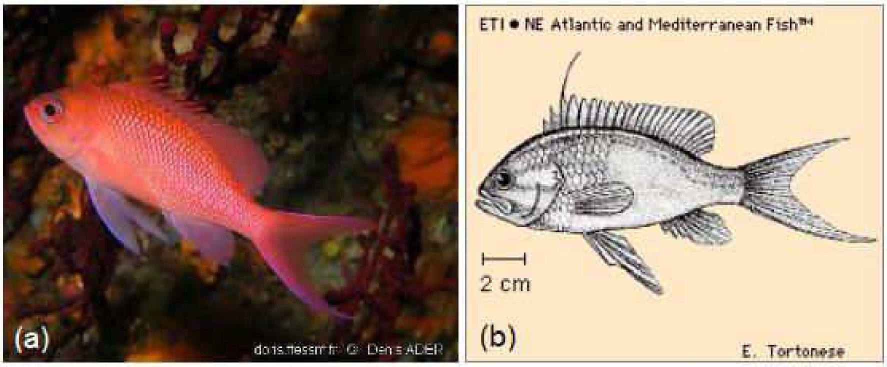


Figure 4-28: *Anthias anthias*. Images were obtained from (a) Chevallier and Le Granche (2013), and from (b) Marine Species Identification Portal (2013).

Table 4-15: Taxonomic hierarchy of *Anthias anthias*. Taxonomic Serial No.: 643209 (Chevallier and Le Granche 2013; ITIS 2013).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Perciformes
Suborder	Percoidei
Family	Serranidae
Subfamily	Anthiinae
Genus	*Anthias* (Bloch, 1792)
Species	*Anthias anthias* (Linnaeus, 1758)

Anthias anthias is a nocturnal marine species that lives in the water column with a 15 to 300 m depth range on the continental shelf. It is usually found at 30 – 50 m depth, and is abundant at 20 m. Our study found that most of this species present at depth between 10 to 30 m (Figure 4-29a), thus matchs the litterature. 50% of our data showed that this species was recorded in the area with depth between 17 m and 99 m. At night, this species is easily observed at depth of 5 – 10 m (Aquabase 2008; Bay-Nouailhat 2004; Froese and Pauly 2011; Bailly 2013a).

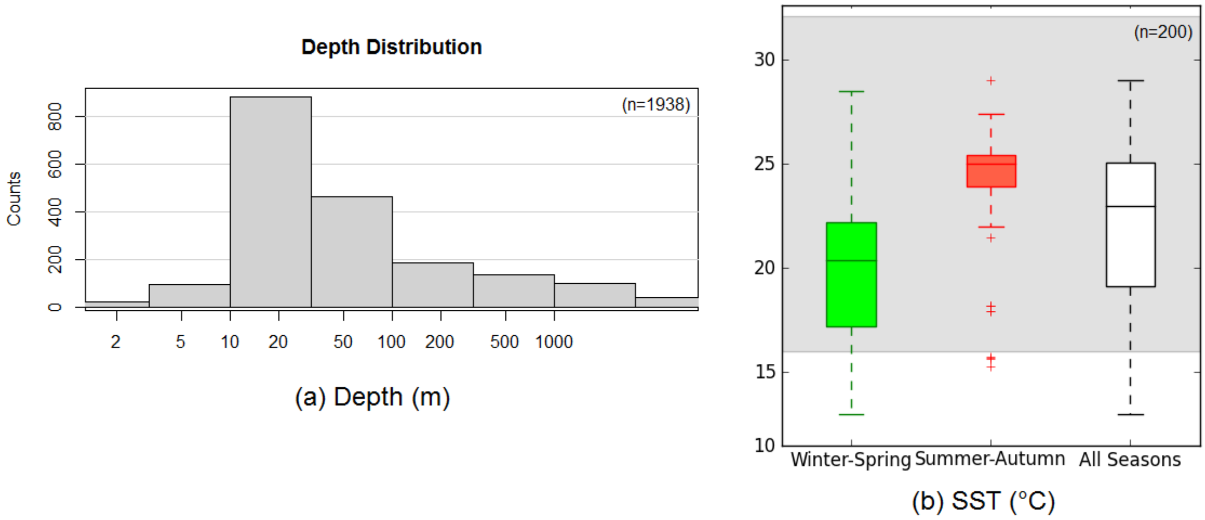


Figure 4-29: Area of (a) depth distribution and (b) SST seasonal distribution of *A. anthias*.

Aquabase (2008) notes that *A. anthias* is found at temperatures ranging from 15 °C to 22 °C. In our study, this species was mostly observed in areas with a SST between 17.68 and 25.03 °C (Figure 4-29b). This species was found in different seasonal range of temperature (Figure 4-29b), reflected that this species is not a long migratory species. In the first semester (winter and spring), this species was observed mostly in the areas with temperatures between 17.17 °C and 22.2 °C, while in the second semester (summer and autumn), it was observed mostly in the areas with temperatures between 23.89 °C and 25.43 °C.

Anthias anthias is distributed in the Eastern Atlantic, from the European waters (along the Spanish and Portuguese coasts), to Angola, including the ZEE of the Azores (Figure 4-30). It is also found in the Mediterranean Sea (Aquabase 2008; Bay-Nouailhat 2004; Bailly 2013a). Its distribution range was reported to extend south to northern Namibia.

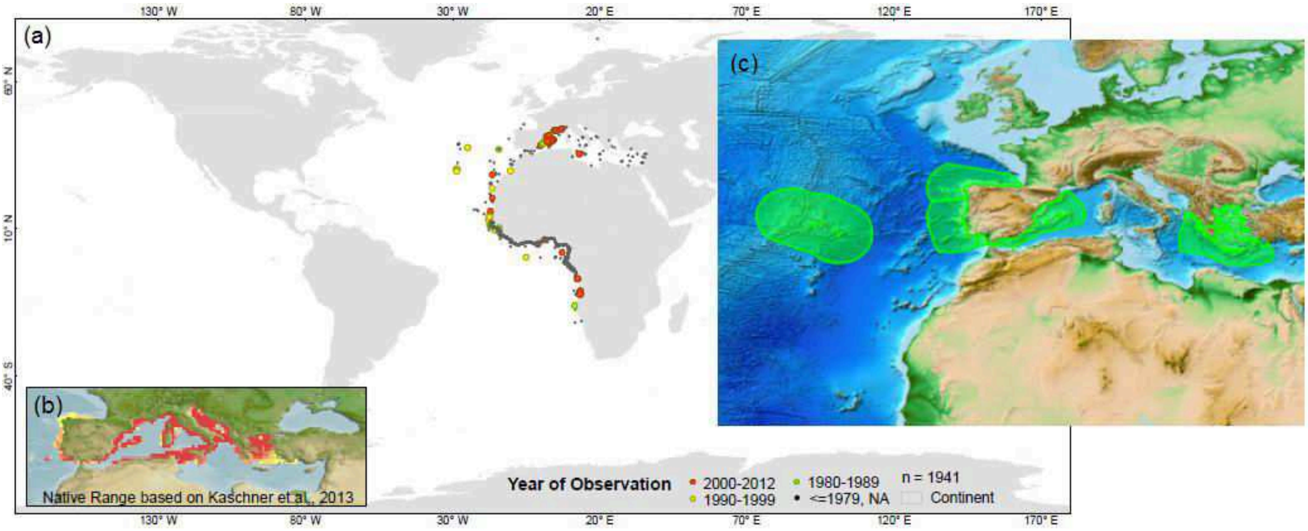


Figure 4-30: (a) Distribution of *A. anthias* in this study; (b) Native range model from Kaschner et al. (2013); (c) Distribution from Bailly (2010).

Figure 4-31 presents the distribution of *A. anthias'* occurrences compared with the seasonal models obtained in this study. The black points showing the species occurrences in the Bay of Biscay were probably observed during the summer period, when these areas became suitable for the species as the temperature increased. Yellow points, that represent the spring observations, were found mostly in the southern part of the study area, which perfectly matches the spring model of the most and the preferred suitable area. Likewise for the summer occurrences, represented by the red points, those were observed mostly off the coast of Morocco and in southern Spain. The summer model predicted effectively the most and preferred suitable areas for this species. Thus, our model predicted accurately enough for the data-poor areas. It shows their effectiveness in predicting the areas of distribution of *A. anthias* seasonally.

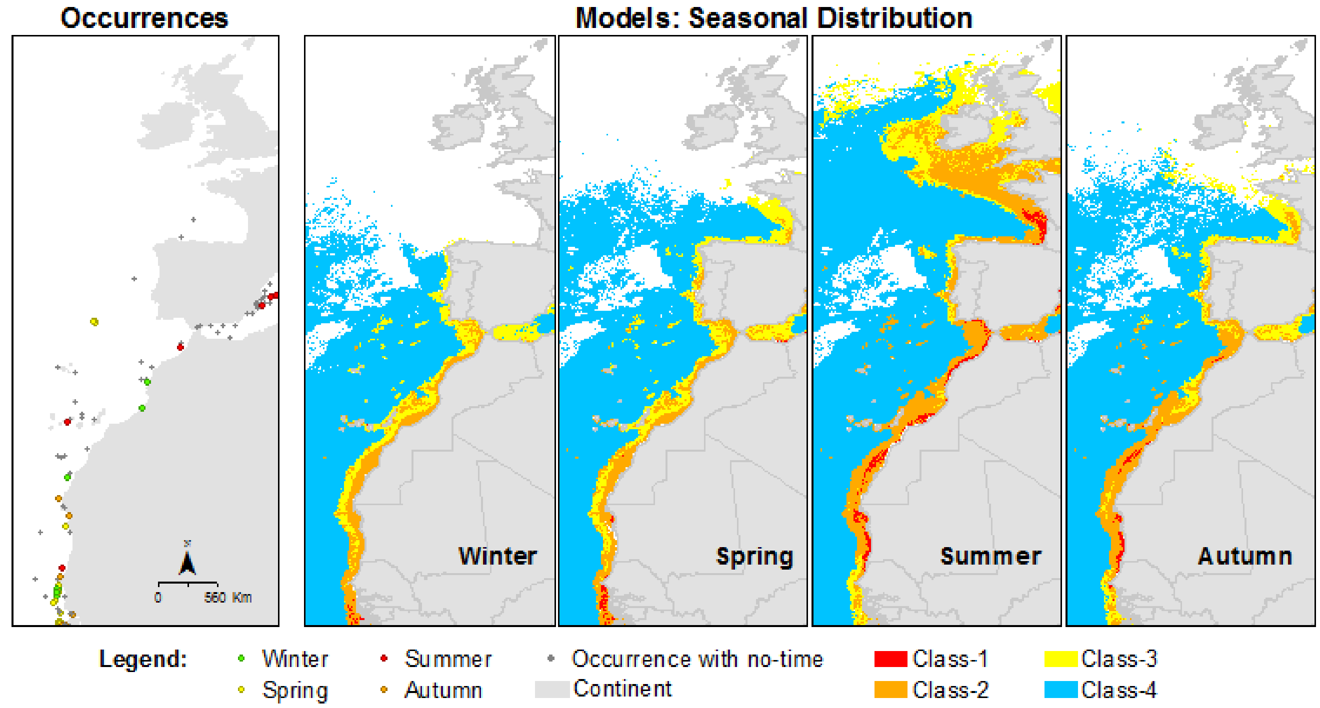


Figure 4-31: Occurrences of *A. anthias* and its seasonal distribution models (climatology). Evolutions of seasonal distributions from 1982 to 2012 are available in the supplementary files.

The reproduction period of *A. anthias* was observed in the spring and the summer (Marine Species Identification Portal 2013). Chevallier and Le Granche (2013) mentioned that the reproduction of this species occurs from June to October. They also explained that the male demarcates a territory and cleans a nesting surface on which the eggs will be fixed by an adhesive filament. It is also the male that ventilates eggs. *A. anthias* is a *protogynous* species, whose female reproductive organs come to maturity before the male ones. The male dominates a group of females. When the dominant male dies, the largest female in the group becomes male and takes up his role (Aquabase 2008).

4.5.2 *Balistes capriscus*

Environmental characteristics of *B. capriscus* have been discussed in the previous sub-chapter (sub-chapter 4.4). In this section, we will present in more detail its biological and environmental characteristics related to the seasonal models produced in this work.

Balistes capriscus has many common names, such as *grey triggerfish*, *filefish*, *leatherjacket*, *pig-faced* and *turbot*. In French, the common names of this species including *baliste*, *baliste cabri* or *cochon de mer* (Bester 2013). Another common name in Breton traditional language is *Peroked* (Tourenne et al. 2011).

Balistes or *βαλλίστρα* in Greek means *to throw*, and in Latin means *to launch*, or designates a machine used to launch projectiles, in reference to the first dorsal spin (Figure 4-32) which quickly recovers when this species is threatened or when hunting (Tourenne et al. 2011). *Capriscus* in Latin means *goat* or *sheep*, which explains where the French name *cabri* comes from (Froese and Pauly 2011).

Figure 4-32: *Balistes capriscus*. Images were obtained from (a) Marine Species Identification Portal (2013), (b) Bester (2013), and (c) Tourenne et al. (2011).

The Triggerfish is a commercially and recreationally important fish (Bester 2013), consumed mostly fresh, smoked or dried and salted, and the flesh of this fish is considered to be of excellent quality. It is also highly prized as a show fish in public aquarium facilities. Human consumption of this species has been linked to cases of *ciguatera poisoning* (Froese and Pauly 2011; Bester 2013). In the IUCN Red List, this taxon has a status of Not Evaluated (IUCN 2013). The taxonomic hierarchy of this species is presented in Table 4-16.

Table 4-16: Taxonomic hierarchy of *B. capriscus* (Tourenne et al. 2011).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Order	Tetraodontiformes
Family	Balistidae
Genus	*Balistes*
Species	*Balistes capriscus*

Balistes capriscus inhabits bays, harbors, lagoons, seaward reefs, chiefly over rocky bottoms and often under floating wreckage. The adults usually live solitary, in pairs or in a small group, drifting along or near the bottom (Marine Species Identification Portal 2013; Aquabase 2008). At early stage, the juveniles drift at the surface with sargassum (Froese and Pauly 2011; Bester 2013; Kate 2008; Bay-Nouailhat 2009). Maximum length of this species is 60 cm, with a common length of 44 cm (Froese and Pauly 2011; Froese and Pauly 2011a; Aquabase 2008). Bester (2013) mentioned that this species can grow to a maximum length of 76 cm. He further mentioned that the triggerfish can weight up to 5.9 kg and reach a maximum age of approximately 13 years.

Balistes capriscus has a daytime activity and lives mainly from temperate to tropical warm waters (Figure 4-33). It is native to North American shores such as Nova Scotia in Canada, southeast to Bermuda, Florida as well as in the Gulf of Mexico and extens south to Argentina. This species is also present in the East Atlantic, from England and Ireland, south to Angola, and is also commonly found in Mediterranean Sea (Marine Species Identification Portal 2013; Aquabase 2008).

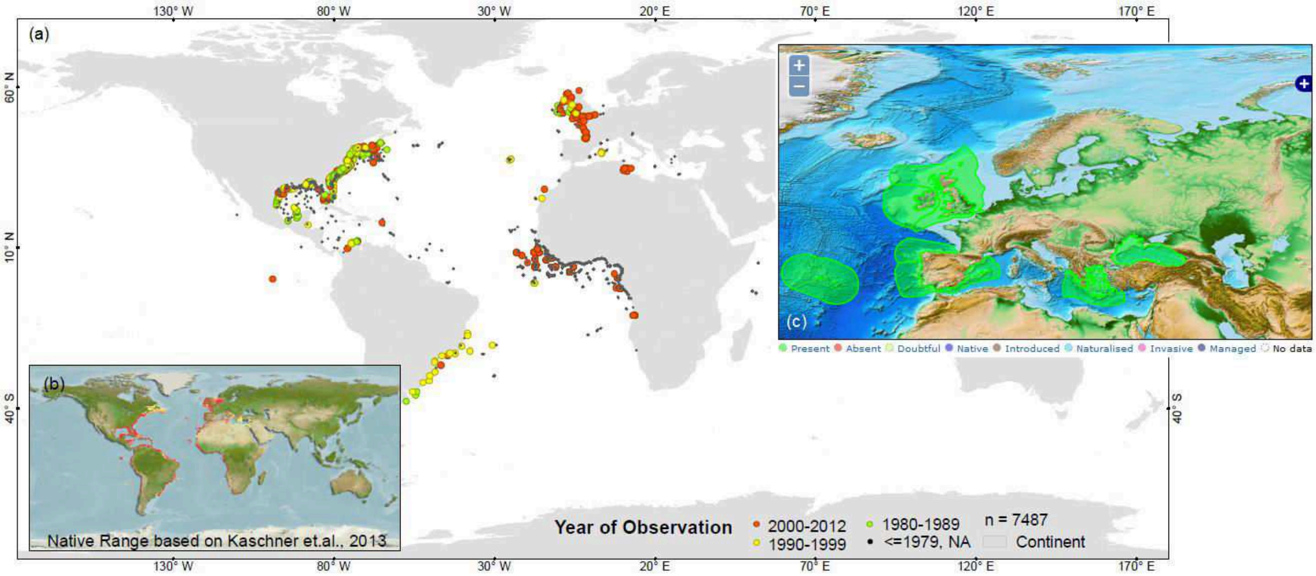


Figure 4-33: (a) Distribution of *B. capriscus* in this study; (b) Native range model from Kaschner et al. (2013); (c) Distribution from Bailly (2010).

Bester (2013) explained that as a diurnal predator, the gray triggerfish feeds primarily on benthic invertebrates such as shrimp, crabs, sea urchins, sand dollars, sea stars, sea cucumbers, and bivalve molluscs. Its little mouth is equipped with strong teeth that allow it to break the shells of shellfish, especially mussels, or crustacean shells (Bay-Nouailhat 2009). Juvenile triggerfish are associated with *Sargassum* communities they feed on algae, hydroids, barnacles, and polychaetes (Bester 2013).

Tourenne et al. (2011) mentioned that the triggerfish from further north does not have the attractive colors of tropical triggerfish, but rather uniformy gray, while those in the south have small iridescent scales and more marbling.

Balistes capriscus lives in the water column not far from the coast, a maximum depth of 100 m (Marine Species Identification Portal 2013), and is more usually found from 0 to 55 m (Froese and Pauly 2011; Froese and Pauly 2011a; Aquabase 2008; Bester 2013; Bailly 2013b). This species is also abundant in both near-shore and offshore locations (Bester 2013). Tourenne et al. (2011) stated that during the warmer periods, the common triggerfish is found along the coast at depth between 5 and 30 m, while during the winter, this species is found in area up to 100 m deep.

Our study found that this species was observed in areas less than 100 m deep (Figure 4-34a). Nevertheless, an important number of occurrences were observed in the areas where depth was more than 1000 m. The large number of observation means that this finding is not merely due to a misidentification of the species. This is possible if we consider that these observations is for species at juvenile stage. Aggrey-Fynn (2007) mentioned that Triggerfish species are more *planktivorous* at juvenile stage, so that this species has a wider and deeper habitat range and its foraging behaviour might be more independent of light and temperature. Aggrey-Fynn (2007) further showed that this species has been catched in areas with a depth range of 50 m, 200 m and 1000 m offshore.

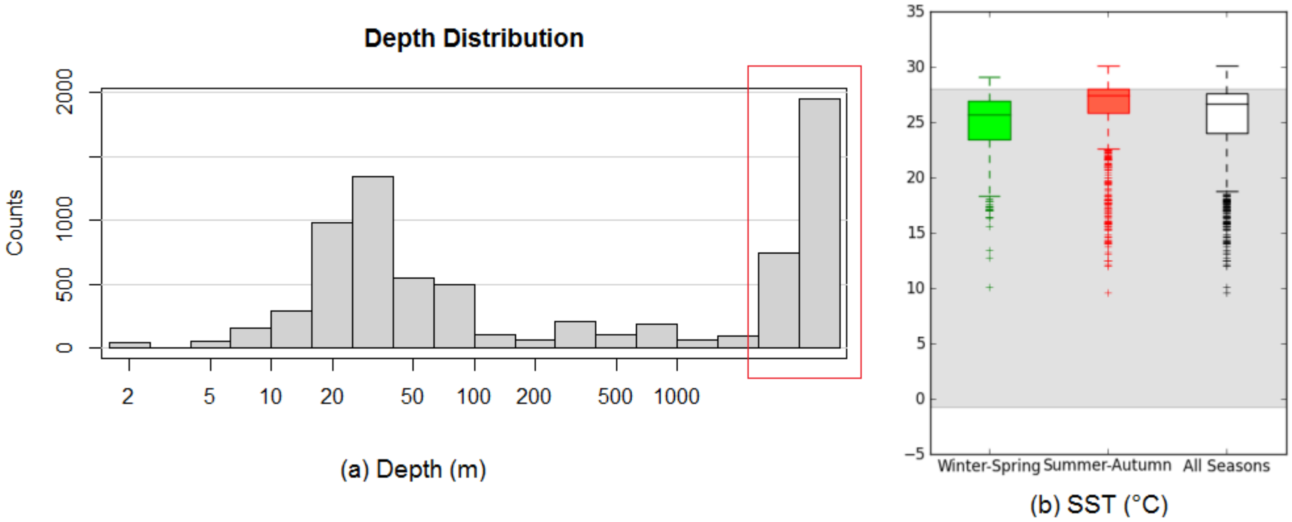


Figure 4-34: (a) Depth distribution and (b) SST distribution of *B. capriscus*. Red rectangle in the depth distribution graph indicates values that require further investigation. The figure presents the area where the species occurred and not the water column where the species lives.

The range of temperature where *B. capriscus* was found in this study was between 9.58 °C and 30.09 °C. Most of the occurrences were observed in the range of temperature between 24.01 and 27.6 °C. Small seasonal variations of preferred temperatures reflected that this species migrates to areas where the temperatures are in its preferred range when the season changes (Figure 4-34b).

The reproduction period of *B. capriscus* occurs in summer, from June to August (Tourenne et al. 2011). When the temperatures reach 21 °C, the gray triggerfish lay their eggs in a cavity or a hollow nest scooped out of the sand, made by the female and guarded from predators by males (Marine Species Identification Portal 2013; Aquabase 2008). Bester (2013) explained in detail that after hatching (approximately 48-55 hours), the juveniles leave the nest and head to the surface of the waters, often associated with *Sargassum* communities so that the survival rates of young triggerfish are often correlated with the sargassum production. When autumn approaches, the juveniles leave the sargassum habitat for bottom reef habitats.

Our models show its effectiveness at predicting spring distribution (yellow points in the first map in Figure 4-35). In this season, the occurrences were mainly observed in the southern part of the study area as predicted by the model (red areas/the most preferred class).

In summer and autumn, this species was mainly observed off the western coast of Britain and Ireland. Although the occurrences recorded during theses periods happened only in areas that the model deemed “less preferred”, many studies conducted in these areas supported our models. For example, Tourenne et al. (2011) stated that the observation of *B. capriscus* in the English Channel and North Sea still occasionally happens. Kate (2008) explained that adult specimens have been recorded in increasing numbers around the western coasts of Britain and Ireland but there is no current evidence of a breeding population in Britain and Ireland. This species has appeared on the tip of Brittany in the late 1960s, each capture resulting in a generally delusional newspaper article such as “tropical fish lost in the Gulf Stream”. In fact, this species was already present in 1900, and then disappeared for over half a century before reappearing again. This species was again observed occasionally in recent years (Tourenne et al. 2011). Tourenne et al. (2011) further mentioned that the number of observation of this species has risen in 30 years, probably due to warming waters.

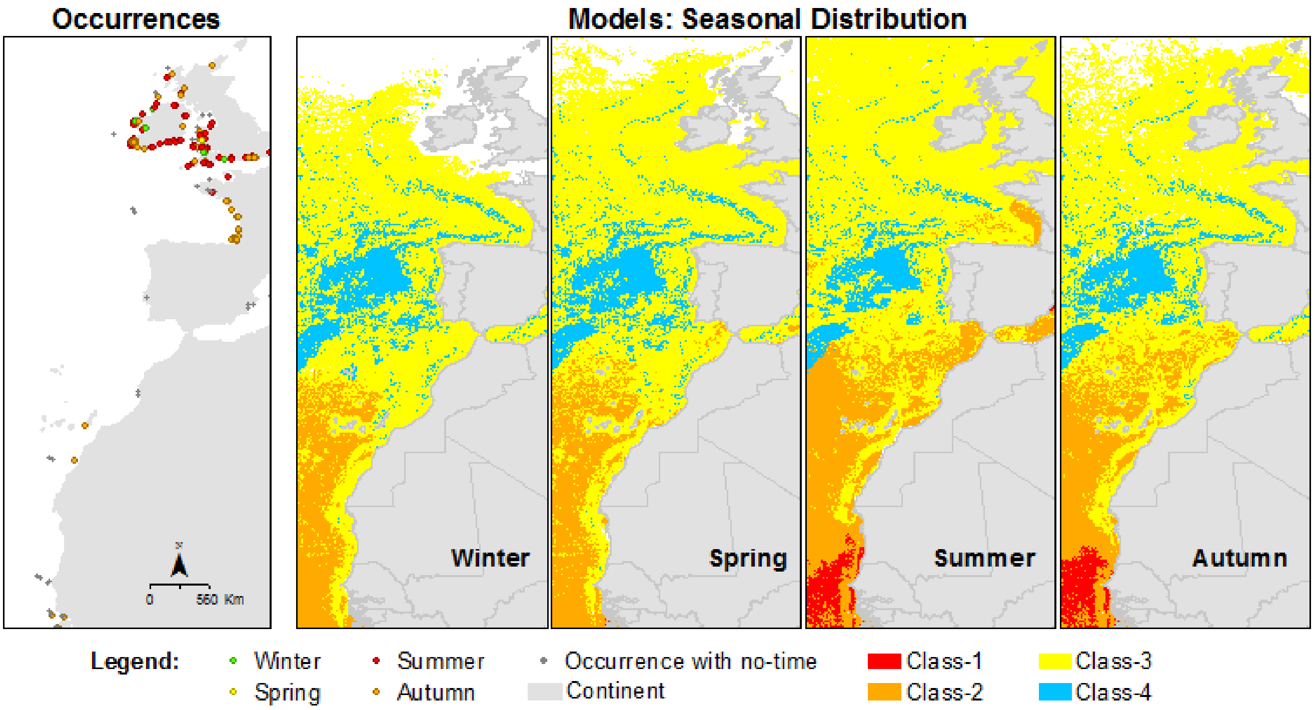


Figure 4-35: Occurrences of *B. capriscus* and its seasonal distribution models (climatology). Complete seasonal distributions from 1982 to 2012 are available in the supplementary files.

4.5.3 *Umbrina canariensis*

Umbrina canariensis (Figure 4-36) is a marine demersal species (Bailly 2013c). This species has several common names, such as *Canary Drum* and *Tassel fish*. In French, it is known as *Ombrine bronze* or *Ombrine noire* (Whitehead et al. 2013; Froese and Pauly 2011). The taxonomic hierarchy of this species is presented in Table 4-17. In the IUCN Red List, the status of this species is Not Evaluated (IUCN 2012).

This species can reach a maximum length of 80 cm, with a common length of 40 cm (Figure 4-36). All individuals larger than 20 cm are mature (Brinca et al. 2001). It is an important commercial fish; accounting for more than 30% bottom-trawl catches in certain fishery grounds, such as in the Mediterranean countries and several countries along the Atlantic coast such as Portugal and Morocco. This species is also sought for by sport fishermen (Whitehead et al. 2013; Bailly 2013c).

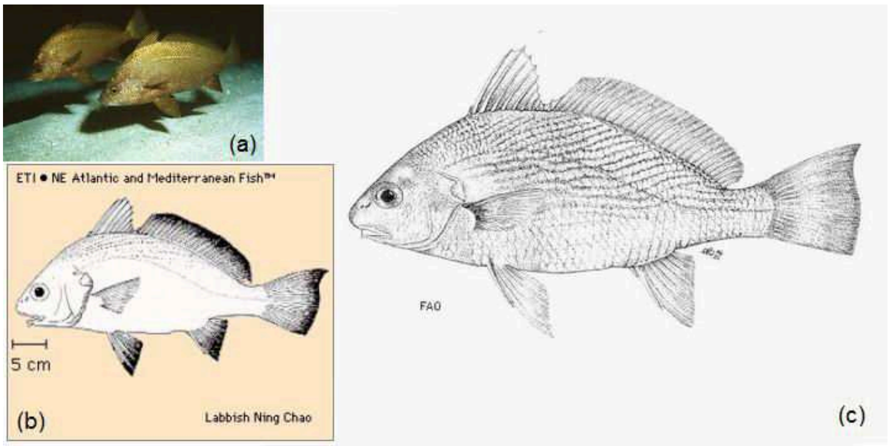


Figure 4-36: *Umbrina canariensis*. Images were obtained from (a) Froese and Pauly (2011), (b) FAO (2013), and from (c) Whitehead et al. (2013).

Table 4-17: Taxonomic hierarchy of *U. Canariensis*. Classification based on Whitehead et al. (2013), Bailly (2013c), and ITIS (2013).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Perciformes
Suborder	Percoidei
Family	Sciaenidae
Genus	*Umbrina* (Cuvier, 1816)
Species	*Umbrina canariensis* (Valenciennes, 1843)

Umbrina canariensis is a tropical and warm temperate species. This species is distributed along the Atlantic Coast from the Bay of Biscay southward to Angola, and off the east coast of Africa, along Tanzania, Somalia, Kenya and Mozambique (Figure 4-37). It is also found in the Western Mediterranean Sea, up to Algeria. In the Arabian Sea, this species was probably observed under other synonyms (Whitehead et al. 2013; Froese and Pauly 2011).

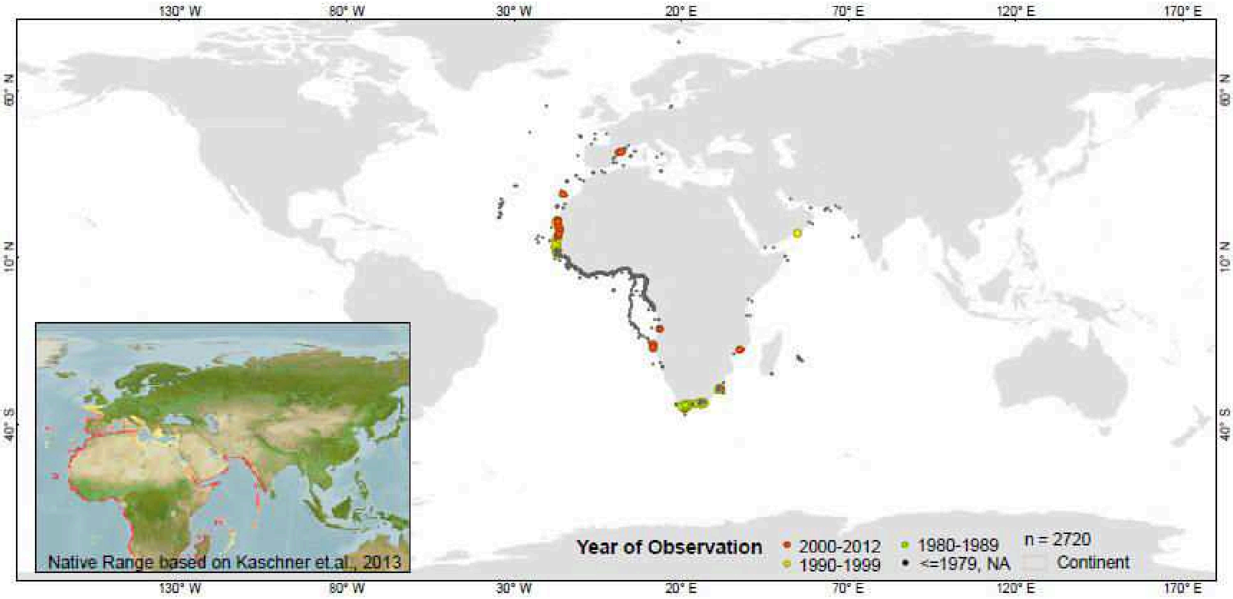
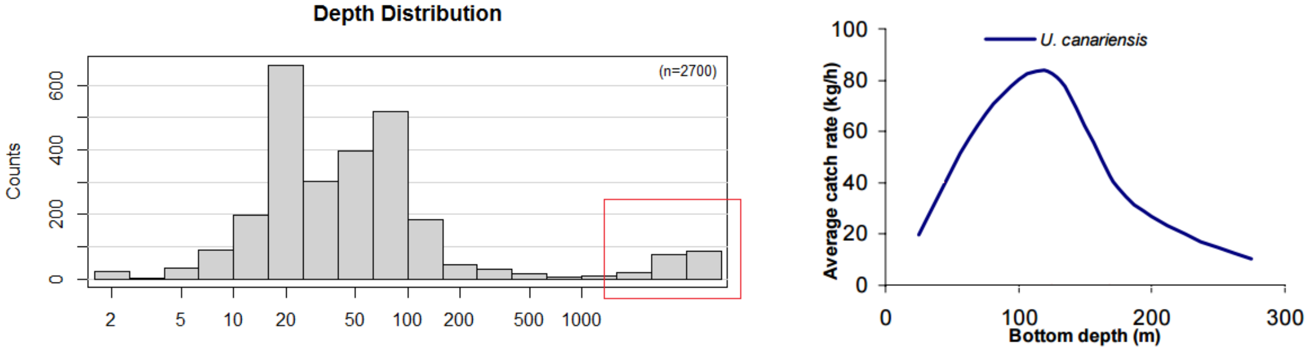


Figure 4-37: Distribution of *U. canariensis* by period of ten years. Inset map is a distribution model of this species obtained from (Kaschner et al. 2013).

Umbrina canariensis feeds mainly on smaller fishes, small shrimps, worms and other bottom invertebrates. It is found in coastal waters, over muddy or sandy bottoms and among rocks in some cases, at depths that range from 50 to 300 m (Whitehead et al. 2013). Our study confirmed that this species was mainly found in area less than 300 m deep (Figure 4-38a). Several occurrences of this species were observed in areas more than 1000 m deep. Most of the occurrences were observed in areas less than 100 m deep. The juveniles are usually found near shore, while sub-adults often enter estuaries and coastal lagoons (Whitehead et al. 2013; Froese and Pauly 2011; EOL 2013). Our data showed that this species was observed in areas with a minimum depth of 2 m (Figure 4-38a). The occurrences found in areas with depth exceeding 1000 m need further investigation (red rectangle in Figure 4-38a).



(a) Depth distribution (m) obtained in this study

(b) Depth distribution from Dr. Fridtjof Nansen survey in 2001

Figure 4-38: (a) Depth distribution of *U. canariensis* from this study. Red rectangle in the depth distribution indicates values that required further investigation. (b) Depth distribution from the data collected in the R/V Dr. Fridtjof Nansen survey in March 2001 (Brinca et al. 2001).

Umbrina canariensis was found in areas with a minimum SST value of 12.34 °C and a maximum of approximately 29 – 30 °C (Figure 4-39). 50% of the occurrences were found in areas where the temperature ranged from 16.46 – 20.7 °C, indicating its temperature preferences. This range of temperature varied slightly seasonally (Figure 4-39). When the bottom temperature drops below 16-18 °C, this species moves to mid-water or deeper slope areas (Whitehead et al. 2013; Bailly 2013b).

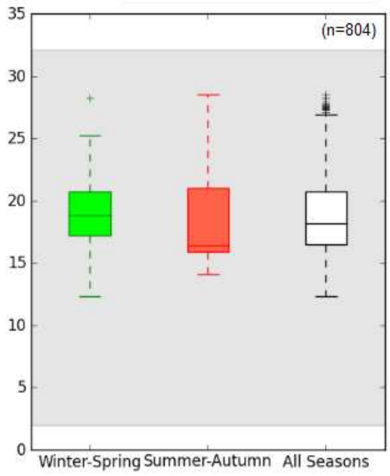


Figure 4-39: SST distribution of *U. canariensis*.

Our models in Figure 4-40 show the distribution of the species' suitable areas, including the reproduction season from spring to autumn. Whitehead et al. (2013) stated that the reproduction periods of this species range probably from late spring to early autumn. Froese and Pauly (2011) stated that the reproduction periods of this species in the coastal eastern Atlantic range from May to November. Spawning occurs offshore or along the coast, often forming aggregations, usually with a prolonged spawning season (Whitehead et al. 2013; Bailly 2013b).

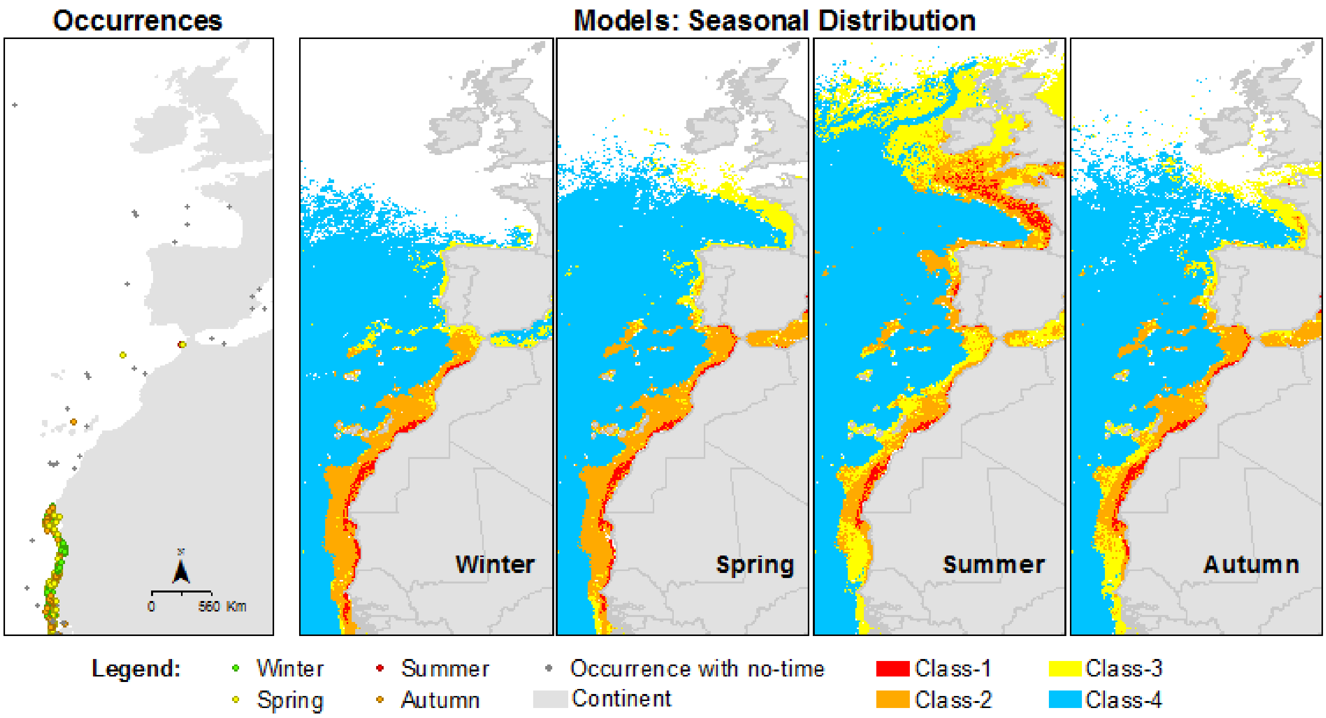


Figure 4-40: Occurrences of *U. canariensis* and its seasonal distribution models (climatology). Evolutions of seasonal distributions from 1982 to 2012 are available in an animation movie in the supplementary files.

The models presented in Figure 4-40 accurately predicted the distribution of several points in the north, especially the yellow and the red points, marking where the species was observed in the spring and winter. Black points in the Bay of Biscay represent occurrences without time of observation, which have not been included in the modelling process. Thus, they could be used to deduce the accuracy of the model. The models predicted that these occurrences could possibly be observed in the period of summer or autumn when the temperature in those areas increases and becomes suitable for the species.

4.5.4 *Arnoglossus thori*

Arnoglossus thori has many common names such as *Thor's scaldfish* or *Spotted scaldfish*. The shape of this species is referred to as the "lamb tongue" or *langue d'agneau* in French (Figure 4-41). This species was described and named by Kyle in 1913 after a Danish oceanographic vessel: *Le Thor*, which is the name of the *Norse God of thunder* armed with a hammer (André and Péan 2013).

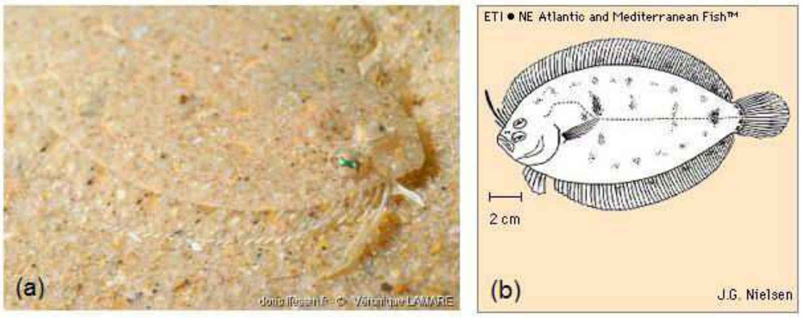


Figure 4-41: *A. thori*. Images were obtained from (a) André and Péan (2013), and from (b) Marine Species Identification Portal (2013).

Arnoglossus thori has a maximum length 18 cm and a common length of 12 cm (Marine Species Identification Portal 2013). This species has a minor commercial interest. It is occasionally sold fresh in Spain, France, Morocco and Greece, more rarely in Sicily and Tunisia (André and Péan 2013). The status of this species in the IUCN Red List has not been assessed (IUCN 2013). Table 4-18 presents the taxonomic hierarchy of this species.

André and Péan (2013) explained in detail that *A. thori* is a coastal species that lives on sandy bottoms, rarely in muddy areas. They further mention that like many flatfishes, it has the ability to change its color quickly to blend effectively with the bottom conditions, and it uses its long radius, a sensory organ, to test the bottom. Like other members of the Bothidae family, this flat-fish buries itself in the mud or sand, with only the outline of her body and moving eyes appearing (Figure 4-41).

Table 4-18: Taxonomic hierarchy of *A. thori*. Taxonomic Serial No.: 172809 (ITIS 2013; André and Péan 2013)

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Pleuronectiformes
Suborder	Pleuronectoidei
Family	Bothidae
Genus	*Arnoglossus* (Bleeker, 1862)
Species	*Arnoglossus thori* (Kyle, 1913)

Arnoglossus thori is a marine demersal species that lives in areas with depth ranges from 15 to 50 m, and up to 100 m on the continental shelf (Froese and Pauly 2011; André and Péan 2013). In this study, this species was mostly observed in areas between 25 and 100 m deep (Figure 4-42a). 50% of the species' occurrences were observed in areas with depth between 57 and 139 m.

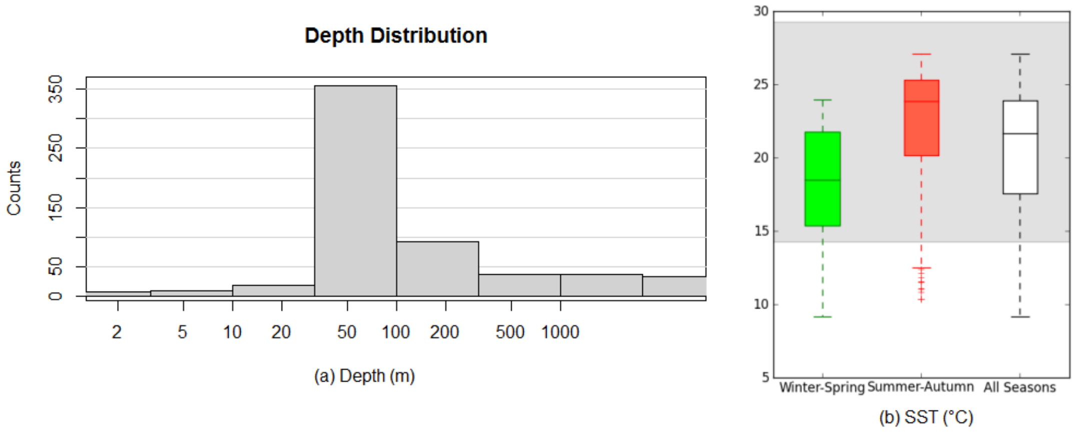


Figure 4-42: (a) Depth distribution and (b) SST seasonal range of *A. thori*.

The range of temperature of this species was between 9.16 °C and 27.08 °C, but most of the species occurrences were found in the area with temperatures between 17.57 °C and 25.41 °C. This range changes seasonally, as presented in Figure 4-42b.

The occurrence of *A. thori* spreads in the Eastern Atlantic, from the west of Ireland southward along the African coast to Senegal (André and Péan 2013). This species is also known in the western Mediterranean and the Black Sea (Froese and Pauly 2011; Marine Species Identification Portal 2013); see Figure 4-43.

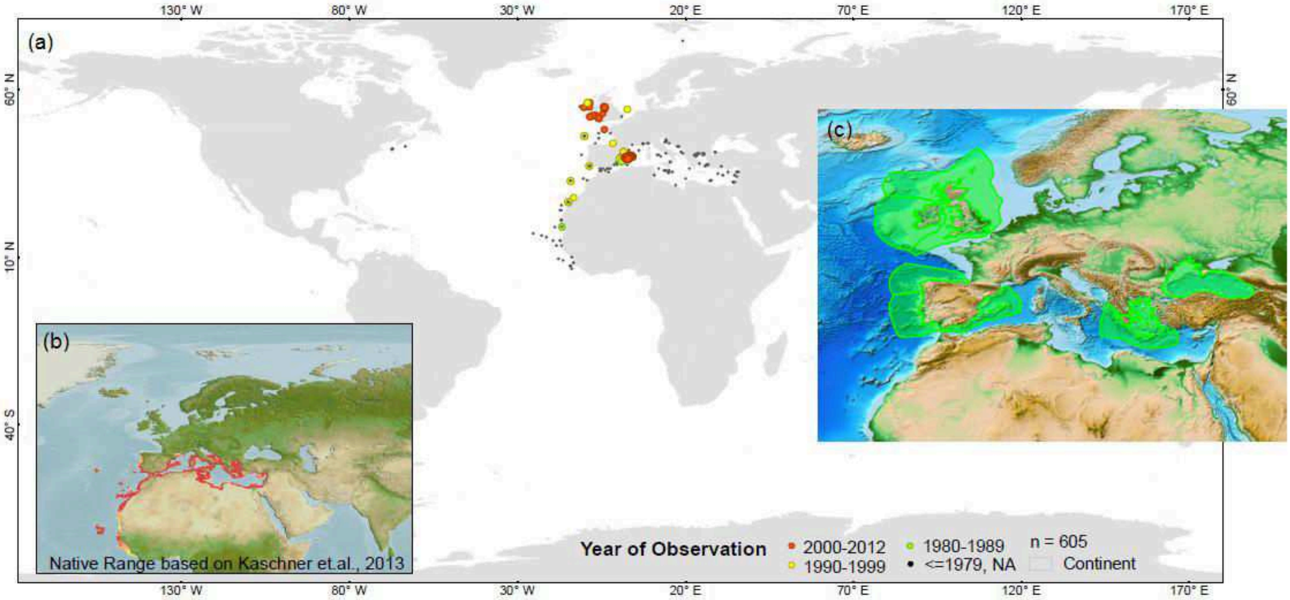


Figure 4-43: Distribution of *A. thori*. (a) Distribution obtained in this study. (b) Native range model from Kaschner et al. (2013). (c) Range of distribution obtained from Bailly (2012).

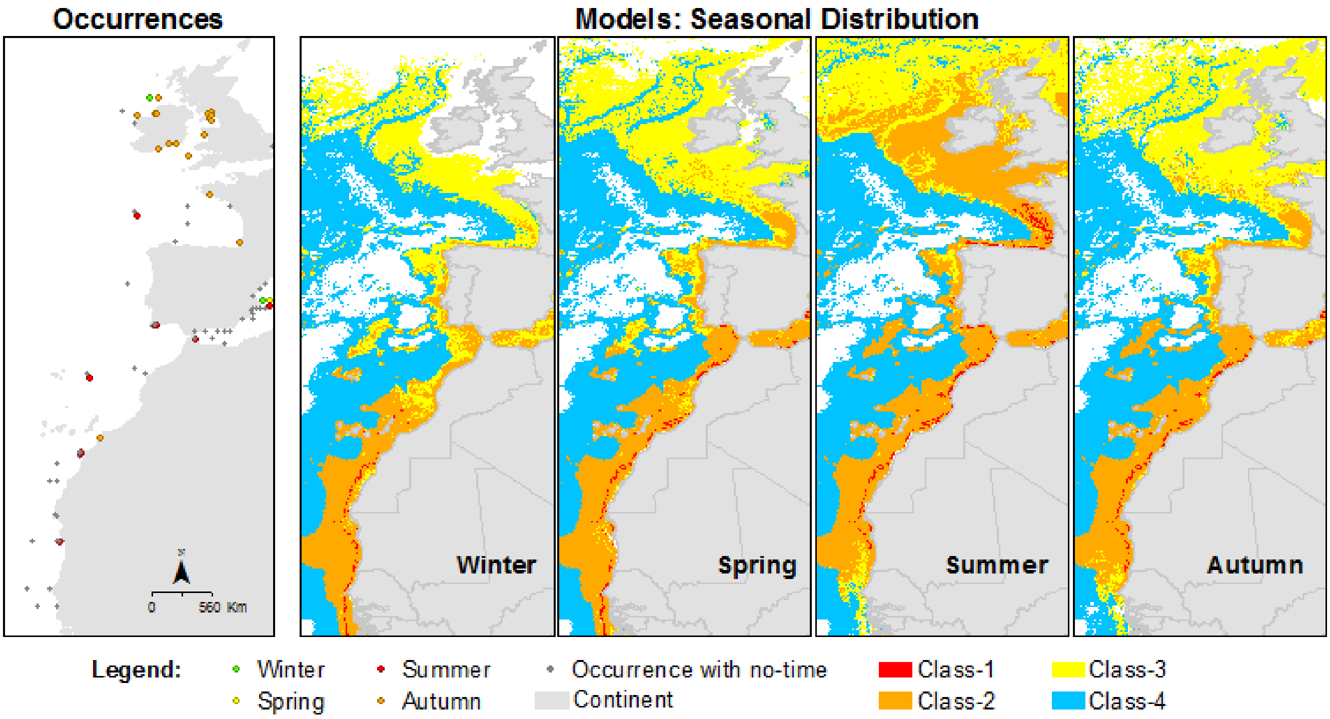


Figure 4-44: Occurrence of *A. thori* and its seasonal distribution models (climatology). Evolutions of seasonal distribution from 1982 to 2012 are available in an animation movie in the supplementary files.

The models of seasonal distribution of *A. thori* produced in this study are presented in Figure 4-44. In the winter and spring, the most suitable area for this species was distributed mostly in the southern part of the study area. The reproduction of this species occurred in this period, between April and July (Marine Species Identification Portal 2013; André and Péan 2013). The European waters in winter and spring were less preferred by this species, except in the Bay of Biscay. This area became suitable in summer. In autumn, the suitable areas for this species were mostly found in the middle regions of the study area.

4.5.5 *Arnoglossus laterna*

The *Mediterranean scaldfish* is the common name of *Arnoglossu laterna* (Figure 4-45). In French, this species is commonly named *Fausse limande*. Its maximum length is up to 25 cm and its common length is12 cm (Froese and Pauly 2011; Marine Species Identification Portal 2013). This species has no commercial value and its status in the IUCN Red List is Not Evaluated/NE (IUCN 2013). Taxonomic hierarchy of this species is shown in Table 4-19.

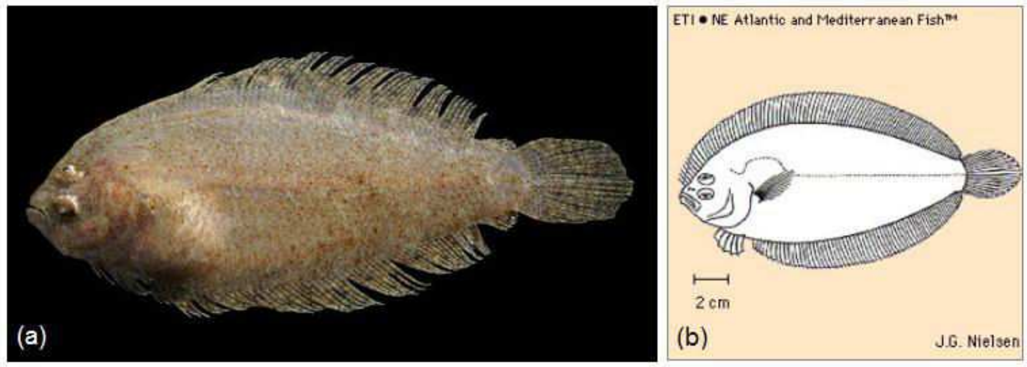


Figure 4-45: *A. laterna.* Images were obtained from (a) Encyclopedia of Life (2013) and from (b) Marine Species Identification Portal (2013).

Table 4-19: Taxonomic hierarchy of *A. laterna.* Taxonomic Serial No.: 172805 (ITIS 2013; Marine Species Identification Portal 2013).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Pleuronectiformes
Suborder	Pleuronectoidei
Family	Bothidae
Genus	*Arnoglossus* (Bleeker, 1862)
Species	*Arnoglossus laterna* (Walbaum, 1792)

Arnoglossus laterna is a marine benthic demersal species that lives on mixed or muddy bottoms of 10 to 200 m depth, but is usually found from 10 to 100 m (Froese and Pauly 2011; Marine Species

Identification Portal 2013; Bailly 2013d). Using 26782 points of occurrence, we found that this species was observed in areas less than 200 m deep (Figure 4-46a). 95% of the occurrences of this species were found in areas less than 113 m deep. 50% of the occurrence data showed that this species preferred the areas with depth between 21 and 42 m. This finding matched the data obtained from observation, as mentioned previously.

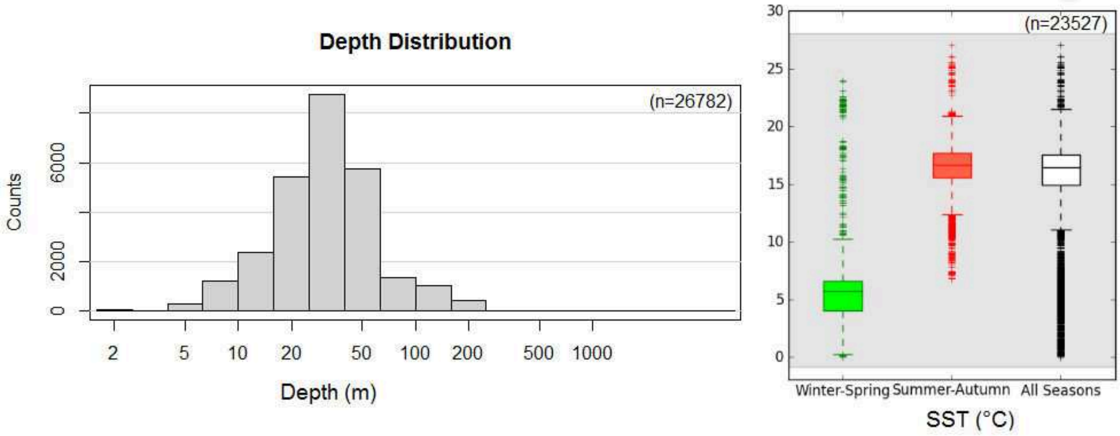


Figure 4-46: (a) Depth distribution and (b) SST seasonal range of *A. laterna.*

In terms of temperature, most of the occurrences of *A. laterna* were observed in areas whose surface temperature ranged from 0.01 to 27 °C. 50% of the occurrences were found in areas with temperatures between 14.94 and 17.55 °C. However, these temperature ranges varied throughout the season. In the first semester (winter-spring), 50% of the occurrences were observed in areas with temperatures that ranged from 4.05 to 6.59 °C, while in the second semester (summer-autumn), 50% of the occurrences were observed in areas with temperatures that ranged from 15.75 to 17.94 °C. This finding reflected that this species experienced a large variation of temperature between the cold and the warm seasons, indicating its large tolerance to temperature change. The results could also suggest that this species is not a long migratory species.

Arnoglossus laterna is distributed in the Eastern Atlantic, from Norway to Angola Figure 4-47. This scaldfish can be found on all British and Irish coasts, although it is mostly recorded in the south where it is more common (Ana 2007). It is also found in the Mediterranean and Black Sea (Froese and Pauly 2011), from Trondheim to Cape Blanc (Marine Species Identification Portal 2013), as well as in the Belgian EEZ, Britis Isles, European waters, Greek EEZ, Israeli part of the Mediterranean Sea – Eastern Basin, Oosterschelde, Portuguese EEZ, Spanish EEZ, Swedish EEZ, UK EEZ, Voordelta, Westerschelde, France, Zeeschelde (Bailly 2013d).

The seasonal distribution of this species, based on the model produced in this study, is presented in Figure 4-48. In the north European waters, the areas were always found suitable in all seasons (orange area on map in Figure 4-48). The reproduction of this species occurs between April and August (Marine Species Identification Portal 2013), around spring and summer. In spring, the most suitable areas for this species were found off the Moroccan coast. In summer, these areas moved northward to the Portuguese coast, the English Channel, and Irish coast. In this season, the model predicted accurately enough the most suitable areas for the species. The areas matched the distribution of occurrence of this species.

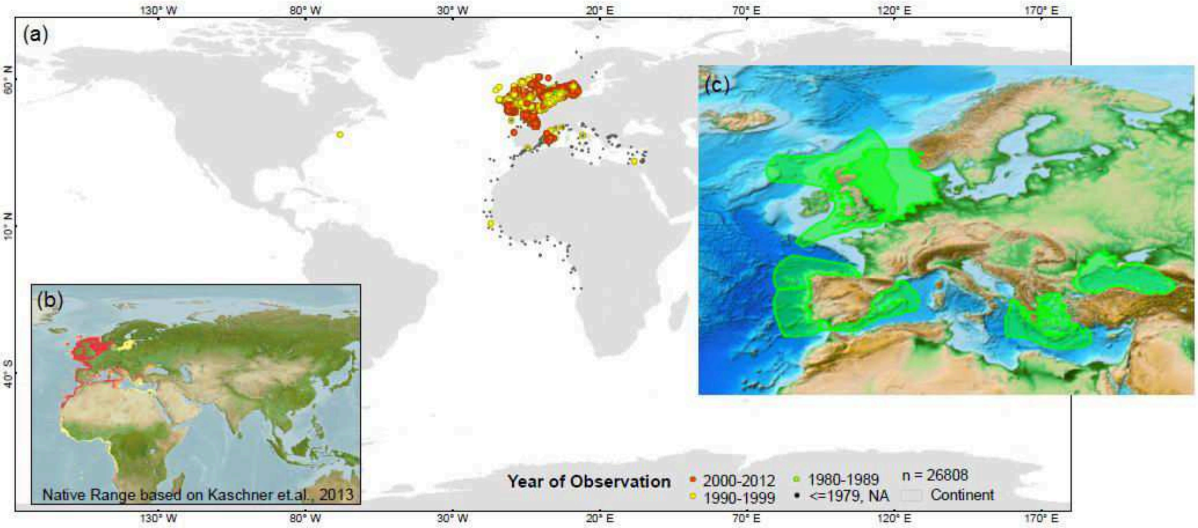


Figure 4-47: Distribution of *A. laterna* in this study; (b) Native range model from Kaschner et al. (2013); (c) Distribution from Bailly (2011).

Many occurrence records with no information on time of observation (black points on map in Figure 4-48) were found off the coast of West Africa. These occurrences were probably observed during winter, spring or autumn, when these areas were suitable for the species.

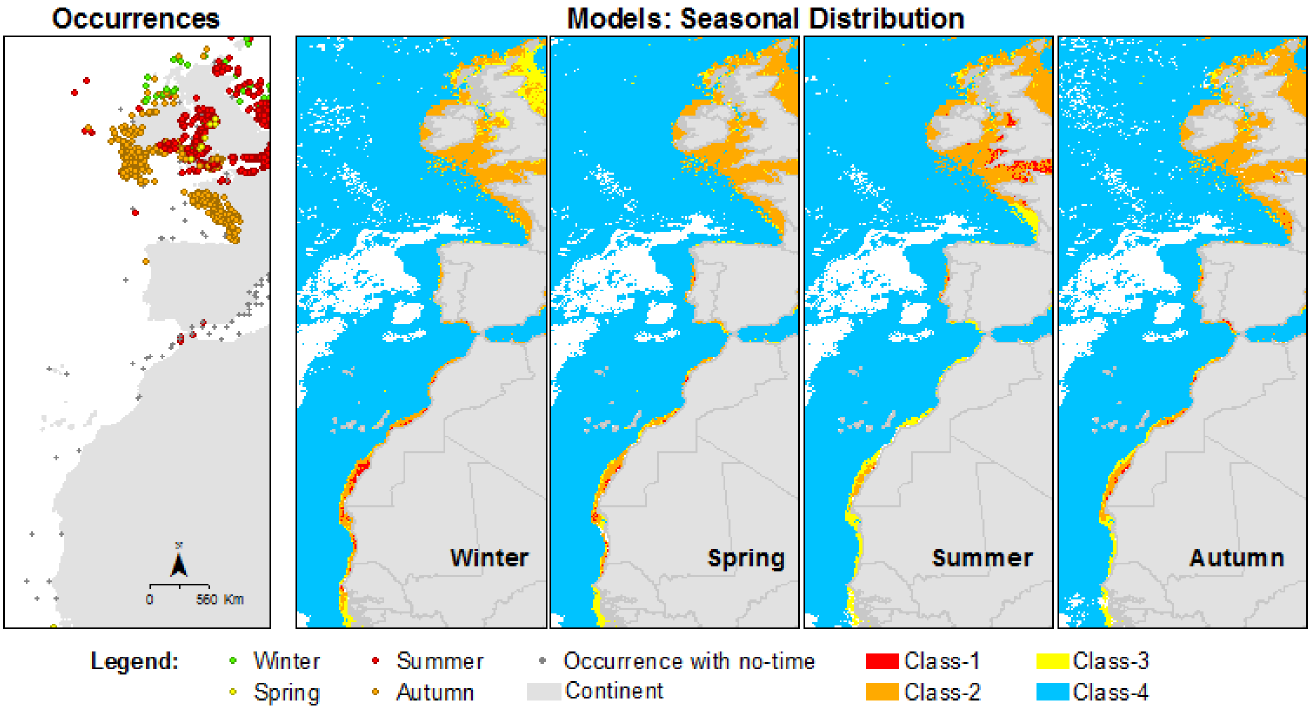


Figure 4-48: Occurrence of *A. laterna* and its seasonal distribution models (climatology). Evolutions of seasonal distributions from 1982 to 2012 are available in the supplementary files.

4.5.6 *Arius parkii*

Arius parkii, an African fish, is a commercial demersal fish with a common length of 40 cm and a maximum length from 40 to 75 cm (Schneider 1992). Another common name of this species is *Guinean sea catfish* (Froese and Pauly 2011). The dorsal and pectoral serrated spines of this species are venomous and can cause very painful wounds (Froese and Pauly 2011). In the IUCN Red List, the status of this species is Not Evaluated/NE (IUCN 2013).

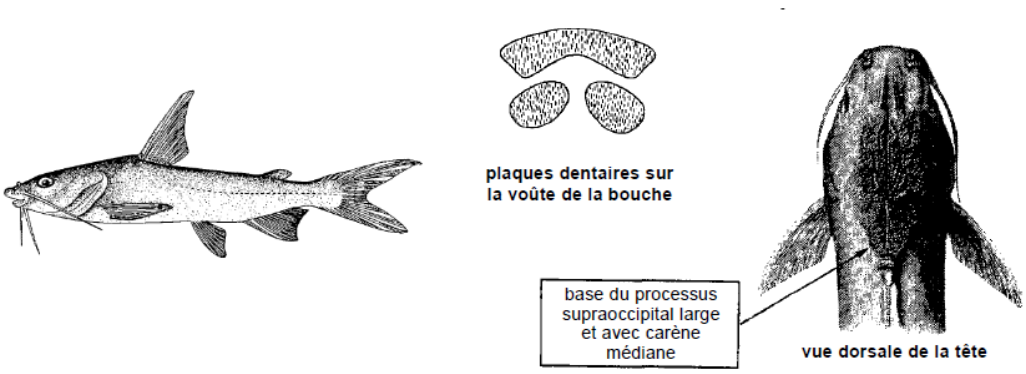


Figure 4-49: *A. parkii* (Schneider 1992)

Table 4-20: Taxonomic hierarchy of *A. parkii*. Taxonomic Serial No.: 680703 (ITIS 2013).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Ostariophysi
Order	Siluriformes
Family	Ariidae (Bleeker, 1862)
Genus	*Arius* (Valenciennes in Cuvier and Valenciennes, 1840)
Species	*Arius parkii* (Günther, 1864)

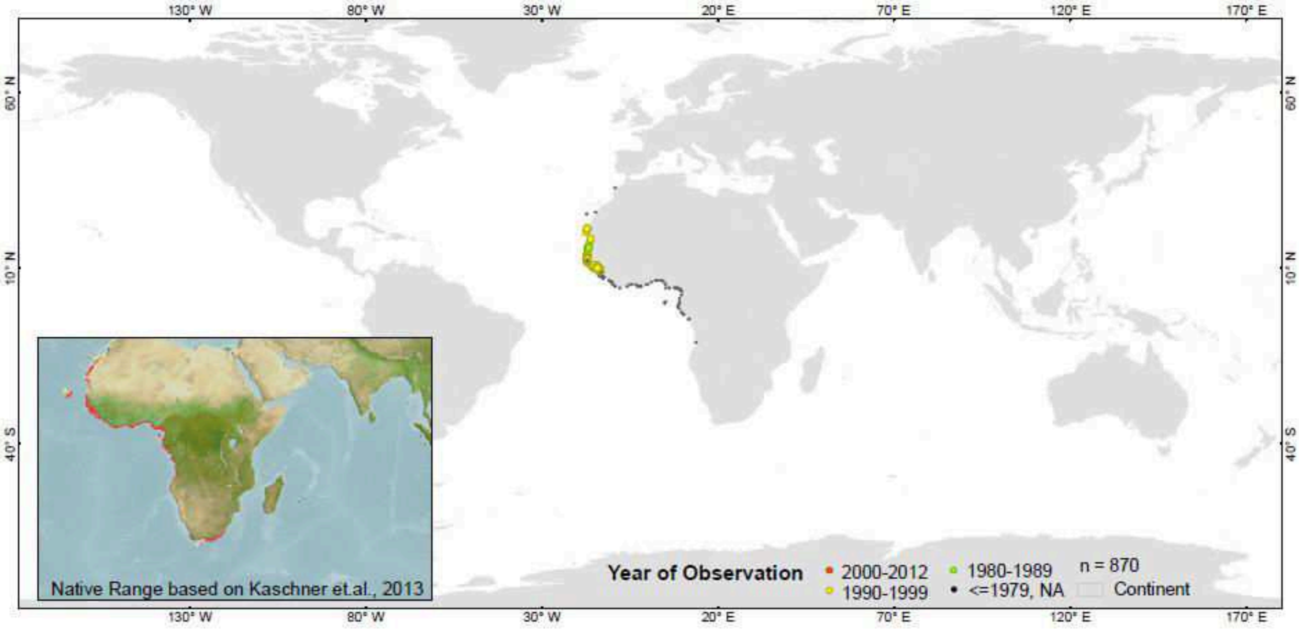


Figure 4-50: Distribution of *A. parkii*. Inset map is a native range model of this species obtained from Kaschner et al. (2013).

Arius parkii is a tropical species distributed in the Eastern Atlantic from the Cap Blanc, in Mauritania to Angola; sporadically to Western Sahara and Morocco (Froese and Pauly 2011), see the distribution of this species in Figure 4-50. The point color marked the period of observation by ten years.

Arius parkii is a demersal species that lives along the continental coast, from the freshwater rivers to the area with 50 – 80 m deep (Froese and Pauly 2011; Bailly 2013; Schneider 1992).

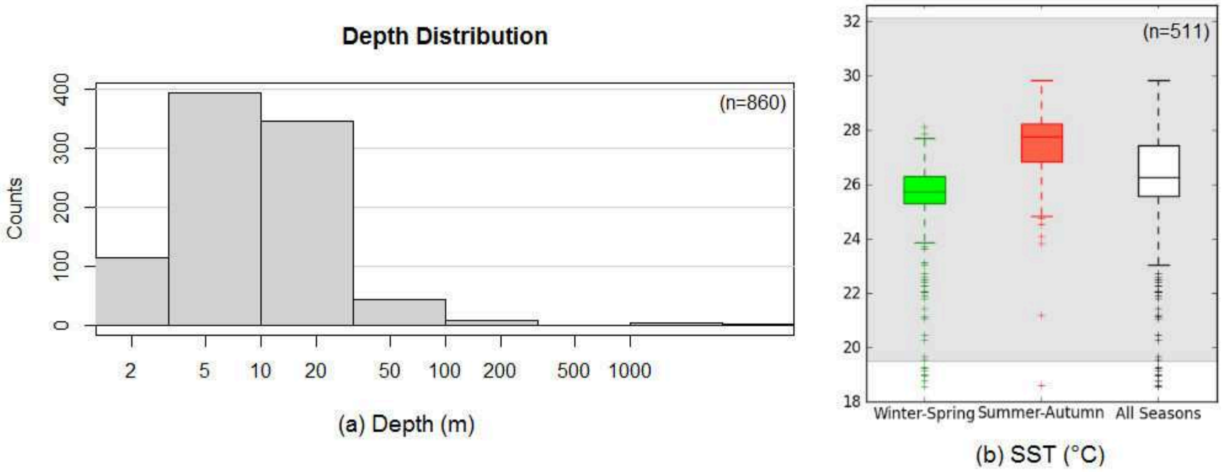


Figure 4-51: (a) Depth area distribution and (b) SST seasonal distribution of *A. parkii.*

We could not find any model of distribution model of *A. parkii*. Hence, our model will provide a basis or necessary information regarding the distribution of this poorly-known species (Figure 4-52).

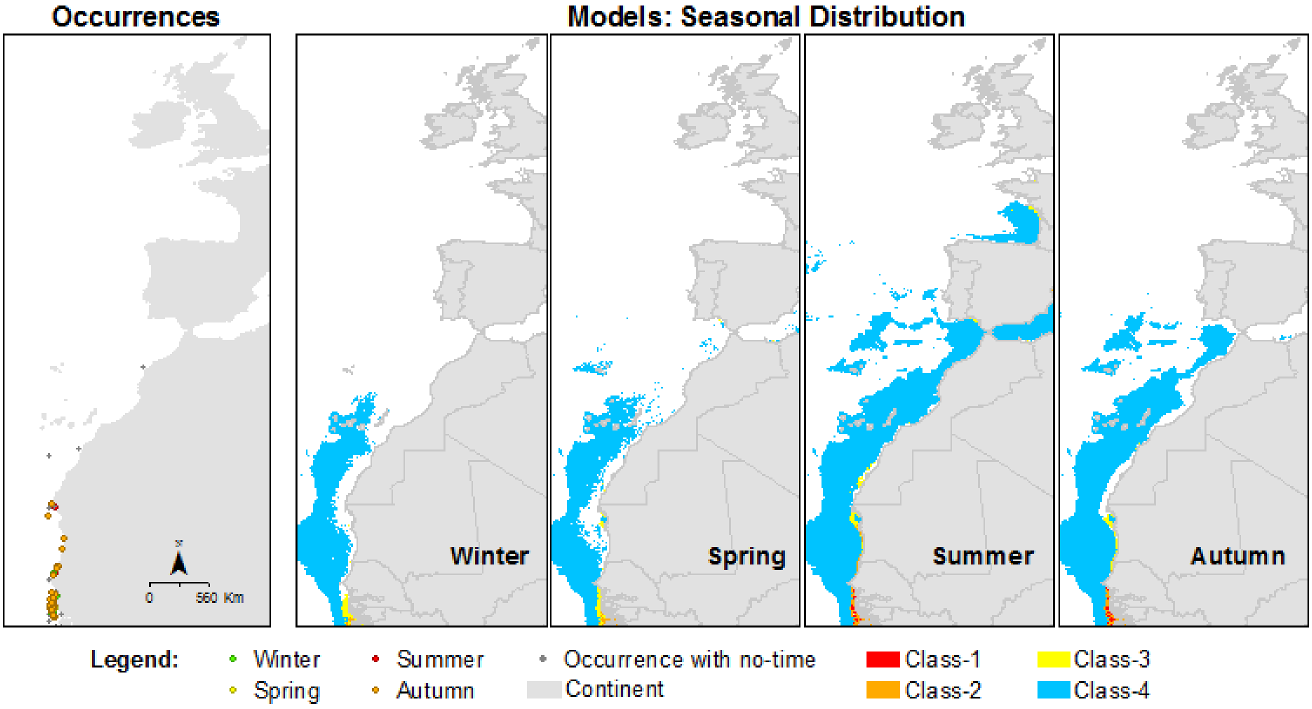


Figure 4-52: Occurrence of *A. parkii* and its seasonal distribution models (climatology). Evolutions of seasonal distributions from 1982 to 2012 are available in an animation movie in the supplementary files.

Our models in Figure 4-52 show its effectiveness in modelling *A. parkii*'s seasonal distribution. In winter, the model predicts the species' suitable areas in the southern Senegal which matches the observation data (occurrences on map in the most left-hand side of Figure 4-52). It is not likely to find this species off the coast of Morocco in winter, spring, and autumn because in these areas, the environmental conditions are simply not suitable during these seasons (white area along the western Moroccan coast in Figure 4-52). Three non-dated occurrences in these areas (black points on map) were probably observed in summer, when the temperature was in the range of the species' tolerance. However, because this environmental condition during this period was in the range of species' extreme class, the northward movement of the species should be very limited.

4.5.7 *Solea senegalensis*

Solea senegalensis took its name from the Latin word, *Solea*, whichs mean sandal (shoe), referring to the flat shape of the fish (Froese and Pauly 2011). It is a commercial fish whose status in the IUCN Red List is Not Evaluated/NE (IUCN 2013).

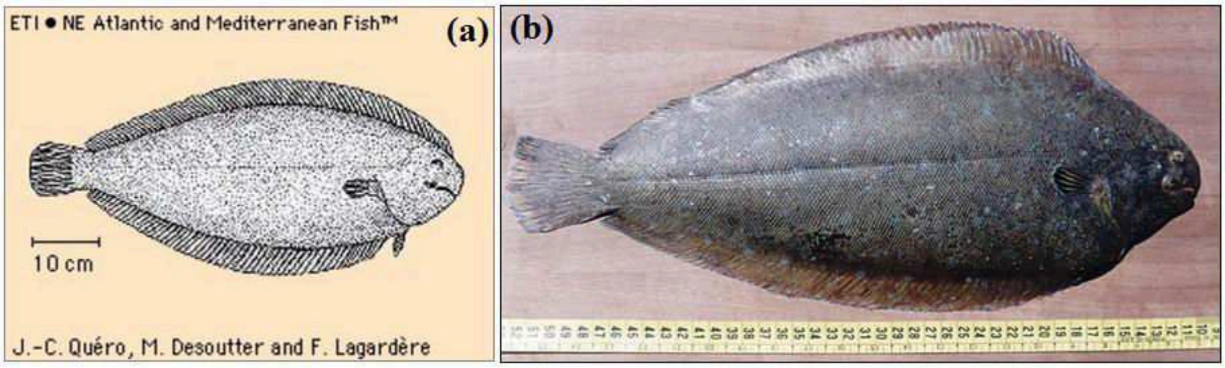


Figure 4-53: *S. senegalensis*. Images were obtained from (a) Marine Species Identification Portal (2013) and from (b) Froese and Pauly (2011).

Table 4-21: Taxonomic hierarchy of *S. senelagensis*. Taxonomic Serial No.: 173016 (ITIS 2013)

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Pleuronectiformes
Family	Soleidae
Genus	*Solea* (Quensel, 1806)
Species	*Solea senegalensis* (Kaup, 1858)

Solea senegalensis is distributed in the Eastern Atlantic subtropical areas, from the Bay of Biscay to the coasts of Senegal. It is less frequently observed in the Western Mediterranean Sea (Froese and Pauly 2011). In our database, some occurrences of this species were also observed off the coasts of Ghana and Angola.

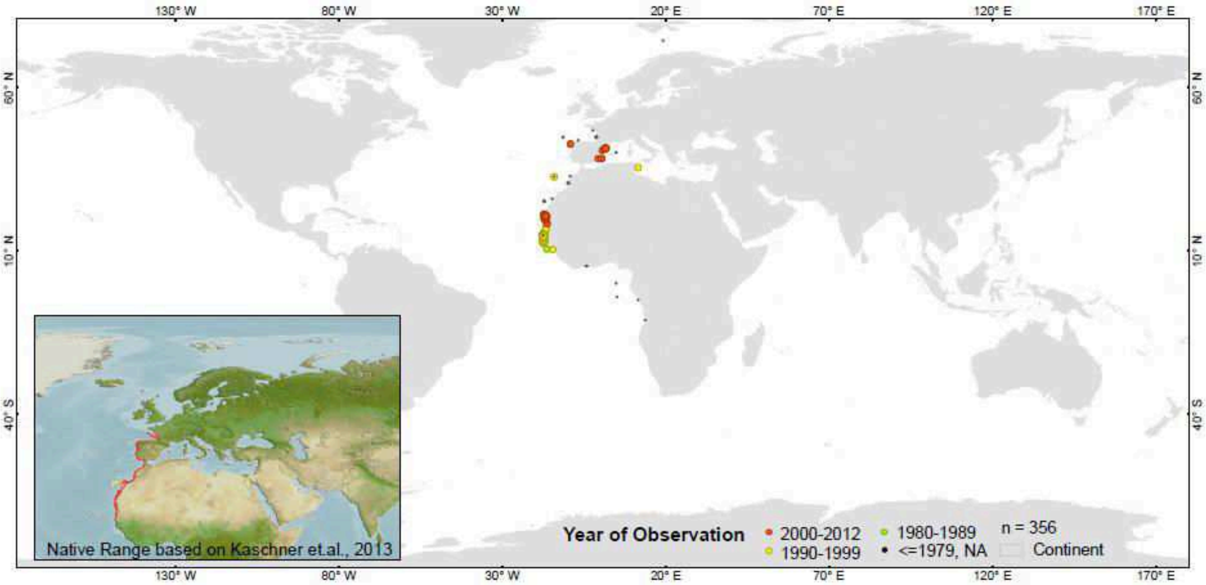


Figure 4-54: Distribution of *S. senegalensis*. Inset map is a native range model of this species obntained from Kaschner et al. (2013).

Solea senegalensis is a predominantly littoral marine demersal species, which can also be found in brackish lakes. This species lives in areas whose depth ranges between 12 – 65 m and up to 100 m (Froese and Pauly 2011). Our data showed that this species was mostly observed in areas less than 100 m deep (Figure 4-55a). 50% of the occurrences were observed in areas between 13 and 48.5 m deep, which is very close to the values obtained from the observational study mentioned previously. In terms of temperatures, the occurrences of this species were observed in areas where SST ranged from 12.5 to 28.16 °C (Figure 4-55b). In the first semester (winter and spring), this species was mostly found in the areas from 12 to 22 °C. In the second semester (summer and autumn), this species was mostly observed in areas with SST ranged from 18.31 to 27.36 °C.

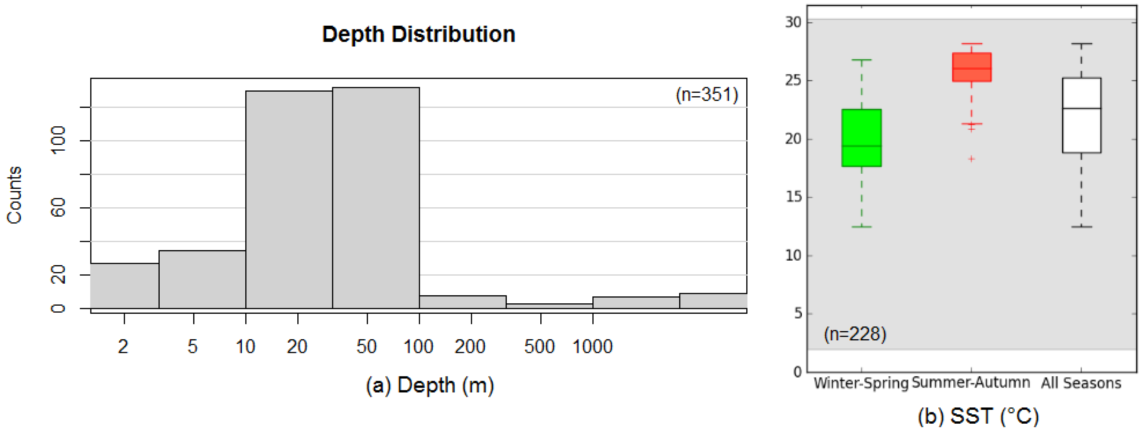


Figure 4-55: (a) Depth area distribution and (b) SST seasonal distribution of *S. senegalensis.*

The maximum length of this species can attain 60 cm, while the common length is usually 45 cm. At size of 30 cm, The species usually reaces sexual maturity at 30 cm and the spawning happens from March until June in spring (Froese and Pauly 2011). During this season, our model predicted that this species would be observed off the Mauritanian and Senegalese coasts, where the most suitable areas happen, and the same in autumn (Figure 4-56). This prediction matched most of the observational data. Several non-dated occurrences were observed in the Bay of Biscay, probably in warmer seasons when the environmental conditions were suitable for this species as predicted by the model.

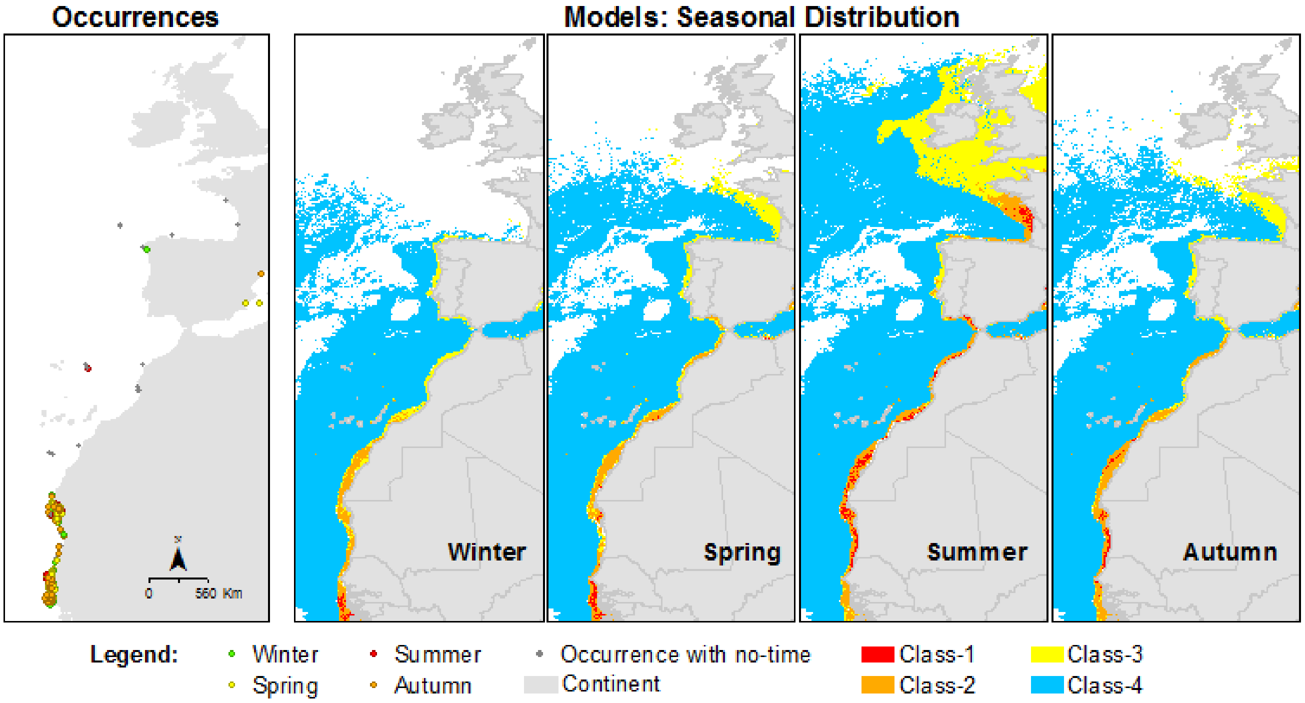


Figure 4-56: Occurrence of *S. senegalensis* and its seasonal climatology distribution models. Evolutions of seasonal distributions from 1982 to 2012 are available in an animation movie in the supplementary files.

4.5.8 *Diplodus vulgaris*

Diplodus vulgaris, whose name come from Greek; *Diploos* = twice and *odous* = teeth, is known as the two-banded seabream (Froese and Pauly 2011). This species is listed by the IUCN as Least Concern because its range of distribution overlaps with a number of marine protected areas in several regions (Russell et al. 2014).

Figure 4-57: Diplodus vulgaris (Couard 2006).

Diplodus vulgaris is a euryhaline migratory species inhabiting areas with a depth of up to 160 m and is commonly found at less than 50 m (Russell et al. 2014). In our data, many occurrences of this species were observed in areas with a depth less than 100 m (Figure 4-58). 50% of the occurrences were found in the areas with depths between 29.75 m and 77 m. In terms of temperature, this species was never been observed in area with SST less than 12.56 °C (Figure 4-58). The maximum SST for this species was 27.5 °C.

Table 4-22: Taxonomic Hierarchy of *D. vulgaris.* Taxonomic Serial No.: 182919 (ITIS 2013).

Kingdom	Animalia
Phylum	Chordata
Subphylum	Vertebrata
Superclass	Osteichthyes
Class	Actinopterygii
Subclass	Neopterygii
Infraclass	Teleostei
Superorder	Acanthopterygii
Order	Perciformes
Family	Sparidae
Genus	*Diplodus* (Rafinesque, 1810)
Species	*Diplodus vulgaris* (Geoffroy Saint-Hilaire, 1817)

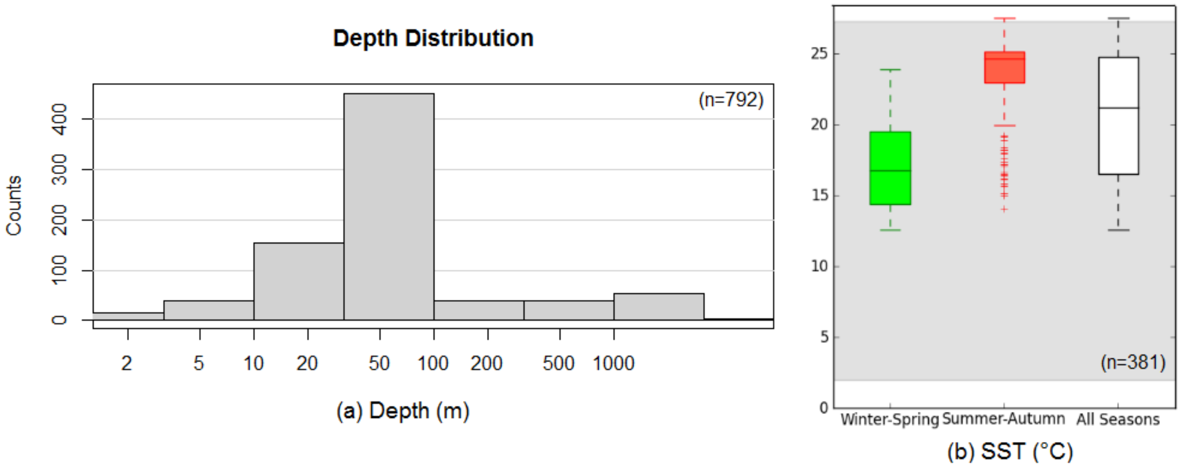


Figure 4-58: (a) Depth area distribution and (b) SST seasonal distribution of *D. vulgaris.*

Diplodus vulgaris is an important commercial species. Its length attains 45 cm and its common length is 22 cm (Froese and Pauly 2011). This species is common and abundant in the Mediterranean Sea and along the West African Coast (Russell et al. 2014). This species is also valuable in Portugal and usually present in France. In the eastern Atlantic, this species present from the Bay of Biscay to Senegal, including Cape Verde, the Mediterranean, Madeira and the Canary Islands (Russell et al. 2014). The records from Angola to South Africa in our database need to be verified (Figure 4-59). These records are the non-dated occurrences. Thus, they were not incorporated in the modelling process of species distribution.

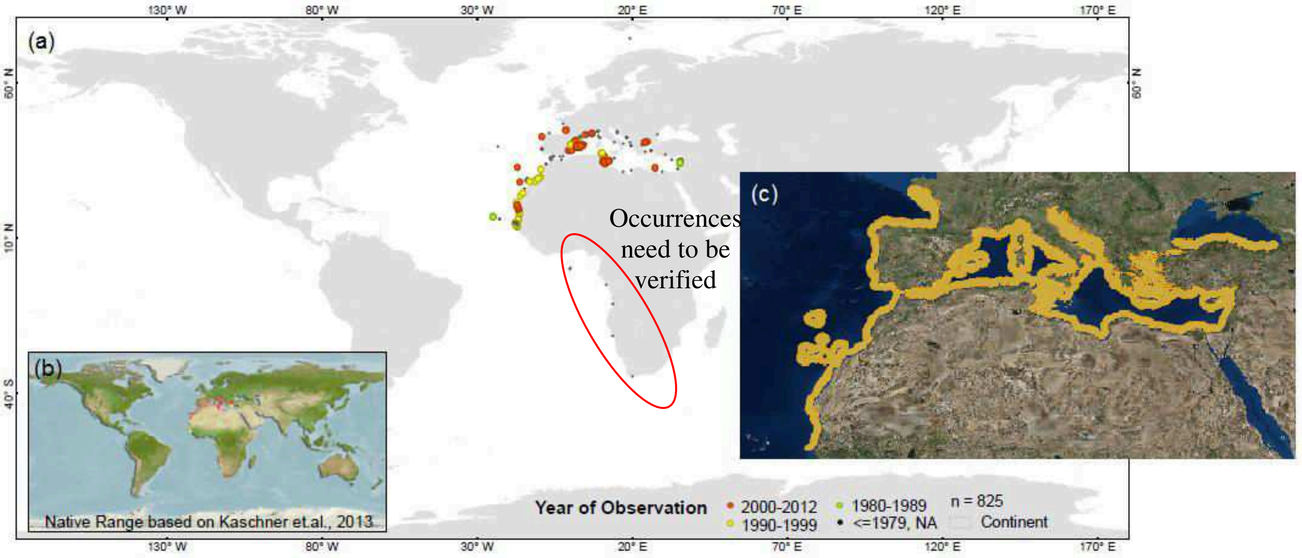


Figure 4-59: Distribution of *D. vulgaris* (a) in this study; (b) Native range model from Kaschner et al. (2013) and (c) species range from Russell et al. (2014).

Our seasonal model of distribution of this species matched the occurrence records from observational data (Figure 4-60). This tropical species, has been observed in the Bay of Biscay (west France) in autumn. This area was suitable for this species during this season (including summer) as shown by our models.

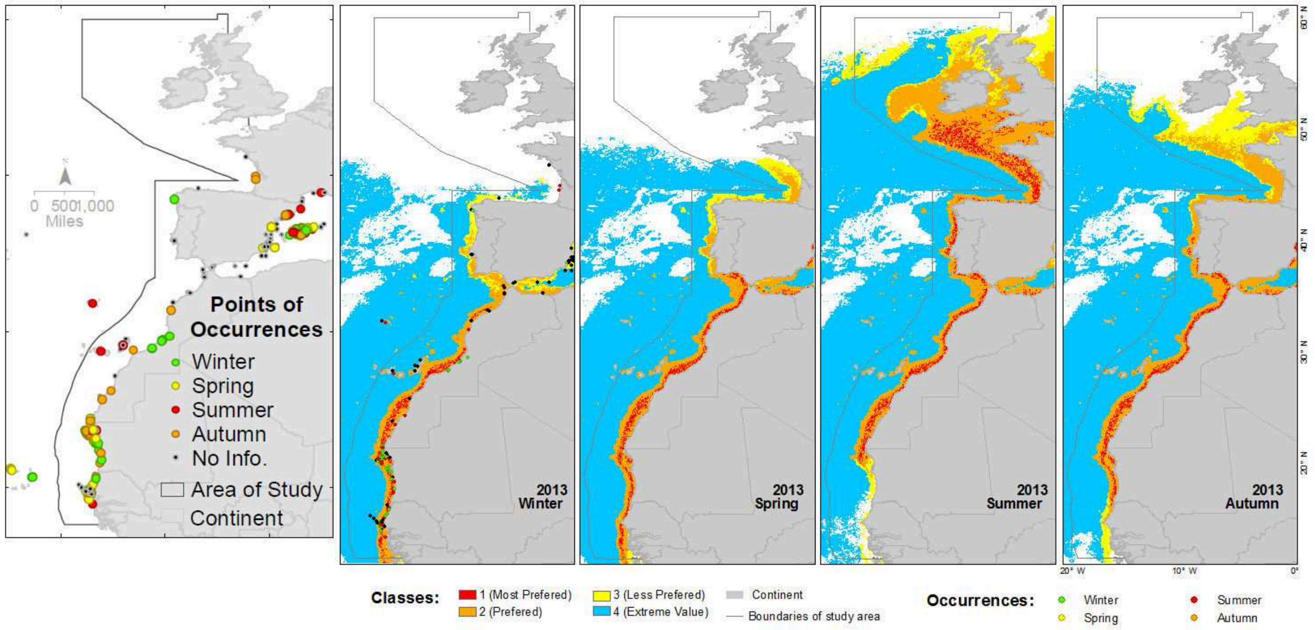


Figure 4-60: Occurrence of *D. vulgaris* and its seasonal distribution models for 2013. Evolutions of seasonal distributions from 1982 to 2012 are available in the supplementary files.

4.5.9 Climatology models and evolution of species distribution

We selected four species inhabiting different type of environment to demonstrate the evolution of northernmost point of their suitable area over time: *Myctophum punctatum*, *Pomatomus saltatrix, Ammodytes tobianus,* and *Lepidorhombus whiffiagonis*. This result allowed understanding the impact of climate change on species distribution. The environmental envelopes of each selected species used to build their models of distribution are given in Table 4-23. The seasonal climatology model and the evolution of the northernmost point of their suitable areas are given in Figure 4-61 to Figure 4-68. Seasonal climatology models used the climatology data as predictors. “Climatology data” in this study refers to the combined seasonal files by mean of all years studied (1982-2012).

Table 4-23: Envelopes of selected species for analysis of northernmost/southernmost point evolution of species suitable area.

No	Species	Class[a]	SST (°C)	Bathymetry constraint		
				Depth (m)	**Slope (°)**	**B. Z.[b]**
1.	*M. punctatum*	1	14.2-18.8	909-3726	4.2-26.4	4
		2	9.4-14.2 & 18.8-20.2	291-909 & 3726-4697	1.8-4.2 & 26.4-43.1	3
		3	6.7-9.4 & 20.2-23.4	129-291 & 4697-4955	0.1-1.8 & 43.1-50.7	1
		4	1.8-6.7 & 23.4-26.3	4955-5603	50.7-78.2	2
2.	*P. saltatrix*	1	16.8-21.2	5-27	1.1-4.5	3
		2	15.01-16.8 & 21.2-23.8	2-5 & 27-59	0.6-1.1 & 4.5-8.3	4
		3	13.7-15.01 & 23.8-26.2	2-2 & 59-65	0.3-0.6 & 8.3-8.5	1
		4	6.01-13.7 & 26.2-30.1	65-5421	8.5-75.9	2
3.	*A. tobianus*	1	5.7-14.7	20-61	0.5-2.4	3
		2	4.3-5.7 & 14.7-16.4	10-20 & 61-79	0.3-0.5 & 2.4-4.7	4
		3	3.6-4.3 & 16.4-17.2	5-10 & 79-108	0.2-0.3 & 4.7-7.9	1
		4	0.17-3.6 & 17.2-19.5	108.0-4842.0	0.1-0.2 & 7.9-45.1	2
4.	*L. whiffiagonis*	1	10.8-13.5	122-173	0.8-3.2	3
		2	8.1-10.8 & 13.54-14.54	99-11 & 173-232	0.4-0.8 & 3.2-7.1	4
		3	7.29-8.1 & 14.5-15.5	83-99 & 232-291	0.3-0.4 & 7.1-13.7	1
		4	0.03-7.2 & 15.5-27	291-4842	13.7-69.6	2

[a] Class: 1 = Most Preferred, 2 = Preferred, 3 = Less Preferred, 4 = Extreme values.

[b] B. Z. = Benthic Zone (1 = Crest, 2 = Depression, 3 = Flat, 4 = Slope).

The charts of species northernmost/southernmost point evolution, accompanying the species climatology distribution, accommodate for the seasonal movement/evolution of the northernmost point, for both upper and/or lower limit of the species’ suitable areas. The color of the chart area represents the class os suitable area (red for the most preferred area/the Class-1, and orange for the preferred area/the Class-2). The X-axis represents the time of the season (Q) of every year: Q1 for winter, Q2 for spring, Q3 for summer and Q4 for autumn. The Y-axis represents latitude values in degree. Bar against the Y-axis represents the three ecosystems liying in the area of study by gradation of green color, indicating the location of the zone in a spatial view: the Celtic Seas (light green), the South European Atlantic Shelf (green) and the Canary Current (dark green). The degree of slope and p-values of the linear regression of the seasonal northernmost point of the species suitable areas (from 1982 to 2012) are presented in Table 4-24.

4.5.9.1 *M. punctatum*

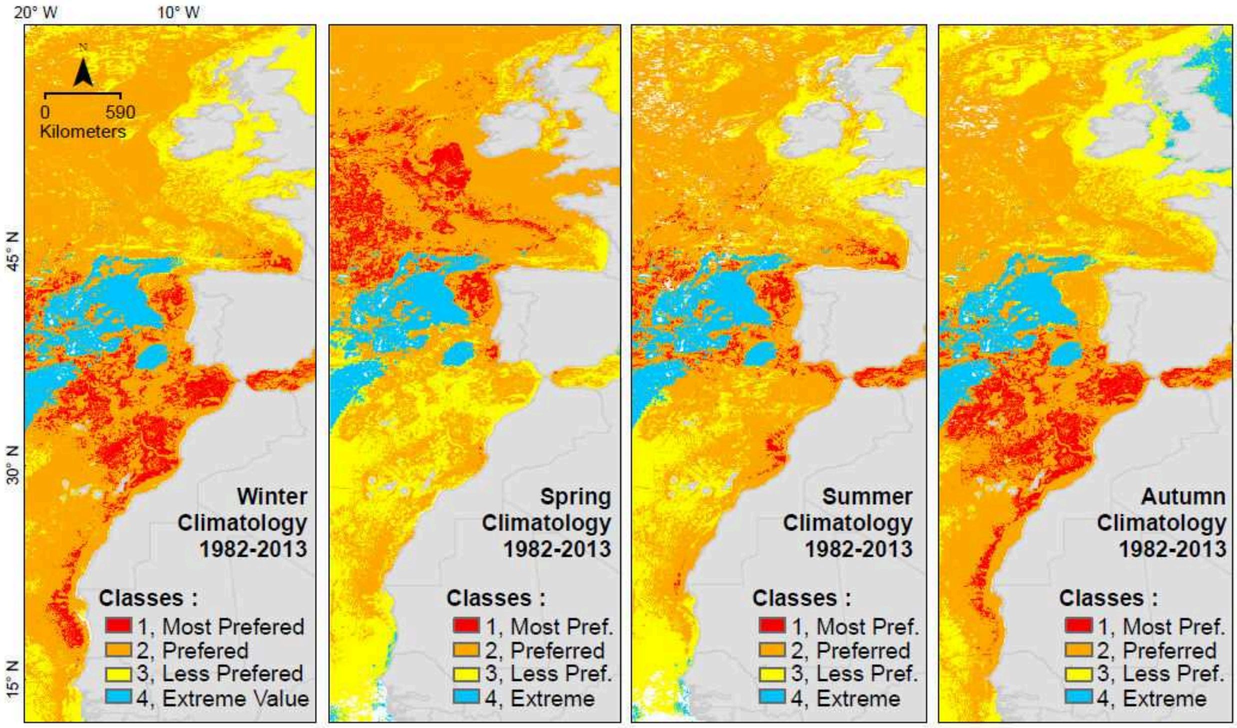


Figure 4-61: Potential distribution of *M. punctatum* by seasonal climatology.

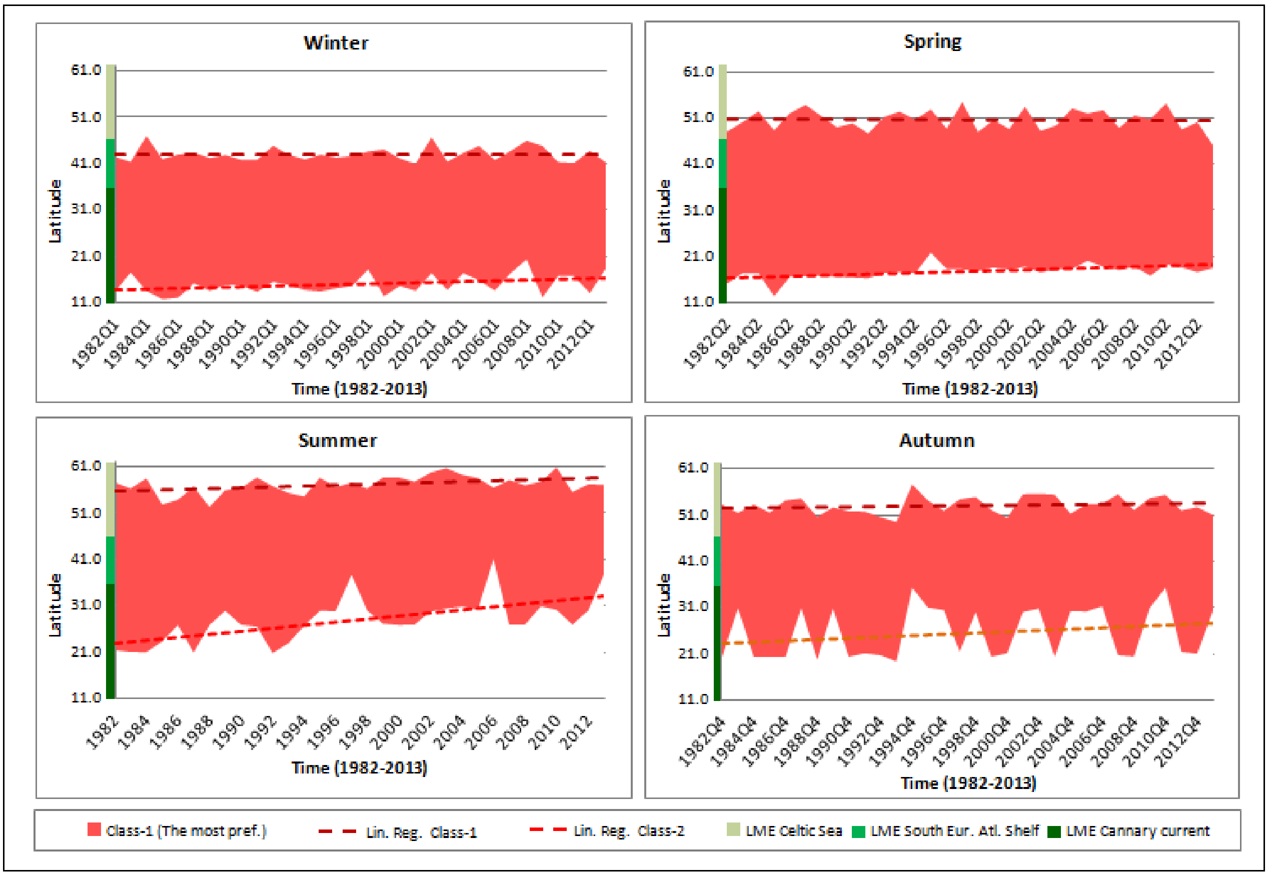


Figure 4-62: Evolution of the northernmost points of the upper and lower limits of the most preferred zone (Class-1) of *M. punctatum* by season.

4.5.9.2 *P. saltatrix*

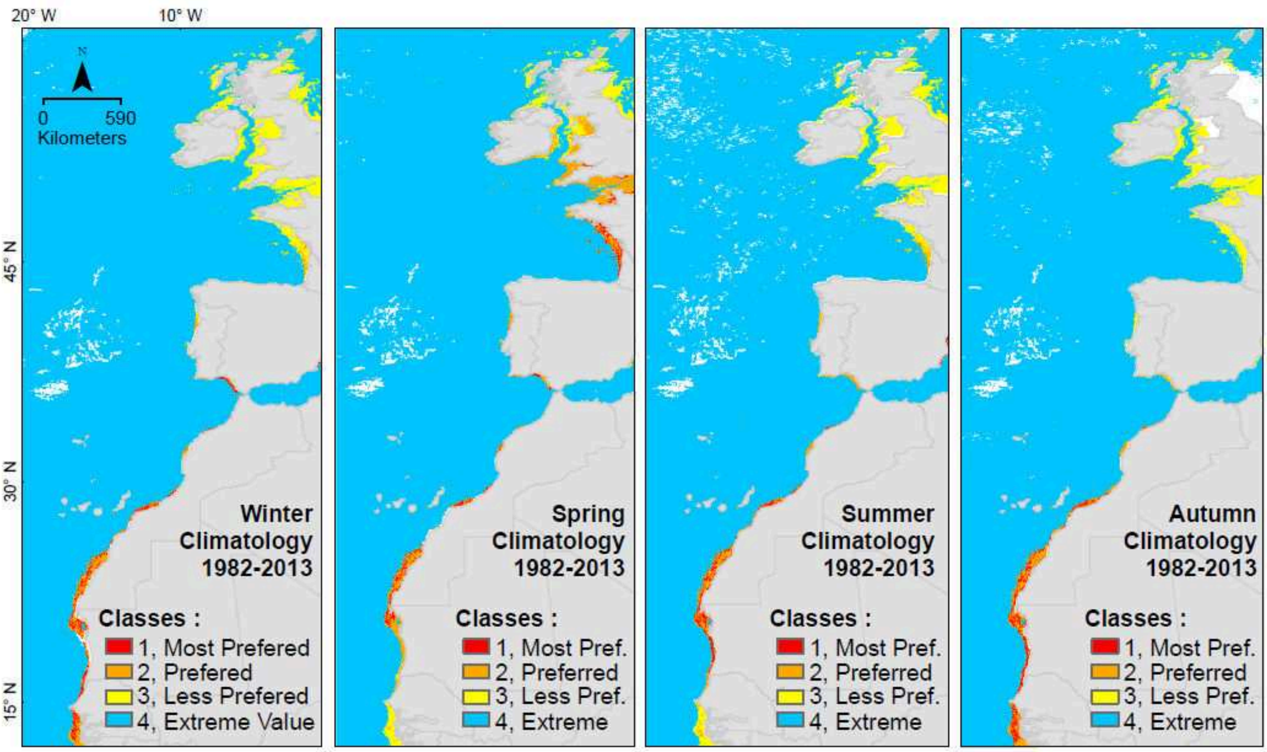


Figure 4-63: Potential distribution of *P. saltatrix* by seasonal climatology.

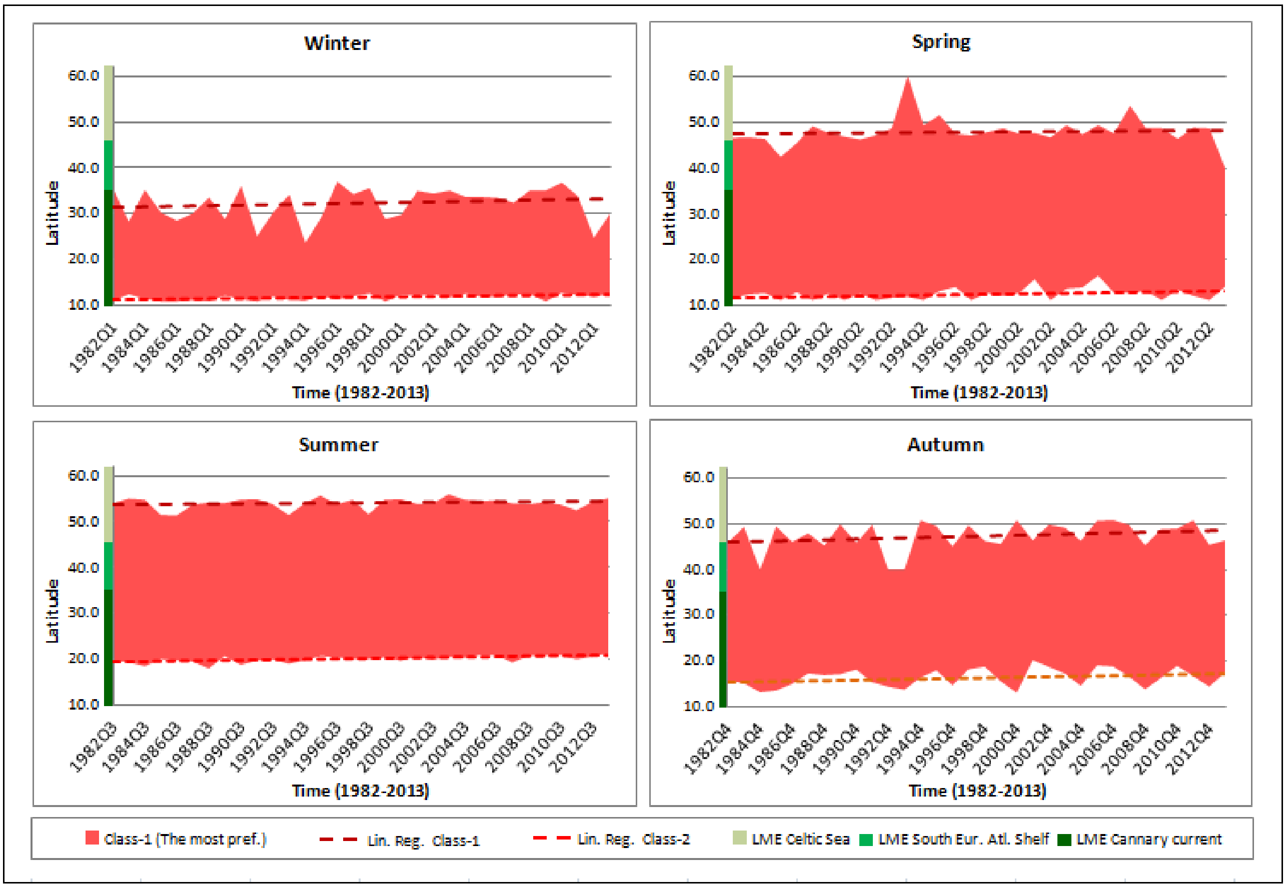


Figure 4-64: Evolution of the northernmost point of the upper and lower limits of the most preferred zone (Class-1) of *P. saltatrix* by season.

4.5.9.3 *A. tobianus*

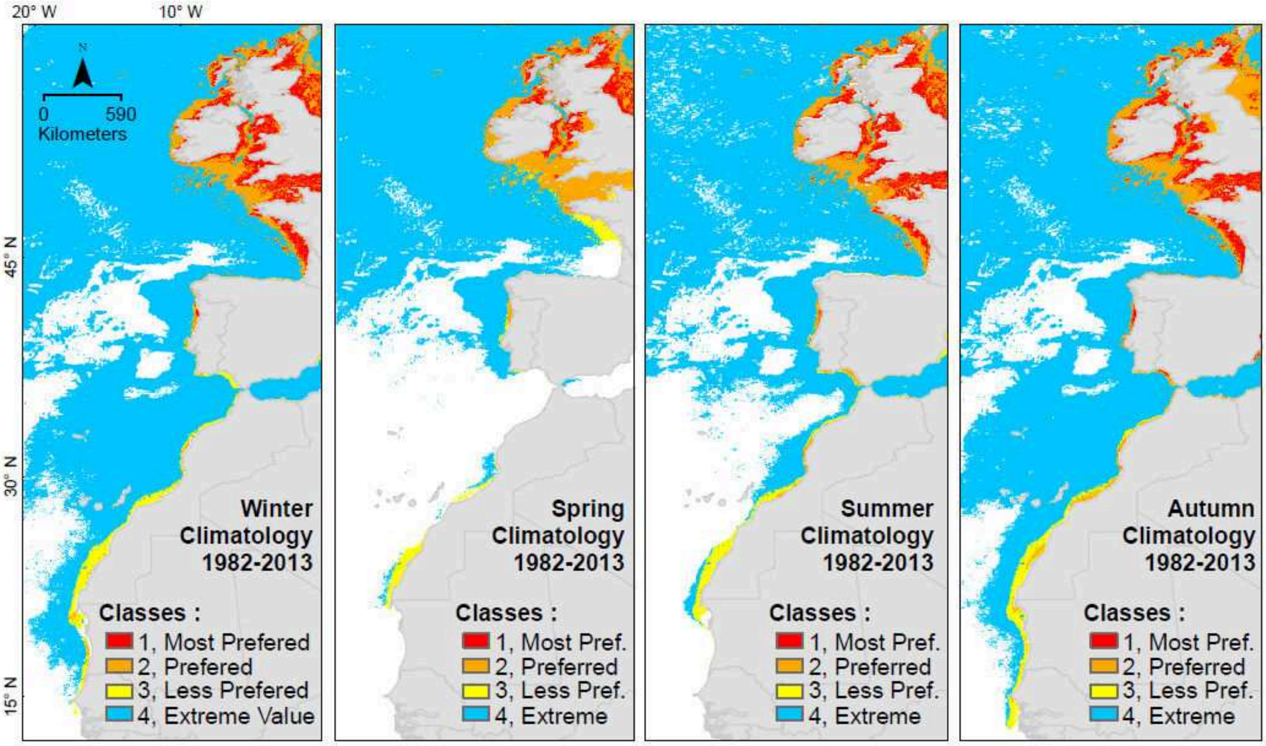


Figure 4-65: Potential distribution of *A. tobianus* by seasonal climatology.

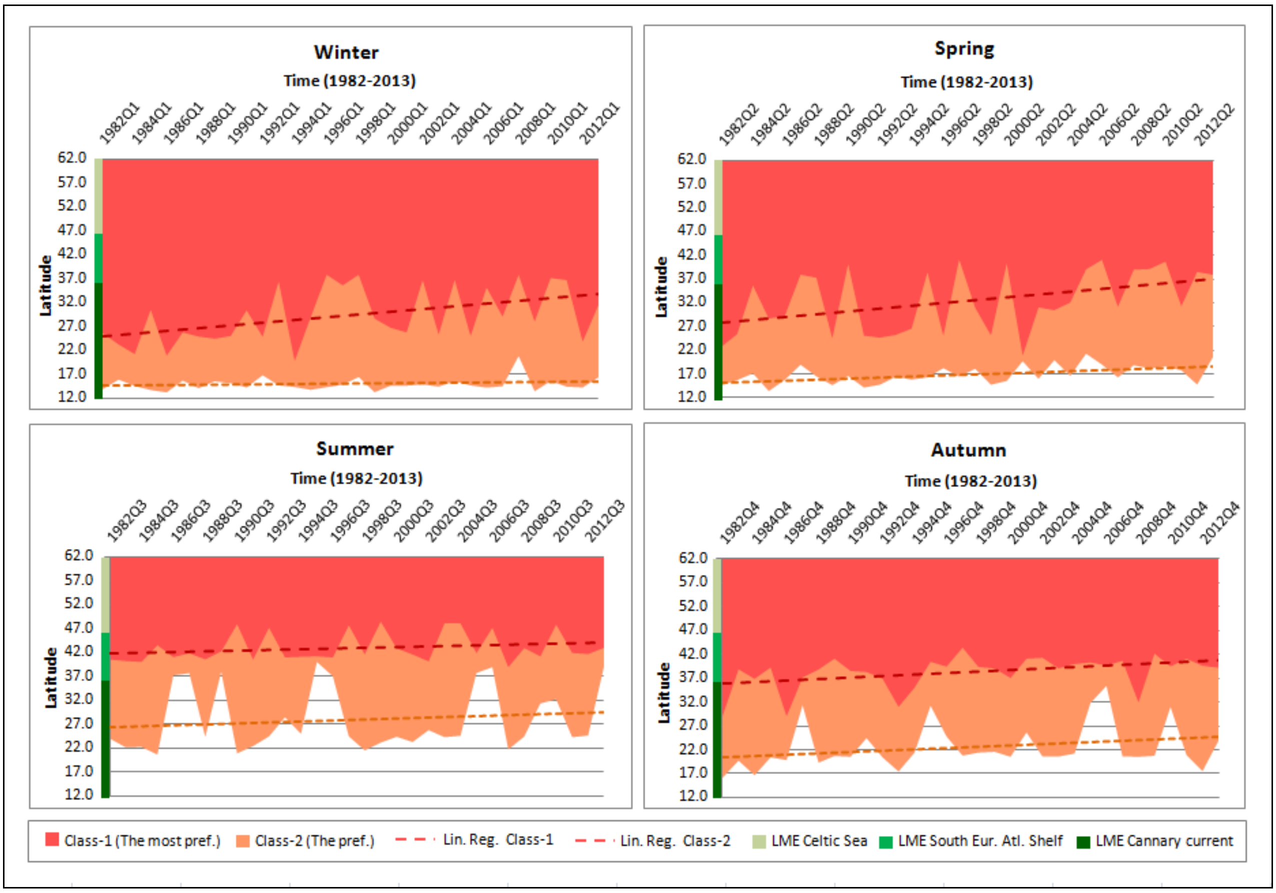


Figure 4-66: Evolution of the northernmost point of the lower limit of the most preferred zone (Class-1) in red color and of the preferred zone (Class-2) in orange color of *A. tobianus* by season.

4.5.9.4 *L. whiffiagonis*

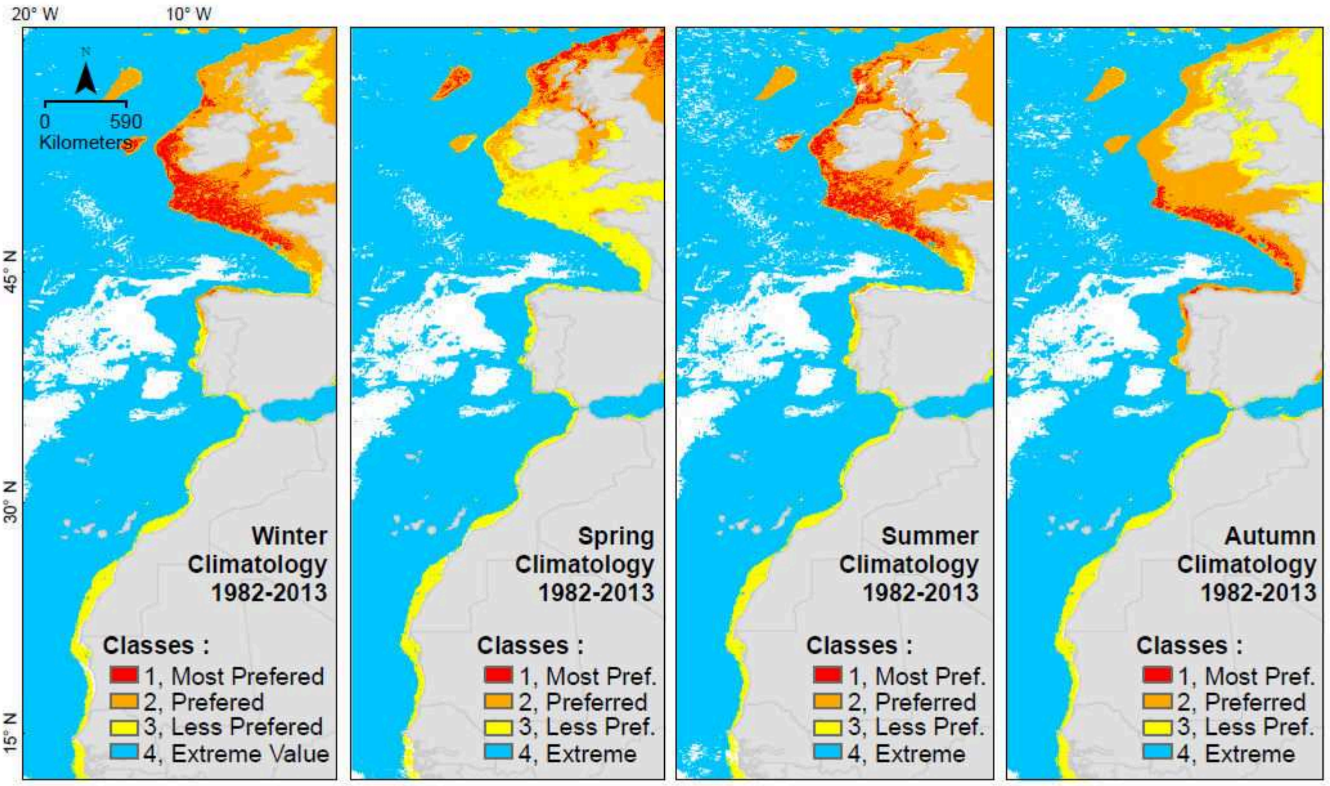


Figure 4-67: Potential distribution of *L. whiffiagonis* by seasonal climatology.

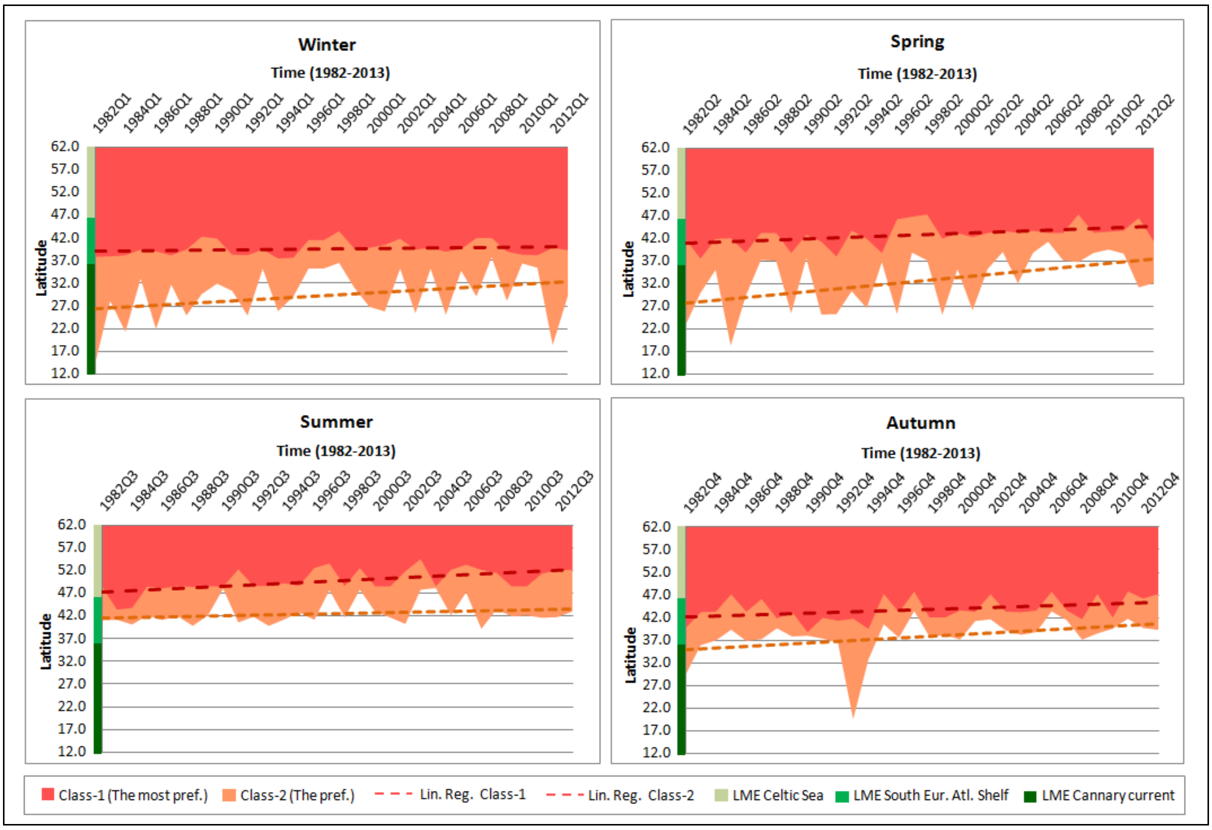


Figure 4-68: Evolution of the northernmost point of the lower limit of the most preferred zone (Class-1) in red and the preferred zone (Class-2) in orange of *L. whiffiagonis* by Season.

Table 4-24: Slope and significance values of the northernmost point evolution over time from winter 1982 to autumn 2013, for both the upper limit and/or the lower limit of the species suitable areas..

Species	**Class**[a]	**Limit**	**Slope (*p-value*) by season**[b]				
			Winter	**Spring**	**Summer**	**Autumn**	**All Seasons**
M. punctatum	1	Upper	0.003 *(0.899)*	-0.013 *(0.755)*	**0.090** ***(0.013)***	0.033 *(0.367)*	0.010 *(0.427)*
	1	Lower	**0.090** ***(0.029)***	**0.094** ***(0.0009)***	**0.317** ***(0.0001)***	0.134 *(0.211)*	**0.049** ***(0.002)***
P. saltatrix	1	Upper	0.064 *(0.359)*	0.021 *(0.739)*	0.021 *(0.347)*	0.088 *(0.144)*	0.016 *(0.410)*
	1	Lower	**0.045** ***(0.0009)***	0.055 *(0.117)*	**0.050** ***(0.0001)***	0.062 *(0.108)*	**0.015** ***(0.110)***
A. tobianus	1	Lower	**0.367** ***(0.001)***	**0.272** ***(0.046)***	0.072 *(0.211)*	**0.154** ***(0.019)***	**0.062** ***(0.0004)***
	2	Lower	0.029 *(0.277)*	**0.109** ***(0.002)***	0.101 *(0.428)*	0.137 *(0.133)*	**0.026** ***(0.091)***
L. whiffiagonis	1	Lower	0.044 *(0.206)*	**0.127** ***(0.005)***	**0.161** ***(0.0004)***	**0.105** ***(0.031)***	**0.033** ***(0.001)***
	2	Lower	**0.189** ***(0.084)***	**0.315** ***(0.004)***	0.062 *(0.227)*	**0.185** ***(0.023)***	**0.050** ***(0.002)***

[a] Class: 1 = Most Preferred; 2 = Preferred.

[b] Positive slope value indicates a north-bound tendency, while negative slope value indicates a south-bound tendency.

Generally speaking, most of the species showed a northbound trend in their distribution (Table 4-2). The significance values (in brackets) were more evident for the lower limit of the species suitable areas. Detailed information on species bathymetric constraints, occurrence distribution, and climatology models are available in the supplementary PDF files. Animated movies of species seasonal distribution are available in the supplementary MP4 file.

4.5.10 Discussion: species distribution models

This study presents the potential and optimal distribution range of a number of key potentially invasive marine fish species.. The method used was a methodological approach using GIS-based model as explained in the previous methodological chapter.

The species seasonal models present the species suitable area distribution in several classes, from the most preferred to the extreme less preferred. They show areas where species are very likely to occur, that is to say the areas in which the requirements of the species are fulfilled (in terms of temperature and bathymetric constraints), and the areas where species are hardly to occur.

The Class-1 or the area most preferred is represented by zones in red. It is the area where the species is most likely to occur because 50% of the species occurrences were found in this zone. The Class-2 or the preferred area is represented by zones in orange. Although, there is less chance to meet the species in this zone than in the Class-1, it is still an area where the species is likely to occur, because 30% of the species occurrences were found in this range. The Class-3 or the less preferred area is represented by zones in yellow. It is an area where species could potentially occur, but the chances are lower than in the two previous zones. This zone represents only 10 % of the species occurrences observed. . The Class-4 is the area where the species are hardly likely to occur but still, this area presents the extreme environmental values where the species has been observed in term of bathymetry. It could be that the environmental conditions there don’t really meet the species requirements due to species misidentification or error in geographical input position. Nevertheless, because there have been observation in this area, then we decided to keep this area in the model with notification. This class is represented by zones in blue. The area that does not meet the species requirement is represented by zone in white. The superficies and the positions of each class vary seasonaly.

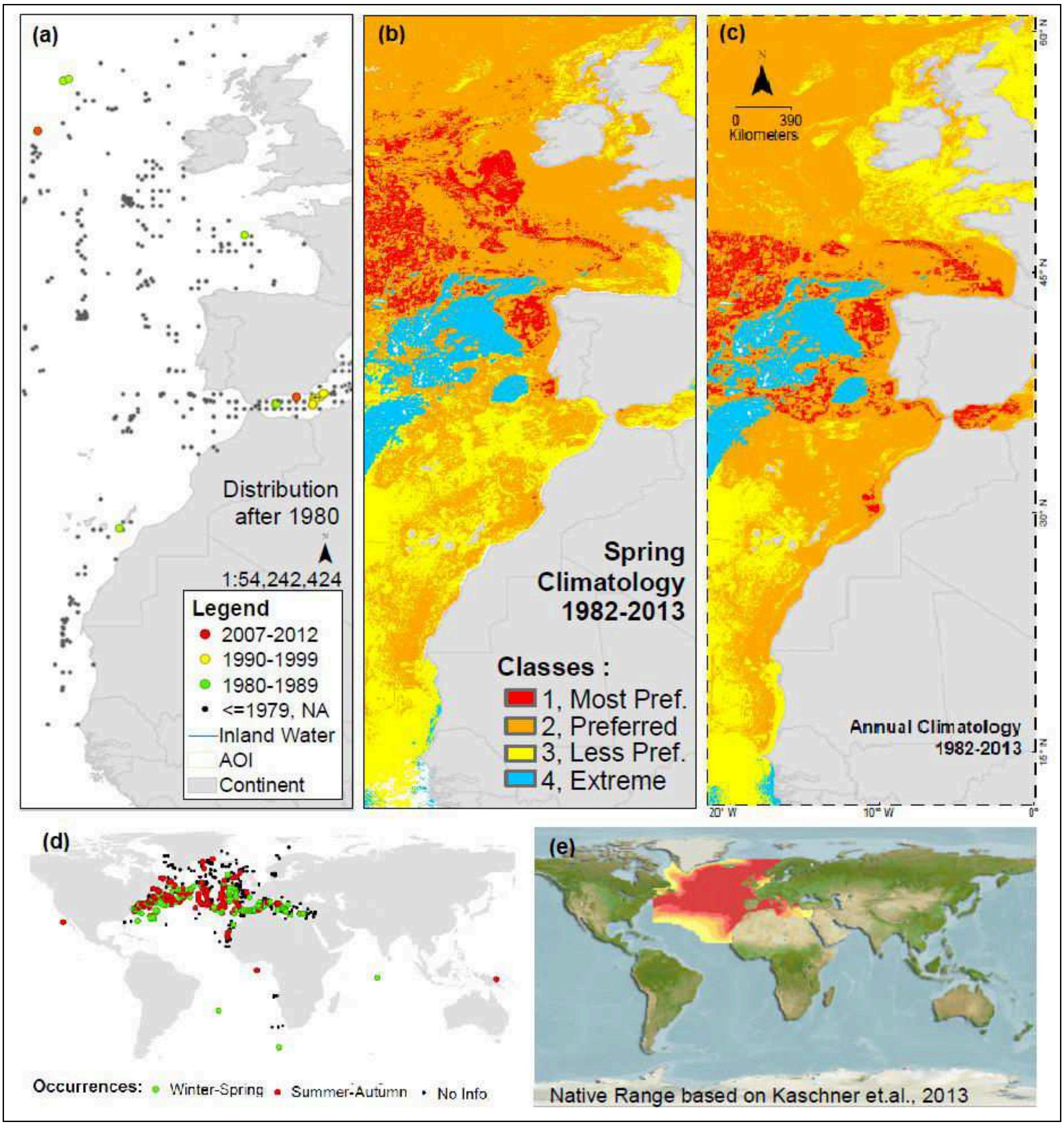


Figure 4-69: (a) Occurrences of *M. punctatum* in the study area. (b) Climatology model of the species’ distribution in spring and (c) Annual climatology model. (d) Species’ occurrences at global scale. (e) Model produced in AquaMaps for supplementary information.

We present the case of *M. punctatum* to demonstrate the capabilities of the GIS technique in modelling species distribution, especially for poor-known species and in data-poor areas (Figure 4-69). Colored points in Figure 4-69a and Figure 4-69d represent species occurrence records with time of observation, which were potentially used to determine the species' SST envelope. Black points represent observations without time of observation, which were only used to form the species' bathymetric envelope. Despite the small number of colored points in the area of study (Figure 4-69a), using the species' observation records at a global scale (Figure 4-69d), the model was capable of depicting the species' potential distribution in the study area following the seasonal environmental change (Figure 4-69b and see also Figure 4-61).

Demersal fish are a key group of marine organisms that influence marine biodiversity (Moore et al. 2011). They are strongly associated with the seafloor. Our dynamic seasonal models offer an alternative prediction of species distribution as baseline knowledge to understand species movements related to seasonal environmental changes. Such information is scarce and direct observation through fieldwork can be costly, time consuming and limited to relatively shallow waters (Moore et al. 2011).

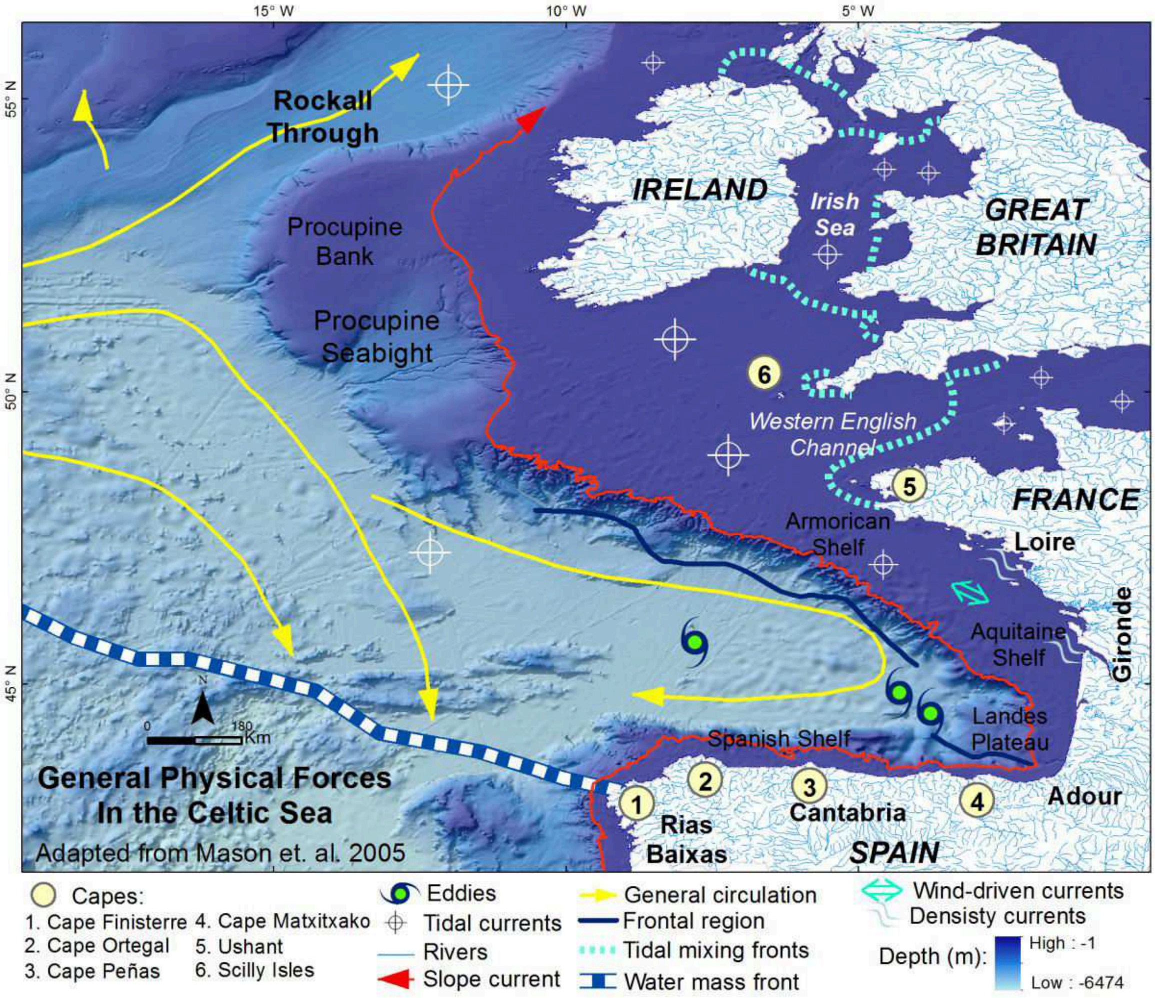


Figure 4-70: Major physical features of the Celtic Seas and the Bay of Biscay.

As expected by many authors, one of the species responses to global warming is a latitudinal shift in their distribution as they seek cooler locations (Pinsky et al. 2013). The environmental conditions in the northern regions of the study area were affected by a greater seasonal variability than in the southern regions (Mason et al. 2005).

Figure 4-70 presents the physical and topographical conditions of the Celtic Seas and the South European Atlantic Shelf (the Bay of Biscay area). The latitudes between 48° N and 52° N is the spawning location for certain fish species, such as *Sardina pilchardus* (Mason et al. 2005). The sea floor of this area has a very complex topography (see Terrain Ruggedness map on Figure 4-3). Their location in the mid-latitudes make the Celtic Seas as well as the English Channel experience strong seasonal surface heating and cooling, and energetic (westerly) winds that prevail for much of the year (Mason et al. 2005).

Tidal waves that proceed from the deep ocean onto the shelf vary in degree according to coastal and seabed topography. Strong tidal events happened in on French coast such as in St. Malo, where the tidal elevation exceeds 8 m, due to the constrained flow in the English Channel and the action of the Coriolis force (Mason et al. 2005). The tidal currents (frequently greater than 1 m/s) in this area are rectilinear and become progressively stronger towards the Bristol Channel (Mason et al. 2005). The friction with the bottom seafloor in the areas of strong tidal influences dampens the residual currents. A transient coastal upwelling off the southwest coast of Ireland has been reported by Edwards et al. (1996). Along with the mechanical energy from the wind, the tides cause a highly mixed homogeneous water column throughout the year in the Western English Channel and the Celtic Seas, except for certain parts of the Celtic Seas that experience summer stratification due to solar heating in the less energetic areas (Pingree and Griffiths 1978).

Tidal mixing fronts support and enhance biological production and biomass. These features are commonly observed in the Celtic Seas. Pingree et al. (1978) reported the high chlorophyll concentrations in the Ushant tidal front, off northwestern Brittany, one of the most prominent tidal mixing fronts. Enhanced nutrient concentrations and biomass in the vicinity of the Scilly Isles, off the southwest of the U.K., were also reported by Simpson and Tett (1986).

4.5.10.1 GIS technique for species distribution modelling

In this report, we described the application of GIS technique and ocean satellite data as environmental layers for marine spatial ecology in creating the species-specific distribution models. We applied this approach to rare fish species found in the central area of the AOI. Some of the species have been well studied because of their important commercial value. By presenting high temporal and spatial resolution maps of species preferential habitats, this study tried to provide information as a response to the questions on species preferential habitat that were not well understood until these days, as stated by Summerson et al. (2007).

Species distribution modelling is widely used in terrestrial studies, due to the huge availability and readiness of terrestrial environmental raster data. The boundaries of the area to model are also already fixed by the land-shorelines. Thus, one can easily perform a distribution model of a terrestrial species using freely available modelling software, i.e., MaxEnt.

Unlike terrestrial areas, the boundaries in marine ecosystems are not clear. In addition, these boundaries change over time, following many environmental factors such as seasonal change. Before performing species distribution modelling in a marine ecosystem, one first needs to fix the boundaries of the area of study for all environmental raster data, because some modelling applications would not work if these boundaries are not identical.

A GIS model does not require fixed boundaries and allows a great flexibility in preparing and performing spatial and temporal analysis of time series of environmental raster data.

Most of the models predicting a species potential distribution are based on the relationship between the species and the environmental conditions in the areas where the species occur. The models existing today are very dependent on the set of occurrences of the species modeled in the focussed study area. There have been long discussions about this method in various articles. One should have a representative number of occurrence records well distributed in the study area in order to have a good model. GIGO (gold in, gold out or garbage in, garbage out), a concept common in computer science, applies here. Hence, in order to model distribution of a given species in a given area, one should first have a good number of observations with an appropriate distribution at those sites, so a study area with too few observations could not be modeled properly.

In this study, we used species occurrence records at the global scale to find species maximum and minimum limits for each environmental parameter taken into account. The outcome of this process is the species ecological niche of each parameter. This niche is then used as an input to project species environmental envelop over a suite of environmental data. Processing the species requirements for all marine environmental raster together in geographical space will produce the potential distribution or habitat suitability of the species. This technique will provide a good, simple approach for species distribution modelling, especially in data-poor areas.

The assumption of a model, as stated by Hijmans and Elith (2013) and Kesner-Reyes et al. (2012), is that the prediction can be made entirely or potentially in a region by relating sites of known occurrence and perhaps non-occurrence with the environmental variables known for those local sites and for all other sites.

Boitani and Fuller (2000) explained that, obviously, one parameter (for example, the temperature) is not enough to predict the presence of a species in every place for which the parameter values are suitable. There are many other ecological parameters that contribute to the determination of species distribution, like the one we used in this study, the bathymetric constraint. Taking into account the species preferred range of these limiting environmental factors, the probability of finding the species will increase if the coverage of the environmental data, otherwise the model will not show strong accuracy. Using GIS techniques with the incorporation of satellite environmental data, the maps of species potential distribution can be produced quickly and efficiently.

Species occurrence records with no information on its time of observation take no parts in the definition of species temperature niche but could be used to measure the effectiveness of the approach; see again Figure 4-69. The model is then used as description of the species occurrence distribution (Franklin, 2009).

The capabilities of GIS to handle large amounts of spatial data allow modelling of species distribution in higher temporal and spatial resolution and to follow their movement. This study provides a quick and efficient method of presenting high temporal and spatial resolution maps of marine species preferential habitat. Any information that assists in a rapid assessment of the species will facilitate a more rapid response and enhance the likelihood of successful management. Extending the work to the 89 fish species and even all species would revealed which species that would more affected by the effect of climate change. The use of the species ecological niches determined using the occurrence records gathered from around the world allows this technique to model the distribution of a poor-known species or modelling in data-poor area even at the global scale with high spatial and temporal resolution. Other environmental raster data measured by MODIS sensors may be incorporated for analysis in smaller areas.

4.5.10.2 Effect of climate change on shifting fish distribution

Ocean warming affects the distribution of marine species by shifting their suitable area over time, as shown by the evolution of the northernmost point of the species potential distribution areas: for both the upper limit and the lower limit of the suitable area (Figure 4-71).

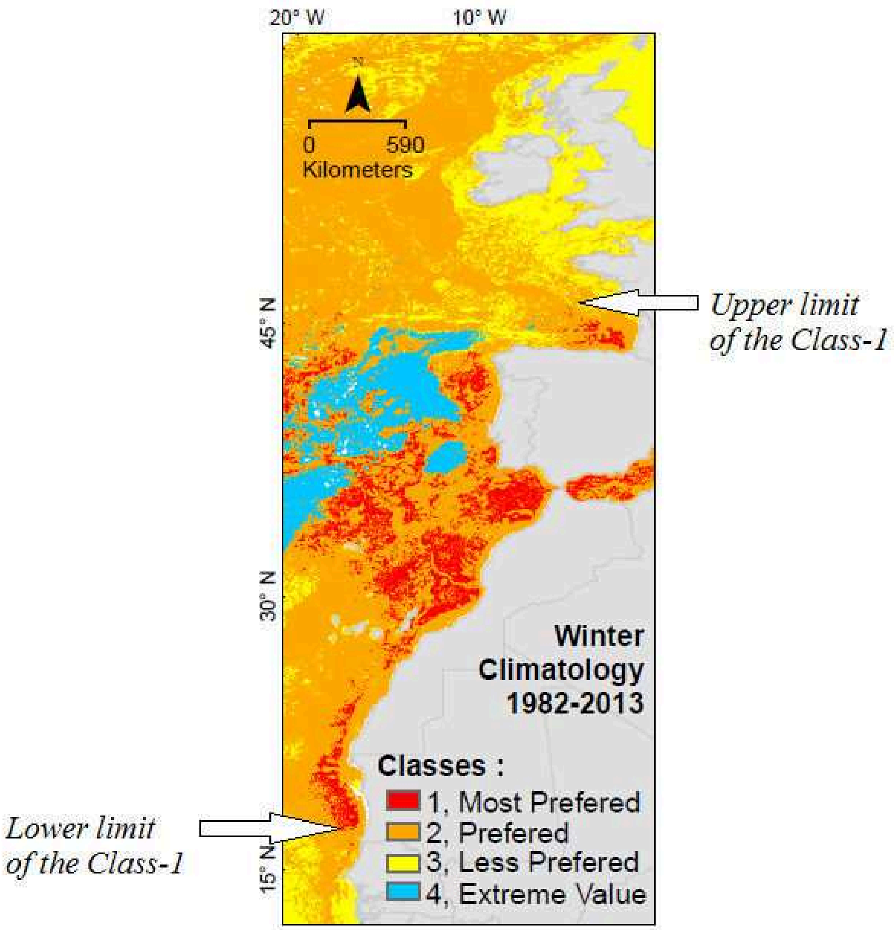


Figure 4-71: Upper and Lower limit of a Zone (Class-1).

The tendency of these movements was more evident in the lower limit (Table 4-25) than in the upper limit (Table 4-26) of the species most/preferred zone.

Table 4-25: Slope and its significancy for the lower limit of each zone/class. ▲ = regression line has a positive slope (tendency of going north); ▼ = regression line has a negative slope (tendency to go south); + = *p-value* < 0.05 (significant).

Species	**Affinity**	**Habitat**	**Depth pref. (m)**	**Class**	**Slope (p-value) by season***				
					1	**2**	**3**	**4**	**All**
M. punctatum	Temperate	Bathy-pelagic	909-3726	1	▲+	▲+	▲+	▲	▲+
P. saltatrix	Sub/Tropical	Pelagic	5-27	1	▲+	▲	▲+	▲	▲
A. tobianus	Temperate	Bentho-pelagic	20.6-61	1	▲+	▲+	▲	▲+	▲+
				2	▲	▲+	▲	▲	▲
L. whiffiagonis	Temperate	Demersal	122-173	1	▲	▲+	▲+	▲+	▲+
				2	▲	▲+	▲	▲+	▲+

*1 = Winter; 2 = Spring; 3 = Summer; 4; Autumn;

The northern-bound tendency was quite evident in the lower limit of species suitable area distribution. It involved all speciestemperate, sub tropical and tropical affinity, indicating the strong effect of global warming. The significance slope values were present every season for each species, bathypelagic, pelagic, benthopelagic and demersal.

Pelagic species are known to have a small niche, which explains their north-south movements toward their suitable area. These movements vary seasonally with a strong variability that furthermore affects the significance value of their linear regressions.

Table 4-26: Slope and its significancy for the upper limit of each zone/class.

Species	**Affinity**	**Habitat**	**Depth pref. (m)**	**Class**	**Slope (*p-value*) by season***				
					1	**2**	**3**	**4**	**All**
M. punctatum	Temperate	Bathypelagic	909-3726	1	▲	▼	▲+	▲	▲
P. saltatrix	Sub/Tropical	Pelagic	5-27	1	▲	▲	▲	▲	▲

*See Table 4-25 for legend

Table 4-26 presents the slope and the significance values from linear regression on the northernmost point evolution of the species suitable area, for every season and for all seasons computed together. In general, the movement of the northernmost latitude was not significant except for *M. Punctatum*, which inhabits a benthopelagic environment. The significant slope values were observed in summer period (Season-3 on Table 4-26) only for this species. For the lower limit of *P. saltatrix*, no significant slope value was observed for the pelagic species (Table 4-26).

The northern-bound tendency of species distribution was also observed for all species in every season, except for *M. Punctatum*, which showed a southward tendency in spring (Season-2). This southward tendencies were very small due to the higher variation of the earlier years (1982 to 1994), thus they are negligible.

A strong variation of the northernmost values of the upper limit and/or the lower limit of the species suitable areas were observed in the range of 22° N to 42° N latitude, from the Mauritanian coast to the southern Portuguese coast. As we mentioned previously in the subchapter on area of study, this particular region is known to represent an environmental transition between subtropical or tropical waters and temperate waters. Hence, many species have their limit of distribution in these areas. The strong movements of seasonal variability in these zones affect the significant values of linear regressions.

Climate change affects most marine organisms by the increasing of ocean temperatures. Summerson et al. (2007) stated that sea water temperature controls the reproduction and growth of the species as well as the availability of their food. Thus, increased temperatures could allow the lower-latitude restricted species to expand their distribution range in the higher latitudes when the temperatures of those areas become warmer in summer and vice versa.

In winter for example, the suitable areas for species with subtropical/tropical affinity, such as *P. saltatrix*, are found in the lower latitudes. In summer, some of the areas in the higher latitudes, that were previously inhospitable in winter, may become favorable to this species and others. This could be one of the major reasons for their movement as stated by Oliver et al. (1989). Ballenger (2014) mentioned that *P. saltatrix* is a warm water migratory pelagic species in the Atlantic seaboard, that generally travels northward in spring and summer, and southward in autumn and winter.

Teixeira et al. (2014) confirmed in their report that the official landing data for commercial species with subtropical/tropical affinity in the middle region of the Portuguese coast showed an increasing trend in warm years, while landing data for temperate species presented an opposite trend and vice-versa for the cold years. Moreover, the Secretariat of the Convention on Biological Diversity (2009) stated that some of the greatest impacts of invasive species may also arise from the intensity of extreme climatic events, because certain species are at advantage with their wide tolerance of climatic conditions and capability to sift their range rapidly and to withstand extreme climatic conditions with less mortality.

The northern-bound tendency was quite evident for the lower limit of the most and the preferred suitable areas for all species studied. The significances of the slope values were present for every season for each fish species living on all type of environments. It indicates the strong effect of global warming confirming the statement by Secretariat of NOBANIS (2012) who mentioned that the increase of ocean warming may facilitate the invasion of marine alien species by increasing the magnitude of their growth and their recruitment relative to the native species, and, for the pelagic marine species, the dispersal of their eggs and/or larvae has a possibility to spread without help of human activity.

Many models today do not take into consideration the effect of seasonal variability that clearly affects species distributions. Most of these models used the mean annual temperature as predictor and species occurrence records distributed in a given area without considering its time of observation. Then, the results obtained could not show the seasonal variation that affect species distribution.

4.5.10.3 Effect of other ocean parameters

Chlorophyll-a concentration was not incorporated in this study due to the presence of no-data areas in many parts over the study area. This fact could reduce the model accuracy, because the GIS model used in this study would exclud areas with no data in any environmental parameters incorporated. However, studies analyzing the patterns of zooplankton (Rutherford et al. 1999), primary productivity (Behrenfeld and Falkowski 1997) and fish diversity (Worm and Lotze 2009) showed that chlorophyll-a was not a good predictor, while SST correlated best with patterns of species richness. Primary productivity clearly affects marine abundance but is not determining to diversity (Whitehead et al. 2010).

An experimental study on microcosm suggested that changes in productivity influenced diversity (Whitehead et al. 2010). However, observational studies of animal diversity at larger scales have often failed to produce consistent patterns (Mittelbach et al. 2001), although the present discrepancies among studies may be explained by differences in scale (Chase and Leibold 2002).

Salinity could have an important effect on limiting species distribution. Many existing models used salinity data from the NOAA World Oceans Atlas. Unfortunately, the incorporation of this data into the model was problematic: The salinity data was produced from ocean physical sampling with low spatial resolution compared to the data on other parameters that we used in the model. Recently, the project of SMOS (Soil Moisture and Ocean Salinity) launched in 2009 was capable to measure this parameter remotely. Nevertheless, the time series data of this parameter that is available covers a very short period and cannot be used in this study. Incorporating this data into the model would result in a deviation of the species real potential distribution. Besides, many invasive marine species have a wide tolerance to salinity, as mentioned by Summerson et al. (2007). Furthermore, they explained that many of the potentially invasive species originated in estuarine environments where the variability of salinity is very large.

Type of substrate, oceanic circulation patterns resulting from the complex interactions between surface currents, wind-driven currents and tidal currents, and the disturbance of the marine environment caused by human activity could also have a major influence on determining demersal species distribution. Substrate type data are available for some regions in the area of study but data that covers a large scale area with sufficient spatial resolution are difficult to find. Incorporating these complex data into the model would hide the effect of climate change. Besides, as added by Summerson et al. (2007), many invasive marine species have wide habitat tolerance that enables them to adapt to the new environments.

Our model used occurrence records requiring only the geo-localization and time of observation and, took advantage of the huge availability of species occurrence records and satellite data. This technique could facilitate the process of gathering information on species occurrence records across the countries, which has been a challenge in the species distribution modelling as stated by then the Yesson et al. (2007).

4.6 Richness model of the studied species

The richness of the studied species in the study area was modelled seasonally over time, from winter 1982 to autumn 2013. It is a dynamic seasonal model derived from individual niche models (subchapter 3.6), and presents the distribution of areas occupied by the species in several classes.

In this section, we compared the richness of the studied species from the actual available data (species occurrences observed from 1982 to 2012) and from the richness model.

4.6.1 Richness from actual data per grid of 50 km^2

In general, tropical waters are more speciose than subtropical or temperate waters, represented by a graduation of color from orange to dark red (Figure 4-72).

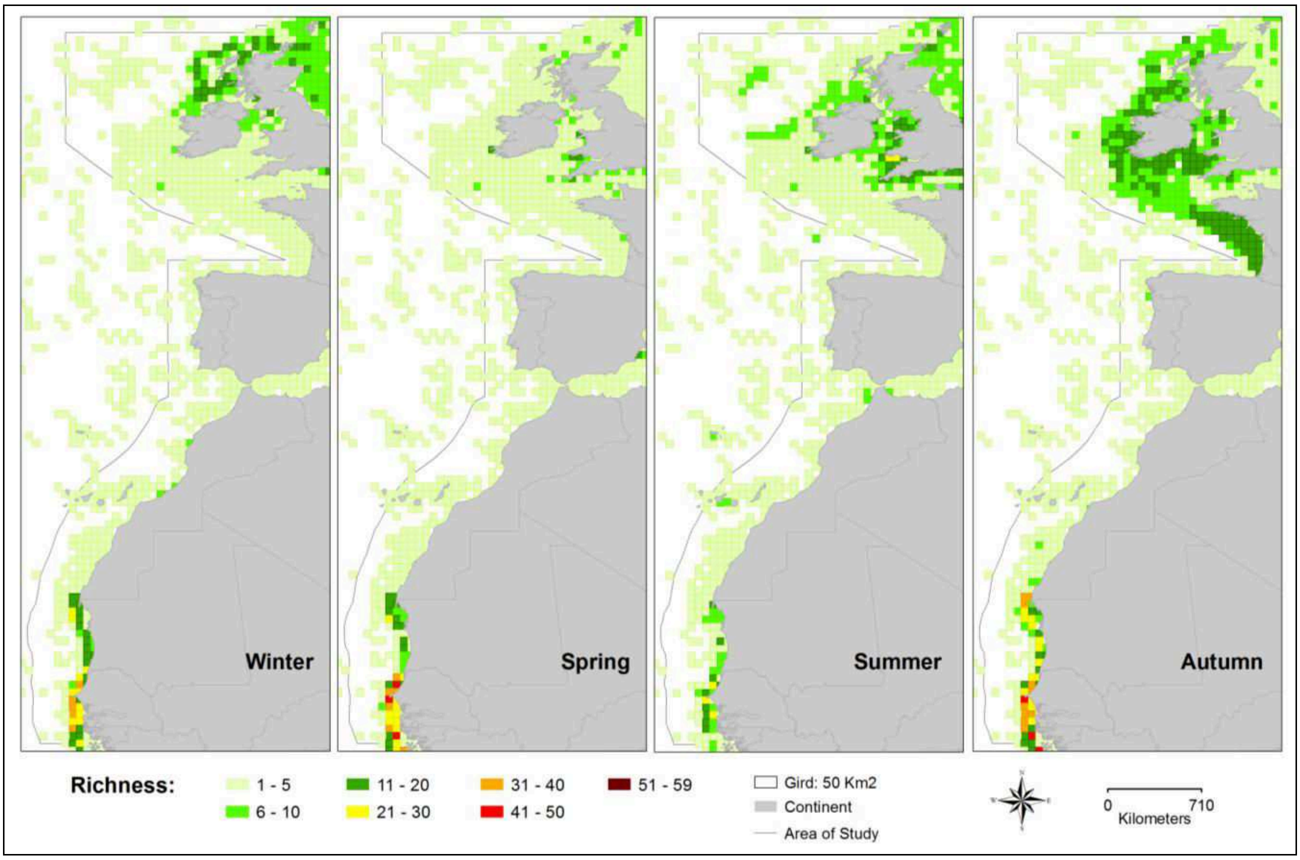


Figure 4-72: Seasonal cumulative number of studied species (1982 to 2012) per grid of 50 km^2 (cell) in seven classes: (1) Lowest class of 1 to 5 species = area in light green, (2) 6 to 10 species in green, (3) 11 to 20 species in dark green (4) 21 to 30 species in yellow (5) 31 to 40 species in orange, (6) 41 to 50 species in red, (7) Richest class of 51 to 59 species in dark red.

Richest areas of more than 31 species (areas in orange and red in Figure 4-72) were observed off the Senegalese coast in every season except in summer. In European waters, the Celtic Seas Ecosystem was generally occupied by less than 20 species. During summer and autumn, the southern part of this ecosystem received many species from the northern area and/or the southern area of tropical waters. It demonstrated by the change of color, from light green to dark green, especially in the English Channel and the Bay of Biscay. The low richness in the middle regions of the area of study (from Portuguese waters southward to Moroccan waters) was strongly influenced by the poor availability of occurrences data.

The species occurrences used in this study were observed from 1982 to 2012 as mentioned previously and collected from various sources (described in the subchapter 3.4.2). The maps in Figure 4-72 revealed that it may not be possible to sample the whole area with a whole range of environmental variation for each species as stated also by Araujo (2002). Inventory of species occurrence records are expensive and limited by time. The use of "indicator" species to estimate species richness is thus common (Fleishman et al. 2005).

Studies of species richness across a biogeographical range are difficult due to the poor availability of species occurrence records. This type of data is usually scarce, especially for marine species in the waters of developing countries such as Morocco, Mauritania, and Senegal. The survey data from these countries are usually not available for public-access. Thus, the possibility to account for seasonal or inter-annual variation is very low.

4.6.2 Model of richness

The classes of richness model were set similarly to those of the actual richness (Figure 4-72): from the lowest class of 1 – 5 species represented by the light green, to the richest class of 51 – 59 species in dark red, see Figure 4-73 for models for the year of 2013.

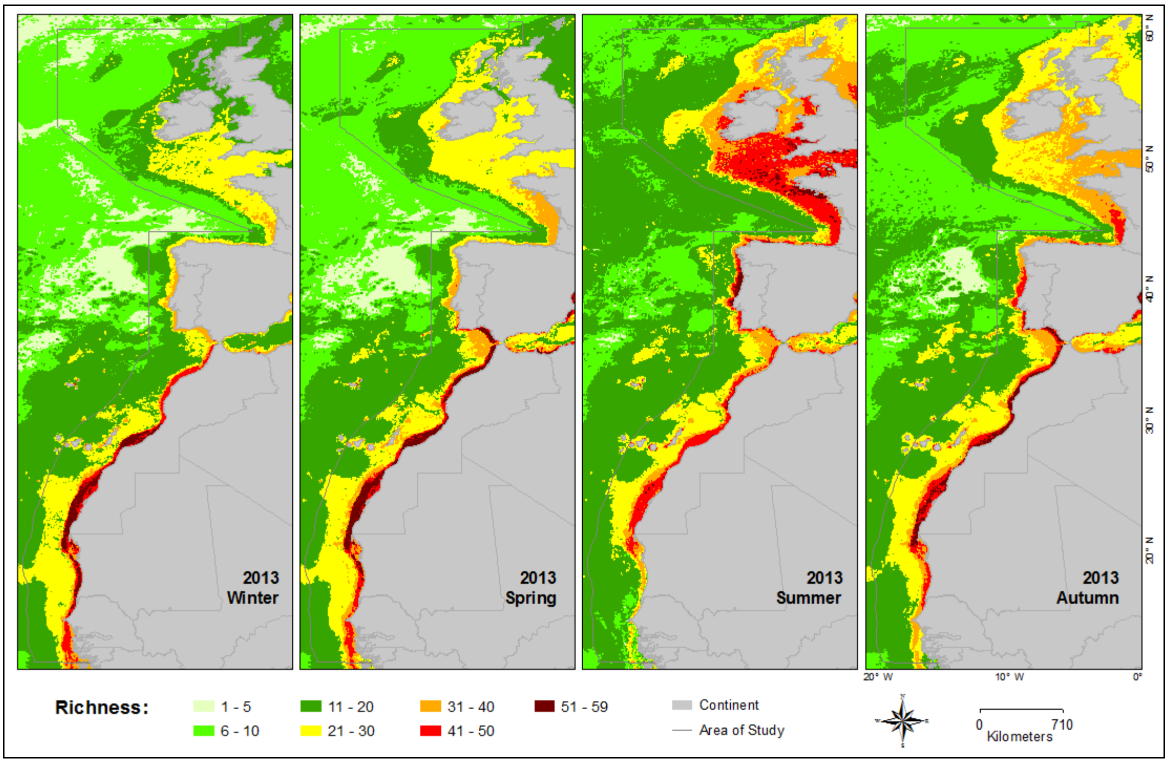


Figure 4-73: Richness models by season in 2013. Complete images of these models from 1982 to 2013 are available in the supplementary mp4 movie file.

Figure 4-73 shows that in winter, the areas most occupied by the species were found along the Moroccan and Mauritanian coasts, which was not captured by the actual data (Figure 4-72). The environmental conditions in these areas during this period were suitable for approximately 51 – 59 species, represented by dark red color on the map (Figure 4-73). In general, the West African waters have more than 41 species of the total studied species (red color in Figure 4-73) than in European waters during winter.

The European waters started to have more species when the sea temperature warmed in spring. The areas most occupied by species (red dark) moved northward to the south of the Portuguese and the Spanish coasts. In summer, as the sea temperature in the European waters increases, several areas such as Portuguese waters, the Bay of Biscay and the Celtic Seas, became suitable for many species. In autumn, the distribution of richness started to reverse and moved southward to the south of the Portuguese coast. Because the sea temperature decreased slowly, most of European waters were still suitable for many species (zones in orange and red) during this period.

4.6.3 Discussion: model of richness

Accounting for ecological transition zones is required in species distribution studies. These transitional zones are likely to depend on time periods. The questions arise about which ecological transition areas are most likely to promote species adaptative responses related to climate change (Araujo 2002). Futhermore in conservation effort, one should consider the effect of seasonal and inter-annual variations, because this could preserve a species adaptative variation across environmental changes.

The idea of making a richness model arose when we were working with individual species models. By simply superposing all models of individual species distribution at a given time, we were able to calculate the potential number of species in an area. This richness model could then be used to assess the effectiveness of MPA location in relation to the areas of high richness/biodiversity (described in the next subchapter).

4.6.3.1 Actual richness vs model richness

The available measurements of species biodiversity are mostly analyzed using expert knowledge or regional observations which cannot be used directly to investigate the potential shift in their distributions under different environmental conditions. Most of existing empirical attempts to measure species biodiversity were based on occurrence records. The lack of data in many places and the fact that the analyses were restricted in taxonomic and spatial coverage reduced the accuracy of species richness studies that based their data from actual species records (Whitehead et al. 2010). In addition, dividing actual observational data into four seasons reduced the number of species occurrence. This made the low data become even lower. Thus, the model of richness is essential for understanding of the seasonal evolution of species richness. The model presents the information of richness of the studied species through their suitable areas.

The actual richness of the studied species (Figure 4-72) and the model of richness of the studied species (Figure 4-73) present a different pattern. The actual richness was strongly influenced by the availability of species occurrences data. The data was generally more abundant in the north European waters (data obtained from the developed countries) than from the coast of Portugal to the south of Moroccan waters.

In the southern part of the area of study (the developing countries), the availability of species occurrences was very poor (see again Figure 3-16). It might be due to the low number of surveys conducted in the area, the limited access to the databases available in the regions, the species movement at large spatial scale and the temporal variability of oceanographic conditions. Species occurrence records are scarce, especially for marine species because it may not be possible to sample the whole range of environmental variation in the area (Araujo 2002). Field surveys on the sea and inventory of species occurrence records are expensive and limited by time. Quantifying patterns of biodiversity requires costly and challenging efforts, particularly in the oceans where the species cannot easily be seen and many of whom are highly mobile, with large areas of distribution that extend far into the open oceans (Tittensor et al. 2010). The use of "indicator" species, which in this study are species considered potentially invasive, to estimate species richness is then common (Fleishman et al. 2005).

4.6.3.2 Interannual variability

The sea temperature in European waters reached its maximum in summer. At this period, most of the northern part of the study area became suitable for many species (above 41 species), especially in the Bay of Biscay and off the Portuguese coast.

Figure 4-74 presents the evolution of richness of the studied species in summer period, from 2010 to 2013. In the Bay of Biscay and the English Channel, the areas most occupied by studied species (red and dark red colors) changed or moved over time. Similar patterns were observed off the Moroccan coast, while on the Portuguese coast, the locations of areas most suitable for the most species were relatively consistent every year.

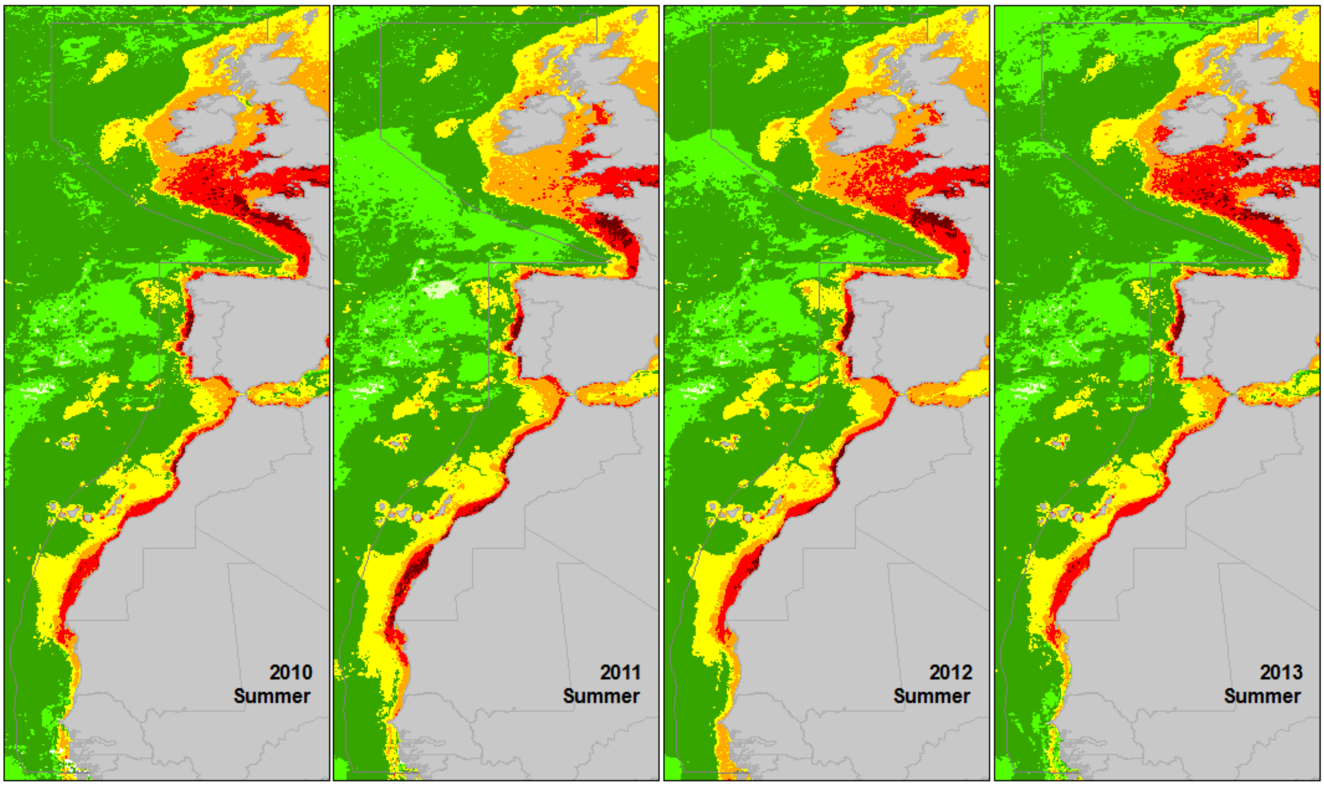


Figure 4-74: Evolution of species richness models of the studied species in summer period, from 2010 to 2013. Complete seasonal models are available in supplementary documents.

Our models of richness are likely to match the results obtained from several articles such as Teixeira et al. (2014). They stated that the species richness in the middle region of the study area

(Portuguese coast) is generally higher because many species have their southern or northern limit of distributions there. This region is a transition area between north-eastern Atlantic warm-temperate waters and cold-temperate waters that makes the zone an area of great sensitivity to the detection of climate change. Official landing data for commercial species with subtropical/tropical waters affinity in this middle region showed an increasing trend in cold years, while in warm years, it was the species with an affinity for temperate waters which showed an increasing trend.

The hotspot boundaries changed following the seasons. Myers et al. (2000) stated that a hotspot should contain endemic or threatened species. In our study, we focused mainly on the potentially invasive species including the threatened species. The hotspots determination should help to pinpoint areas of super priorities for conservation.

Our analysis presents predictions of richness at various spatial and temporal scales. Our approach deals with the lack of occurrence data in many parts of the study area, particularly when considering seasonal periods. The method simply calculated the number of species suitable areas that overlapped. These suitable areas resulted from the GIS models presented in the previous sub chapter. The key environmental data used was sea surface temperature. Whitehead et al. (2010) stated that SST is a key environmental data that needed to be included in the model.

4.6.3.3 Seasonal variation

The areas where the richness reached its peak differed seasonally. Species respond to global warming by shifting their latitudinal distribution as they seek cooler locations (Cheung et al. 2009). This affects the reorganization of local community and could provoke local extinctions.

Taking the model of richness of the studied species in 2013 as example (Figure 4-73), the figure showed that in winter, the richness peaks in the areas between 15° N and 30° N. In spring, the peak was observed in the areas between 18° N and 38° N. In summer, these areas moved northward approximately 40° N around the Portuguese coast and in the area of approximately 48° N of southern Brittany coast, France. In autumn, when the temperature began to decrease, the areas where richness reached its peak were found between 20° N and 38° N. These latitudes reflected the optimal temperature for studied species (area of high biodiversity).

In the higher latitudes, the influence of seasonal variability is strong (Figure 4-74). In the northern region of the study area, the areas most occupied by species were generally found in the Bay of Biscay (Figure 4-74). The general circulation in this region is strongly affected by a complex topography, and hence affects environmental and biological distribution (Koutsikopoulos and Le Cann 1996). Northerly and easterly winds in the central area of the Bay of Biscay produce upwellings on the French and the Spanish coasts, tending to be higher on the French coast (Borja et al. 1996).

The higgest mean wind speeds occur during winter in the Bay of Biscay (Figure 4-75). The colder water at the surface occurred over the French shelf regions as a result of river discharges that reach their maximum in this period (Koutsikopoulos and Le Cann 1996), and bring cold and low-salinity river water. Over the Spanish slopes in the southern part of the Bay of Biscay, the relatively warm and salty Iberian Poleward Current (IPC) proceeds along the shelf edge and upper slope off northern Iberia (Mason et al. 2005). This anomalously warm water is implicated in the formation of SWODDIES (Slope Water Oceanic Eddies) that persist for up to a year (Pingree and Le Cann 1992). These SWOODDIES, with low horizontal diffusion rates, tend to retain made the biological material (Fernández et al. 2004).

In spring, weak upwelling events occur on the Spanish coast of the Bay of Biscay (Figure 4-75). The recruitment of anchovy tends to be higher during this upwelling period (Borja et al. 1996). The seasonal warming of surface waters begins in this season. Off the French coast, over the shelf areas in the southern part of the Bay of Biscay, the offshore spreading of low-salinity freshwater from the river outflows may create an extensive, stable nutrient-rich environment (Mason et al. 2005).

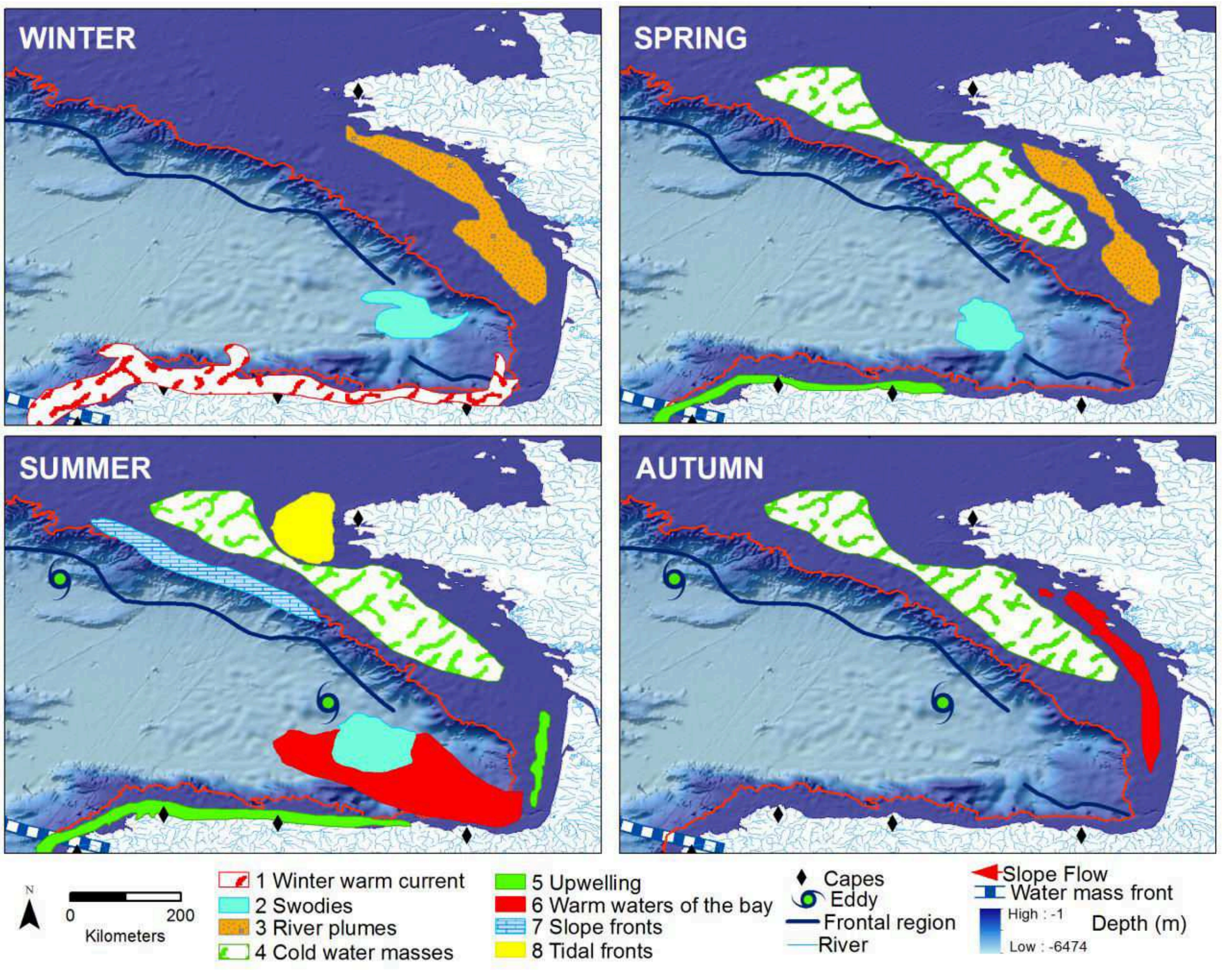


Figure 4-75: Main hydrological structures in the Bay of Biscay, adapted from Koutsikopoulos and Le Cann (1996).

In summer, the sea temperature reaches its highest value in the southeast and leads to the formation of an important warm pool and chlorophyll-rich structure in this area (Gil et al. 2002). This mixing area could have a significant impact on the biology. Upwelling in the northwestern Iberia is particularly pronounced in summer when the persistent northerly winds that active off western Iberia (Mason et al. 2005). The upwelling off the Spanish coast is weaker than off western Iberia and off the French coast during this period (Borja et al. 1996). Interaction between bottom topography and tidal currents over the northern part of the French shelf off western Brittany causes seasonal tidal thermal fronts (Koutsikopoulos and Le Cann 1996). This phenomenon could have biological consequences (Mason et al. 2005). In autumn, homogenous waters resulting from vertical mixing processes occur in the northern French shelf (Mason et al. 2005). The appearance of a “langue d’eau chaude” or narrow warm water tongue inshore along the French coast results from the mixing between tidal and wind-induced currents, and ocean-atmosphere exchanges (Cann 1982).

In the western Iberian offshore, the main upwelling season (northerly winds) occurs during the summer, while in winter, the winds relax with intermittent periods of both upwelling and downwelling (Mason et al. 2005). During spring and summer, the persistent upwelling from about 100-300 m depth occur along the entire western Iberian coastal area (Figure 4-76). The upwelling events are usually intense in the waters of Cape Finisterre, Cape St. Vincent and Cabo de Roca. It extends to more than 100 km offshore.

In the northwest African waters, the year-round upwelling activities occur in the area between 20°N and 30°N (Figure 4-77).The areas above and below this zone, experience seasonal upwelling. Detailed information of the oceanographical condition in this area can be referred to Mason et al. (2005).

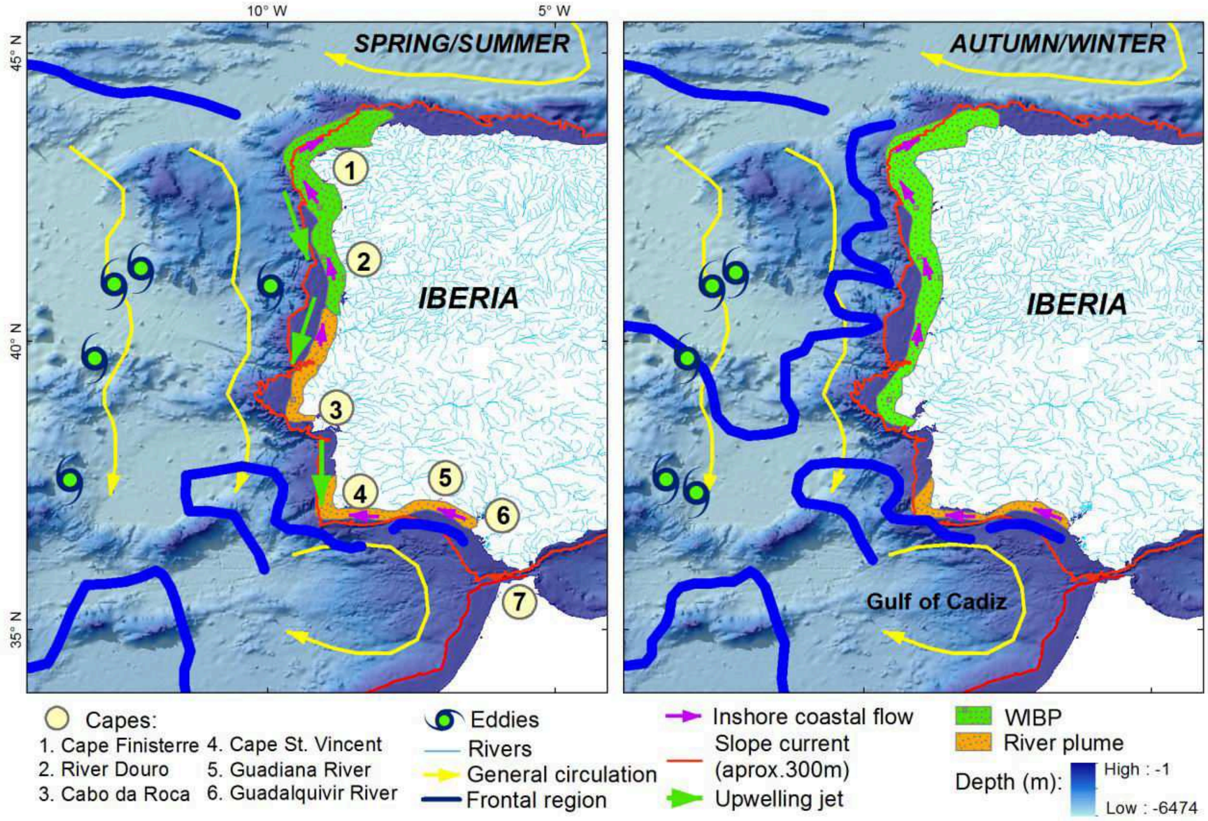


Figure 4-76: The western Iberia regimes in a) spring and summer, and b) autumn and winter; adapted from Mason et al. (2005). Oceanographical features on the images were originaly taken from Peliz et al. (2002) and Peliz et al. (2005). WIBP stands for the Western Iberia Buoyant Plume.

Lack of data limits our comprehension of fish population dynamics, which influences the accuracy of decision in conservation. The required information on species spatial distribution and their environmental characteristics are only available for a little number of marine fishes. In addition, they are available only in some regions. Collecting the necessary quantitative data is costly, which bring difficulties for many developing countries to conduct scientific campaign. In tropical waters, the species diversity is high but resources for monitoring are poor (Cheung et al. 2005).

Our models were derived using species niche models that largely depend on the reliability of environmental data such as satellite-derived ocean parameters. This study showed that the temperature play a major rule in shaping species distribution. Richness of the studied species distributions changed and moved considerably over the year. Thus, the seasonal variations need to be taken into consideration. Further study on SST, productivity and diversity relation in higher scale will be needed.

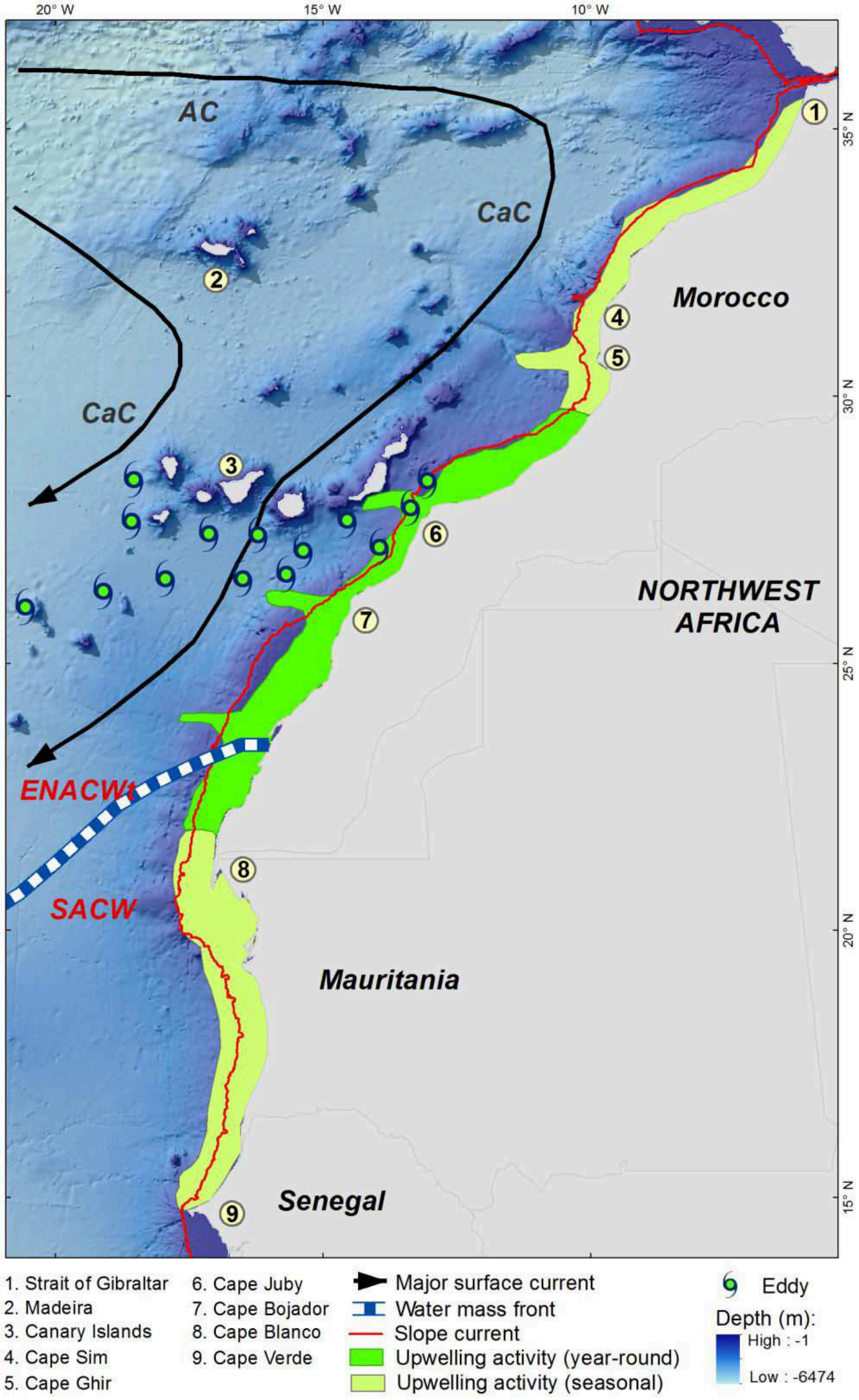


Figure 4-77: Upwelling in the northwest African waters. The zone of strong green color represents areas where the Upwelling activities continue all year. The zone of light green color represents areas with seasonal upwelling activities, adapted from Mason et al. (2005).

4.7 Marine Protected Area (MPA)

In this section, we present the results of MPAs area analysis and the importance of MPAs locations in realtion to the seasonal movement of hotspot areas (zones suitable for at least 30 species).

4.7.1 MPAs areas by ecosystem

In the Celtic Seas, the MPAs cover approximately 5.2% of the total ecosystem area, or 6.7% of the continental shelf area available in the ecosystem (Table 4-27). In the South European Atlantic Shelf, the MPAs cover 7.6% of the total ecosystem area, or 12.4% of the continental shelf area in the ecosystem. In the Canary Current, the MPAs cover 2.6% of the total ecosystem area, or 7.6% of the continental shelf area available (Table 4-27).

Table 4-27: MPAs statistics by ecosystem.

No	Ecosystem	Ecosystem (Km^2)	Continental Shelf (Km^2)	MPAs (Km^2)	MPAs Comparison (%)	
					Ecosystem	Continental Shelf
1	Celtic Seas	1105737	861804	57842	5.2	6.7
2	South European Atlantic Shelf	431988	266783	33256	7.6	12.4
3	Canary Current	1123189	386263	29571	2.6	7.6

Table 4-27 presents the surface area of MPAs related to the total area of the ecosystems and the continental shelf (area less than 200 m deep) in each ecosystem. Although the MPAs coverage in the South European Atlantic Shelf is the smallest among the studied ecosystems, they cover the biggest percentage of the ecosystem area (7.6%) and of the continental shelf area (12.4%).

4.7.2 MPAs areas by country

The study area includes waters belonging to nine different countries: Ireland, United Kingdom (UK), France, Spain, Portugal, Morocco, Western Sahara, Mauritania, Senegal and Gambia (Table 4-28).

Table 4-28: MPAs statistics by country.

No	ID	Country	Number of MPAs		Area in Km^2
			All	Inside AOI*	
1	Irl	Ireland	101	101	7078
2	Gbr	UK	476	275	41671
3	Fra	France	254	105	34304
4	Esp	Spain	183	67	8954
5	Prt	Portugal	72	33	3676
6	Mar	Morocco	43	29	3525
7	Esh	Western Sahara	1	1	5646
8	Mrt	Mauritania	7	7	12656
9	Sen	Senegal	14	14	4110
10	Gmb	Gambia	3	3	383

*AOI = Area of Interest/The study area

Table 4-28 presents, for each country inside the study area, the number of MPAs along with the area they cover in Km^2. The UK has the highest number of MPAs and the largest MPAs, followed by France and Mauritania.

4.7.3 MPAs by 2° latitude

In the northern part of the study area, the number of MPAs and their coverage rates are higher than those in the southern part (red bars on the map in Figure 4-78a). These are the MPAs created by the developed countries such as UK, Ireland and France. MPAs coverage rates in the middle region, from the coast of Northern Spain to the Morrocan waters, were generally low.

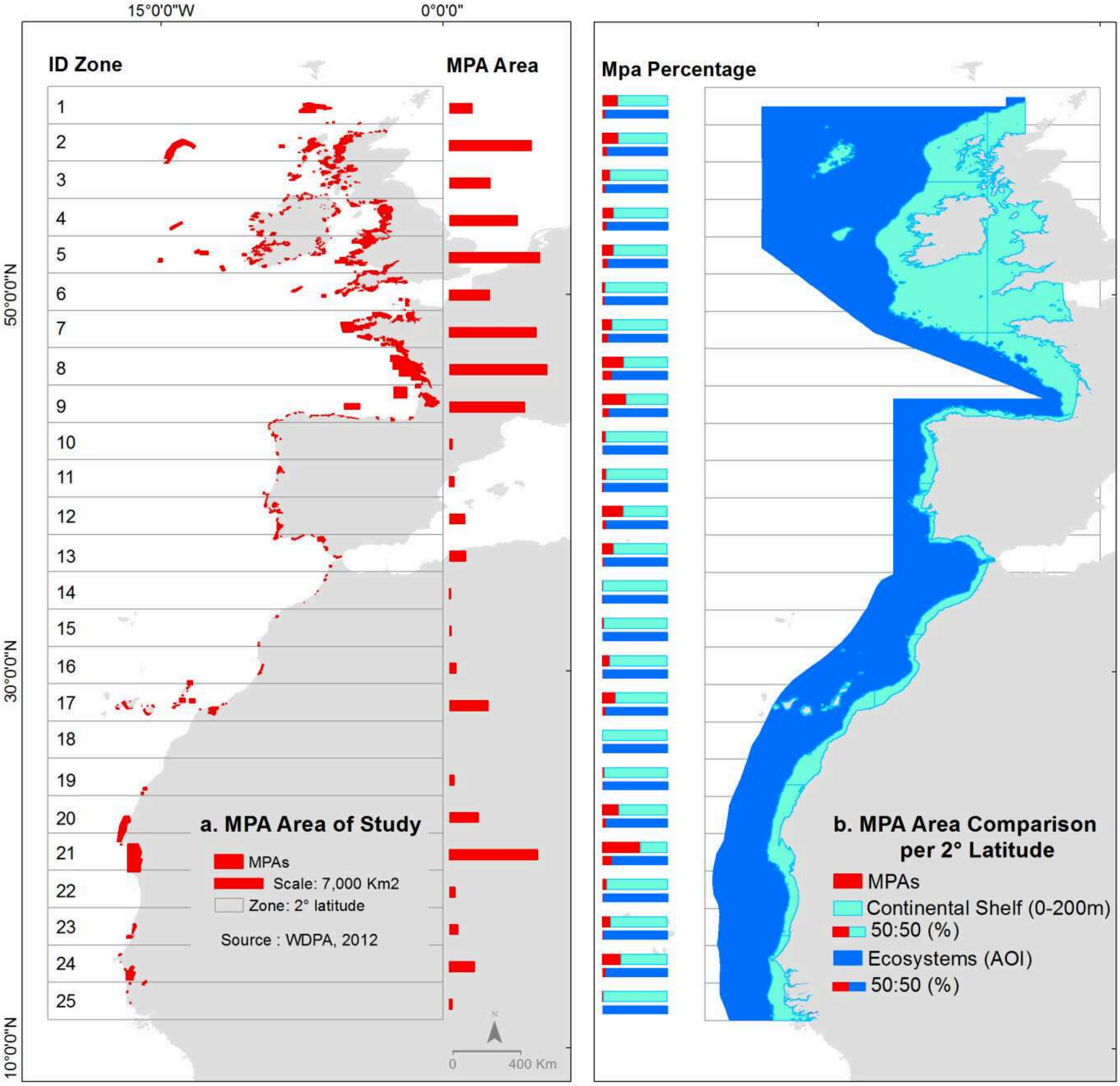


Figure 4-78: MPAs areas by 2° latitude. (a) MPAs areas in Km^2 (red zone on map and red bars); (b) Percentage of the continental shelf areas (light blue zone/bars) and of the ecosystem areas (dark blue zone/bars) covered by MPAs areas (red bars).

In general, MPAs cover less than 25% of the total continental shelf area (Table 4-29). Comparisons between MPAs areas and ecosystems areas showed that less than 15% of the ecosystem areas are covered by MPAs. No MPA was found in the latitude between 28 and 30°N (zone 18) off the Moroccan coast. The lowest MPA coverage rates was found in the zone 14, between 36°N and 38°N, also off the coast of Morocco.

Table 4-29: Areas of MPAs, continental shelf, and ecosystem, along with the percentage covered by MPAs, by 2° latitude.

ID Zone	**Latitude (°N)**	**Continental Shelf (Km^2)**	**Ecosystem (Km^2)**	**MPAs (Km^2)**	**MPAs-Continental Shelf (%)**	**MPAs-Ecosystem (%)**
1	60 - 62	13793	86231	3209	23.2	3.7
2	58 - 60	46804	162809	11700	25	7.1
3	56 - 58	50055	167866	5800	11.5	3.4
4	54 - 56	58757	158836	9709	16.5	6.1
5	54 - 56	74811	163526	12943	17.3	7.9
6	52 - 54	127404	188266	5750	4.5	3
7	50 - 52	81496	143362	12431	15.2	8.6
8	48 - 50	42874	99006	13911	32.4	14
9	46 - 48	29665	108928	10729	36.1	9.8
10	44 - 46	7598	37808	376	4.9	1
11	42 - 44	10853	39282	682	6.2	1.7
12	40 - 42	6833	38318	2180	31.9	5.6
13	38 - 40	13411	91735	2302	17.1	2.5
14	36 - 38	13033	102838	171	1.3	0.1
15	34 - 36	10953	82002	254	2.3	0.3
16	32 - 34	8679	115717	943	10.8	0.8
17	30 - 32	26944	112044	5505	20.4	4.9
18	28 - 30	11785	93311	0	0	0
19	26 - 28	26766	85085	608	2.2	0.7
20	24 - 26	16038	73095	4116	25.6	5.6
21	22 - 24	21612	86012	12658	58.5	14.7
22	20 - 22	11478	101238	751	6.5	0.7
23	18 - 20	9970	90485	1249	12.5	1.3
24	16 - 18	12549	79082	3593	28.6	4.5
25	14 - 16	24800	87608	427	1.7	0.4

4.7.4 Assessing MPA's localization

This section shows the results of MPA localisation assessment in relation to the seasonal movement of hotspot area. The hotspot area assessed is the zone suitable for at least 30 species (see again section 4.6).

We present the cases of selected MPAs in four countries: Ireland, France, Portugal and Mauritania. We considered that the geographical situation of these countries was representative enough to study the effects of climate change on species or hotspots distribution.

Figure 4-79, Figure 4-80, Figure 4-81, and Figure 4-82 present the results of MPAs analysis in the four selected countries. Each figure contains two bar charts that present the intersect analysis between the hotspot zone and the MPAs for each season during 32 years of observation (from 1982 to 2013). The first bar chart (on the left side) presents the frequency of intersection between the MPAs and the hotspot zone. The second bar chart (on the right side) presents the mean MPAs areas intersected by the hotspot zone.

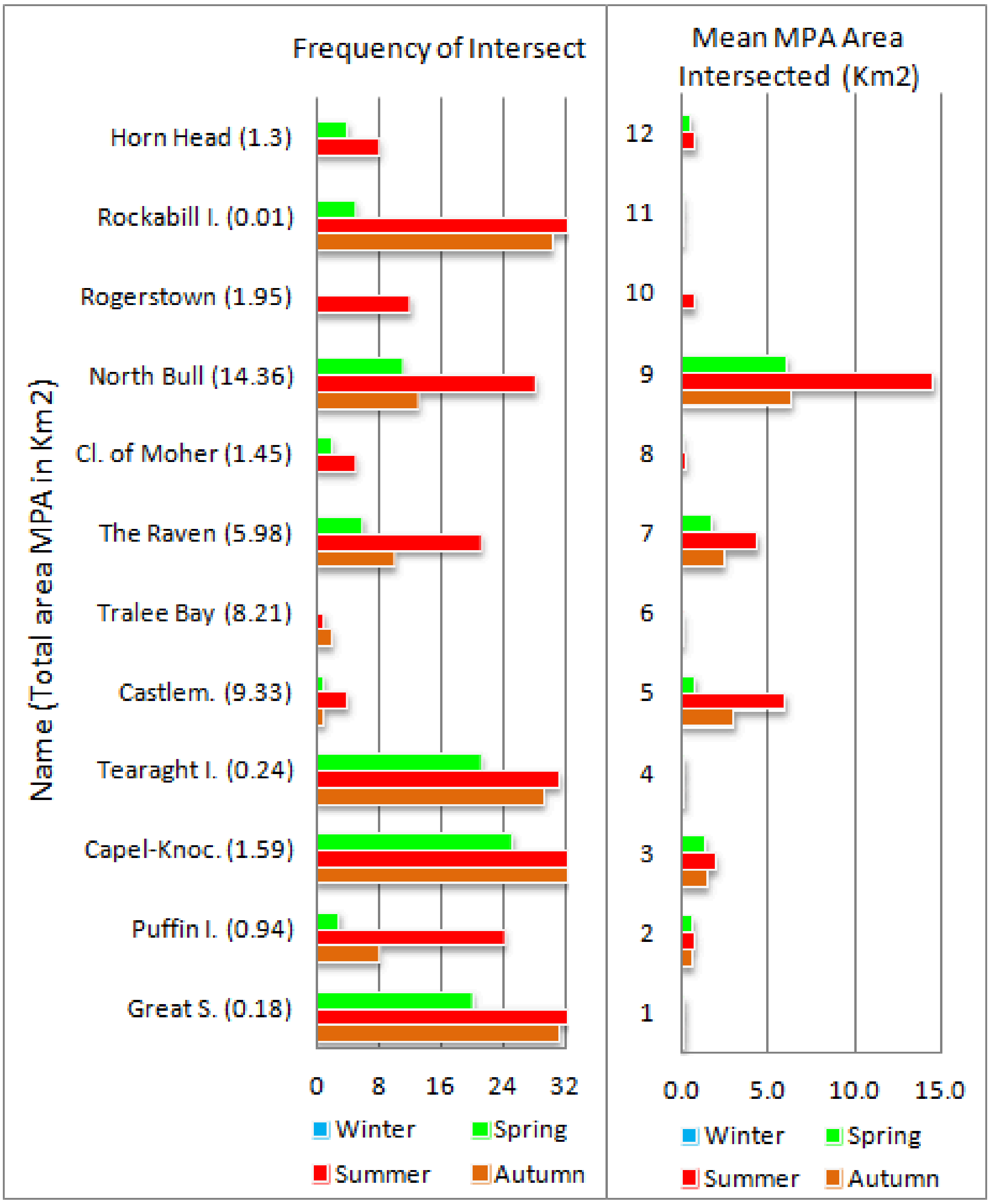


Figure 4-79: MPAs in Ireland. Y-axis presents the selected MPAs in this country along with their areas in parenthesis (Km^2). The bar charts on the left side present the frequency at which each MPA intersected the hotspot zone per season. X-axis represents the number of years observed from 1982 to 2013 (32 years in total). The bar charts on the right side present the mean MPA area intersecting the hotspot zone per season (in Km^2) during the 32 years studied.

Figure 4-79 shows that four MPAs in Ireland waters can be considered as more important than the others regarding their intersection with the hotspot zones: Tearaght I., Great S., Rockabill I., and Capel-Knoc. These MPAs were always intersecting the hotspot zone in summer (bars in red). They were less frequently intersecting during autumn (bars in orange), spring (bars in green) and winter (bars in blue).

In terms of areas intersected, only two or three MPAs have more area intersecting with the hotspot zones than the others: North Bull, Castlem, and The Raven (Bar chart on the right side of the Figure 4-79). The surface and location of these MPAs are thus more important.

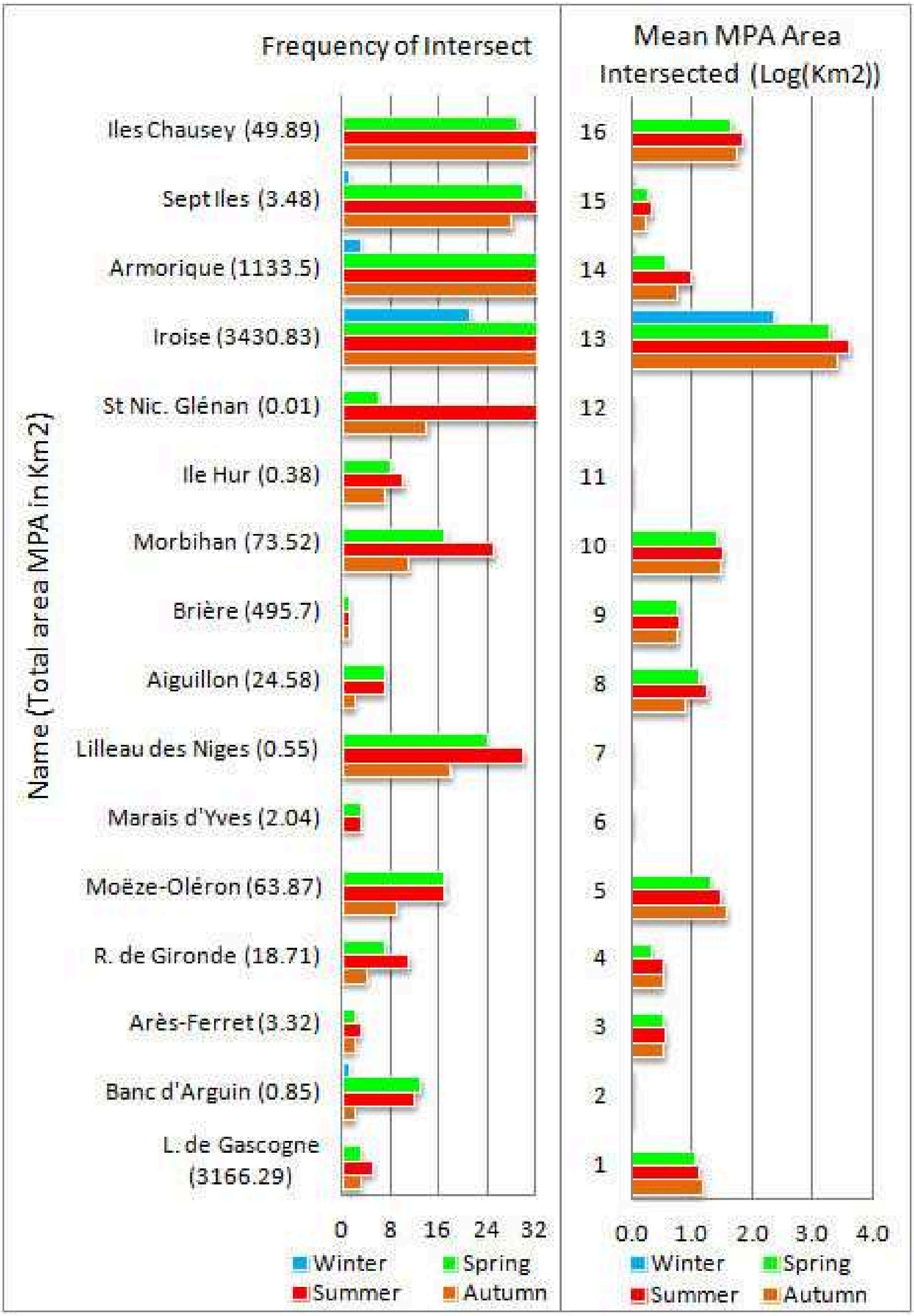


Figure 4-80: MPAs area analysis in France. See legend in the Figure 4-79.

Figure 4-80 shows the MPAs area analysis in France waters. The Iroise is the most judiciously situated of the French MPAs in terms of frequency of intersection and mean area intersecting the hotspot zones. The Iroise was always intersecting the hotspot zone almost every season. The surface area intersected was also higher than for the other MPAs.

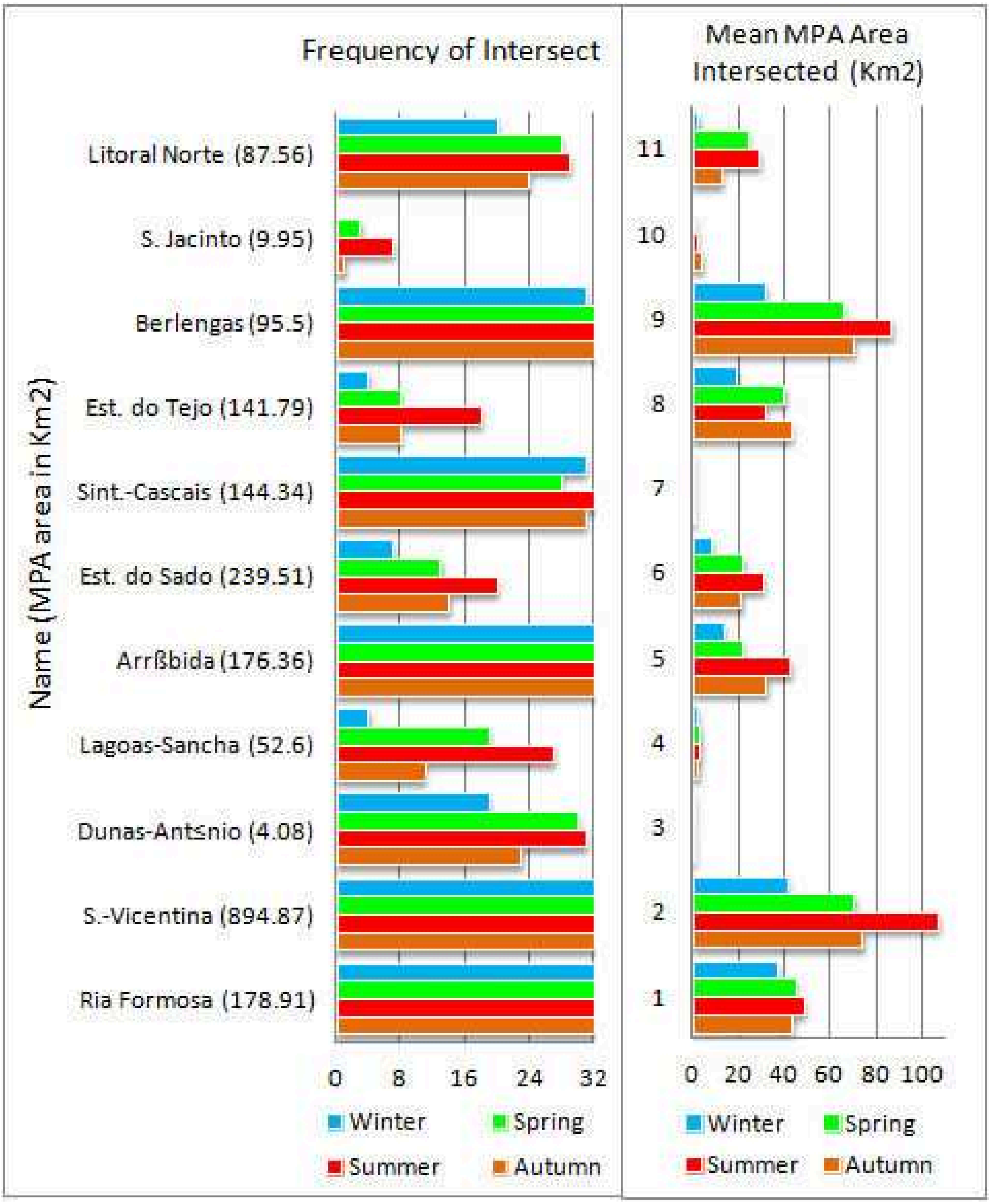


Figure 4-81: MPAs area analysis in Portugal. See legend in the Figure 4-79.

In the coast of Portugal, the localisations of MPAs off this coast are very well-chosen since all MPAs studied were always intersected by the hotspot zone in all seasons except for the Esposende (Figure 4-81). The MPAs areas intersected were also high. In several MPAs, such as in S. Jasinto, the areas of intersection were small due to the small total surface area of the MPA.

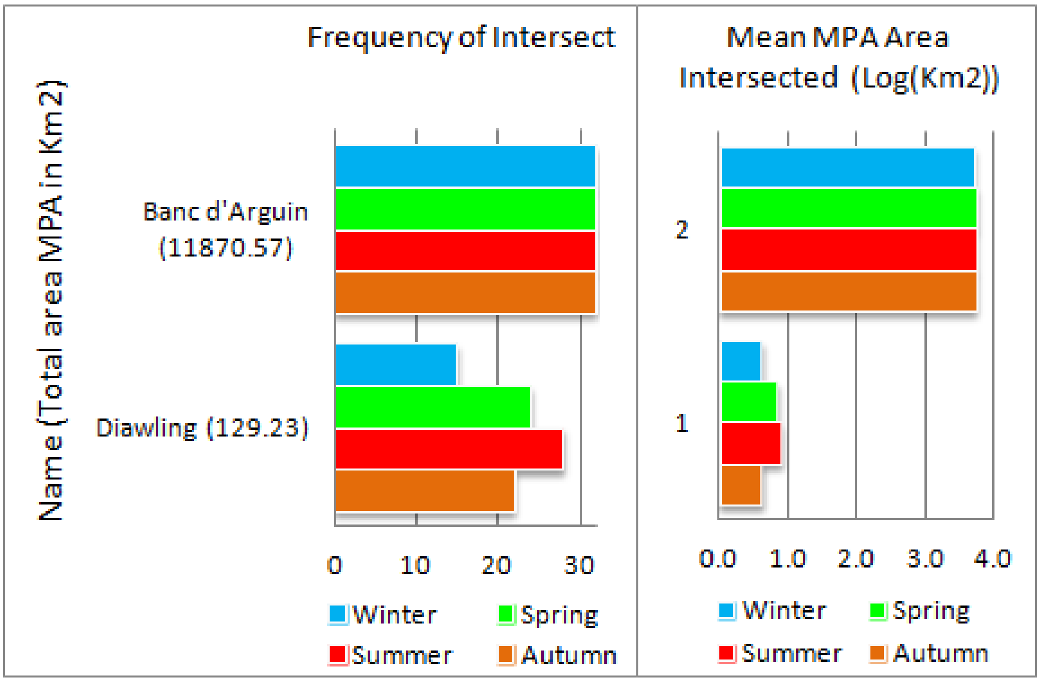


Figure 4-82: MPAs area analysis in Mauritania. See legend in the Figure 4-79.

Figure 4-82 present the MPAs areas analysis in Mauritanian waters. There are only two MPAs selected in these waters (MPAs of IUCN category): the Banc d'Arguin and Diawling. The Banc d'Arguin always intersected the hotspot zone in every season. The mean areas intersected were always similar for each season. This MPA location is more adequate than the Diawling's which intersects less and less often with the hotspot zone.

4.7.5 Discussion: MPA and climate change

A protected area is a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve long-term conservation of nature with its associated ecosystem services and cultural values (Day et al. 2012). Regarding the conservation effort, a question that arises in many situations is which areas of ecological transition are most likely to promote adaptative responses to the climate change (Araujo 2002). This is the challenge of large-scale extinctions (Myers et al. 2000). These transitional zones depend on time period.

The hotspots approach to species preservation at local scale is risky (Smith et al. 2001), while Continental or national scale need to be prioritized. Nevertheless, the areas within the core of many species ranges or the nontransition zones might play a fundamental role (Araujo 2002).

The hotspots of today are unlikely to be the hotspots of tomorrow (Smith et al. 2001). Adaptative variation across environments requires attention to preserve the evolutionary response to environmental and climate change (Smith et al. 2001).

MPAs areas analyses show that the hotspot distribution was also strongly influenced by seasonal variation. Accounting for ecological transition zones is required. Thus, seasonal variation should be considered in conservation effort as well. This could preserve species adaptative variation across environmental changes.

It may be easier to observe climate change effects in protected areas, as they are normally better shielded from anthropogenic impacts than other areas, and therefore likely to be subject to less interference from other causes of change. In this regard, MPAs such as in the Portuguese waters can play an important role as 'sentinel sites', where the effects of climate change can be studied and management strategies can be developed to adapt to, and wherever possible counter, such negative effects (Otero et al. 2013). Individual MPAs and MPA networks in the coastal areas of east Atlantic waters have an important role to play in enhancing our understanding and helping to develop strategies to mitigate climate change effects.

Otero, Garrabou, & Vargas (2013) stated that global changes should be understood as those which affect the whole planet, but not necessarily in the same way everywhere. Nor should mean changes averaged for the world's oceans be confused with specific changes operating on smaller spatial scales.

Climate change is often not explicitly incorporated in most MPA management plans and future assessment of MPA performance will need to take these effects into account (Otero et al. 2013). The assessment of climate change effects on marine biodiversity is also necessary to support adaptation planning in protected areas of conservation value and provide the evidence required to justify investment in mitigation and adaptation measures.

This study demonstrates that MPA monitoring in relation with climate change does not require expensive equipment or highly technical abilities. However, it could help managers understand the vulnerabilities and the importance of different sites. Furthermore, it could help in revising MPA zoning. Monitoring actions in MPA management plans and to link with existing environmental change could be effectively undertaken across the study area.

Our study can provide valuable baseline information to asses not only climate change effects on species biodiversity, but also the localisation of marine protected areas. The impact risks depend on the areas and period, thus this study provide information for allocating efforts to areas that are expected to suffer the most.

4.8 Projected species distribution

Our study could have many applications in conservation. The flexibility of the GIS technique used in this study allows us to keep on working with the current technique of species distribution modelling for future projection. The future models of species distribution are built by projecting the species ecological niches on the projected SST models from the CMIP experiment and the other environmental parameters are taken into account.

The CMIP (Coupled Model Intercomparison Project) is a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs). One of the objectives of this protocol is to facilitate coordination among climate change experiments. The project provides a community-based infrastructure in support of climate model diagnosis, validation or intercomparison. This project will enable a diverse community of scientists to analyse general circulation models in a systematic way and facilitate model improvement. The model used in this work is a CMIP5. Futher info on CMIP is available on the CMIP website, http://cmip-pcmdi.llnl.gov.

The fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) is based on the CMIP phase 3 (CMIP3). The AR4 contains climate model outputs, from simulations of the past, present and future climate, collected mostly during the years 2005 and 2006. The new set of coordinated climate model experiments is introduced in the AR5. The AR5 comprises the fifth phase of the CMIP, or CMIP5. Three objectives of the CMIP5 were to promote a standard set of model simulations to assess how realistic the models are in simulating the recent past, to provide projections of future climate change on two time scales: near (2035) and long-term (2100 and beyond), and to understand some of the factors responsible for differences in model projection. The CMIP5 experiment gathers results of several coupled models with different scenarios. These models showed a similar global trend (Dessert et al. 2015). However, many discrepancies exist due to different sum-model components.

Table 4-30: Official model names of CMIP3 and CMIP5 per modelling centers. The "-" stands for model (or necessary data) not available.

No	Modelling center	CMIP3		CMIP5	
		Model	Run length (years)	Model	Run length (years)
1	IPSL	IPSL-CM4	500	IPSL-CM51-MR	300
2	GFDL	GFDL2.0 GFDL2.1	500	GFDL-ESM2G	500
3	NCC	-	-	NorESM1-ME	252
4	MPI	ECHAM5/MPI-OM	506	MPI-ESM-MR	1000
5	MIROC	MIROC3.2 MR MIROC3.2 HR	500 100	MIROC-ESM	531

In this section, we present the models of species future distribution using two projected SST models: a control model (CTL) and an IPSL model (Table 4-30 and Figure 4-83). The two SST models were produced by Dessert et al. (2015) from the *Institut Universitaire Européen de la Mer* (IUEM). These models simulate the biogeochemical state of the future ocean (to 2100). The atmospheric forcing sets of these models were built from the realistic atmospheric reanalysis products following trends identified in atmospheric outputs of some CMIP5 simulations. Detailed information is available in Dessert et al. (2015).

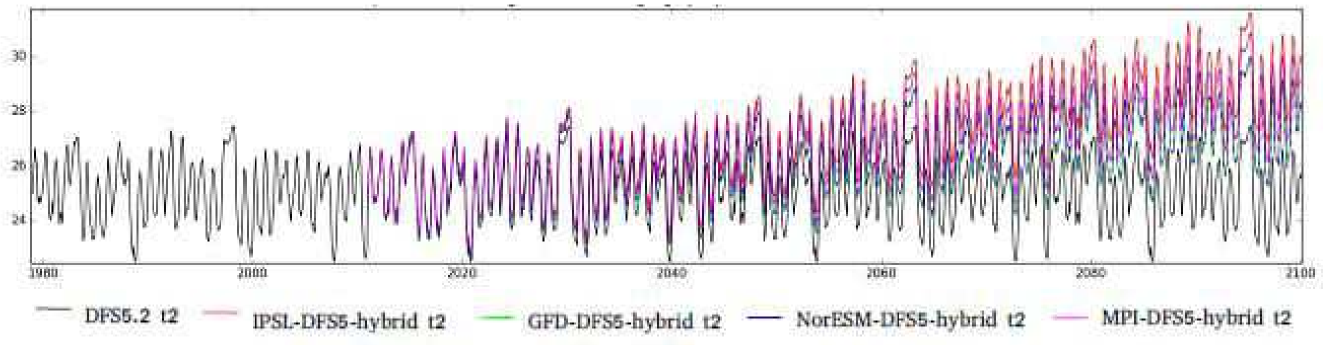


Figure 4-83: Air temperature at 2 m averaged for different forcing products on El Nino3.4 box (21° to 270° longitude and -5° to 5° latitude), computed with long long-term trends and observation (Dessert et al. 2015).

Two species were selected in this study: *Arnoglossus thori* and *Myctotum punctatum*. The results of the species future distribution models will be compared with the models of the recent periods. The periods investigated are 1990-1999, 2000-2009, 2050-2059, and 2090-2099. These periods of ten years were determined following the decadal variability of the SST in the study area (see again Figure 4-4, Figure 4-6, and Figure 4-8).

The projected SST models of the CTL and IPSL are in a monthly raster. These raster were selected according to the ten years periods determined previously. Combining or mosaicing monthly rasters for ten years periods was conducted by season resulting a single raster of mean ten years climatology. In each decadal period, four rasters, one for each season resulted from this process.

a. Period I: 1990-1999 = SST climatology rasters (ten years) of each season.
b. Period II: 2000-2009 = SST climatology rasters (ten years) of each season.
c. Period III: 2050-2059 = SST climatology rasters (ten years) of each season.
d. Period IV: 2090-2099 = SST climatology rasters (ten years) of each season.

The resulting rasters were incorporated for modelling future species distribution using the technique developed in this study (see Chapter 3.6). The analysis of this work will be focussed on the movement of the species most preferred zone (the Class-1). The distance of the northernmost point of this zone among periods will be measured (see flowchart in Figure 4-84).

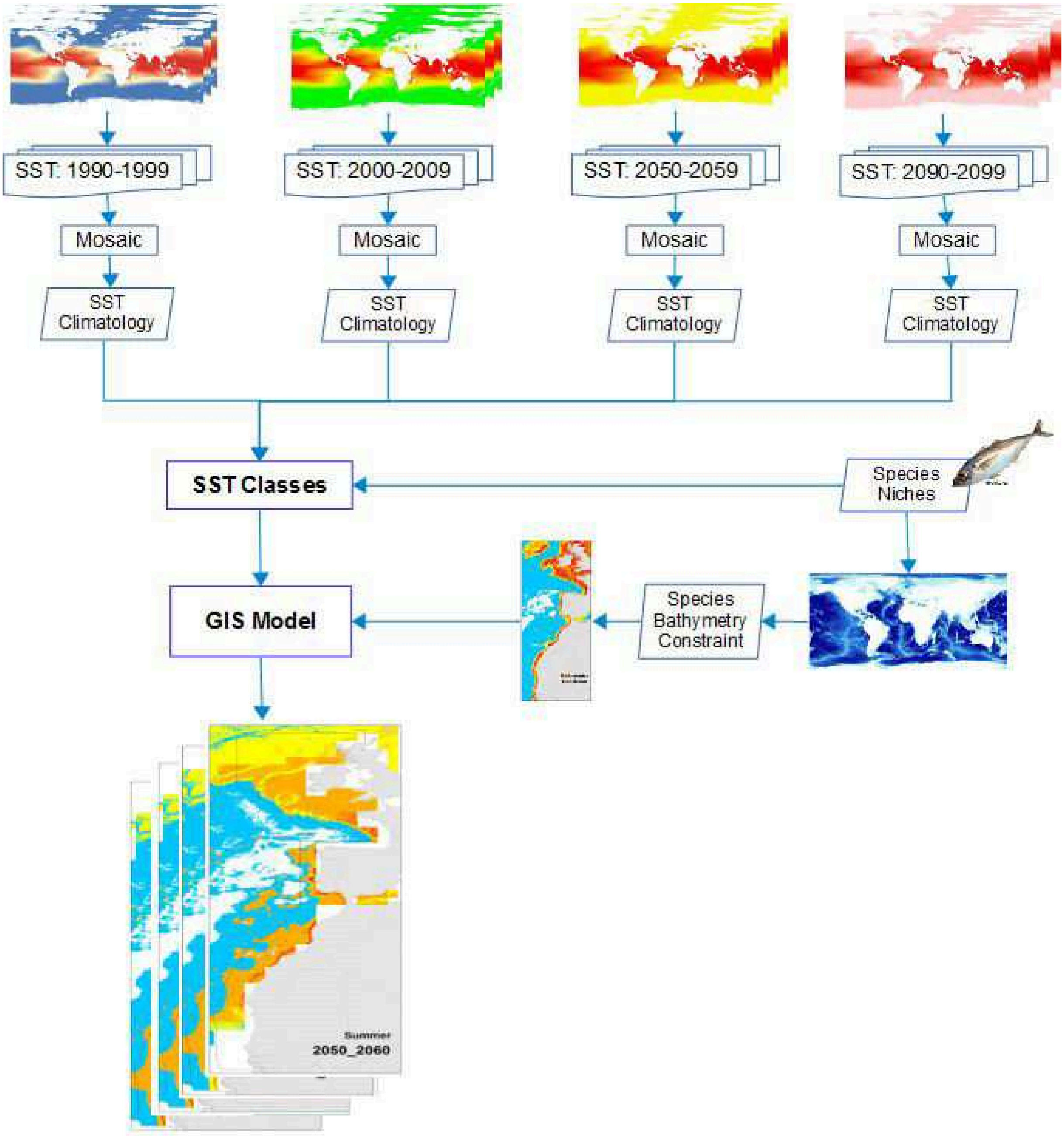


Figure 4-84: Flowchart of modeling future species distribution.

4.8.1 *Arnoglossus thori*

The potential future distributions of *A. thori* in summer of each studied period are presented in Figure 4-85. The figure is composed of five maps presenting the distribution of the species in Period II, III and IV. Map of the Period I is not showed in this section to ensure the clearness of visual presentation. Nevertheless, the values of the upper and lower limit of the species most preferred zone in each period are given in Table 4-32. The maps show potential distributions of *A. thori* in four preferential classes: the most preferred zone (Class-1/red areas), the preferred zone (Class-2/orange areas), the less preferred zone (Class-3/yellow areas) and the extreme zone for the species (Class-3/blue areas).

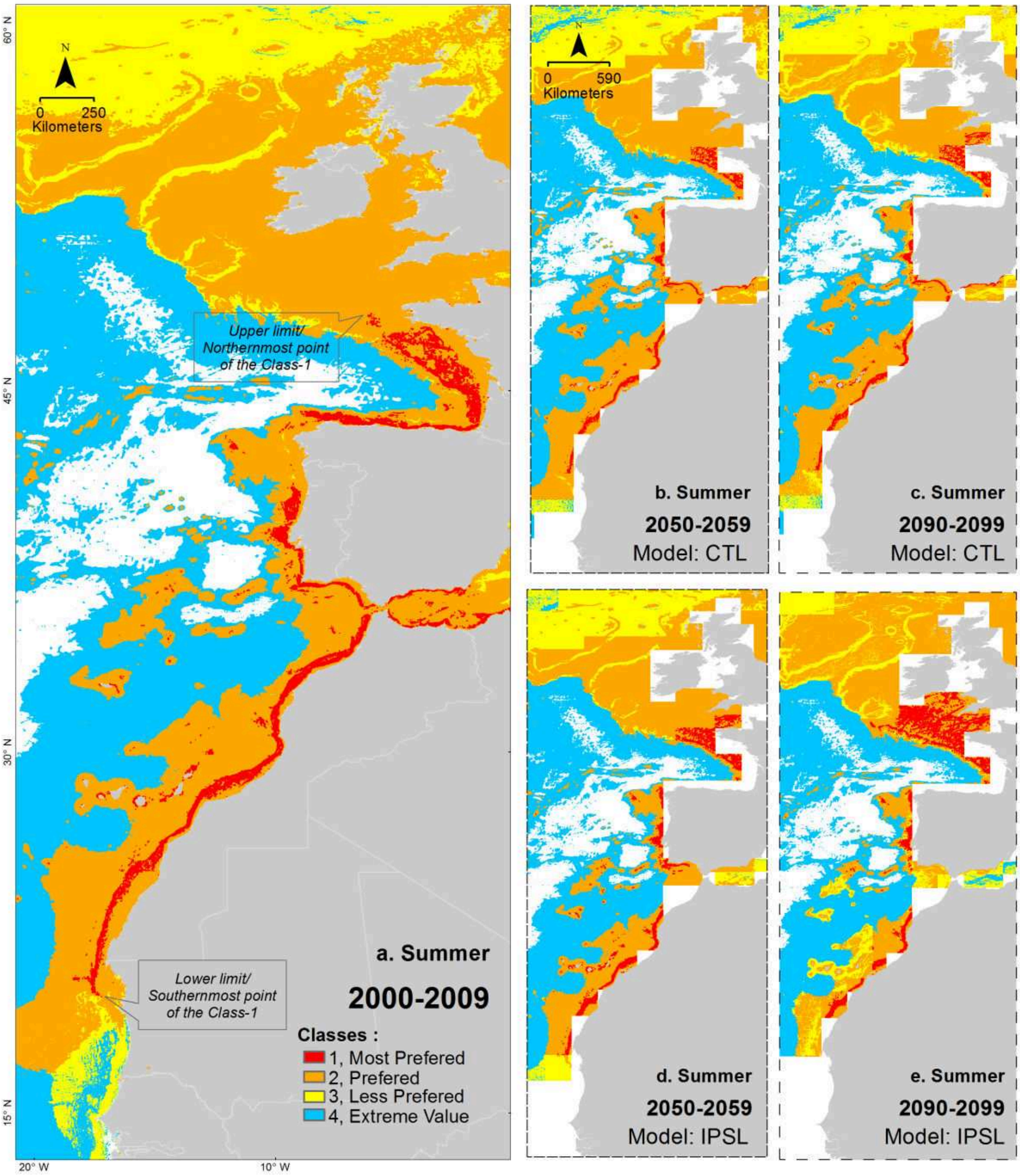


Figure 4-85: *A. thori* potential distribution in summer; a) Distribution in recent years (2000-2009). Distributions from CTL SST model are presented in (b) 2050-2059 and, in (c) 2090-2099; Distribution for (d) 2050-2059 and for (e) 2090-2099 using IPSL SST model.

The future distribution of this species, predicted using the SST CTL model, shows a slight northwards movement of the most preferred zone over time (2050-2059 & 2090-2099), towards the English Channel (Figure 4-85b and Figure 4-85c). The future distribution predicted using the SST IPSL model in the same periods shows a movement further north that reaches the coast of Ireland (Figure 4-85d and Figure 4-85e).

The northernmost point of *A. thori*'s most preferred zone (the Class-1) resulting from the SST CTL model moved from 50.59 °N (2000-2009) to 48.72 °N (2050-2059) in summer and to 49.83 °N in the last period (2090-2099). This movement is more evident with the SST IPSL model, where the northernmost point of the Class-1 moved from 50.59 °N (2000-2009) to 49.83 °N (2050-2059) and to 52.08 °N in the last period (2090-2099). Detailed latitude values of the northernmost point of the Class-1 for all seasons are available in Table 4-32; see also Figure 4-86.

Table 4-31: Evolution of the northermost and southernmost limit (°N) of the *A. thori*'s most preferred zone (the Class-1), by season.

No	**Season**	**Period**					
		1990-1999	2000-2009	**CTL Model**		**IPSL Model**	
				2050-2059	2090-2099	2050-2059	2090-2099
1.	Northernmost limit (°N)						
	winter	31.18	33.03	32.85	32.99	36.32	37.48
	spring	44.15	44.15	37.48	37.48	39.72	43.10
	summer	47.63	50.59	48.72	49.83	49.83	52.08
	autumn	43.72	43.58	39.72	39.72	41.34	45.34
2.	Southernmost limit (°N)						
	winter	11.02	11.02	11.65	12.77	15.02	19.52
	spring	11.02	11.22	15.02	15.02	19.52	19.52
	summer	18.59	19.82	20.63	20.63	20.63	24.01
	autumn	15.68	14.70	19.52	19.52	20.63	24.01

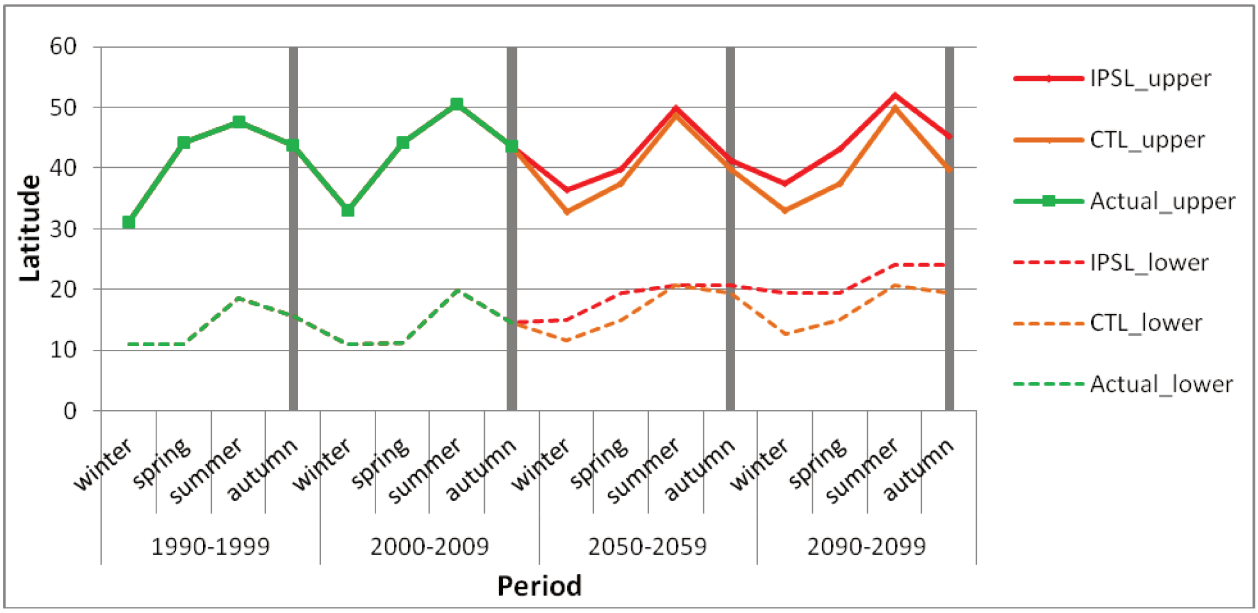


Figure 4-86: Seasonal evolution of the northernmost-point of the preferred zone (the Class-1) of *A. thori*, by ten-year periods. Upper is the upper/northernmost limit of the Class-1. Lower is the lower/southernmost limit of the Class-1.

4.8.2 *Myctotum punctatum*

The future distributions of *M. punctatum* in summer are presented in Figure 4-87. The figure is arranged similarly to that of *A. thori*, composed by five maps of the species summer distributions for the Period II, III, and IV. The values of the upper and lower limit of the species most preferred zone in each season and period are given in Table 4-32.

Figure 4-87 presents the distribution of *M. punctatum* in summer from the period 2000-2009 to 2050-2059 and 2090-2099. The figures show the northwards movement of the species' preferred zone. Distribution with CTL model shows that the northernmostpoint of the preferred zone moved from 54.63 °N to 55.45 °N and 61.01 °N. The IPSL model presents a strong movement further north of the species' preferred zone, from 54.63 °N to 54.32 °N and 55.45 °N (Table 4-32 and Figure 4-88).

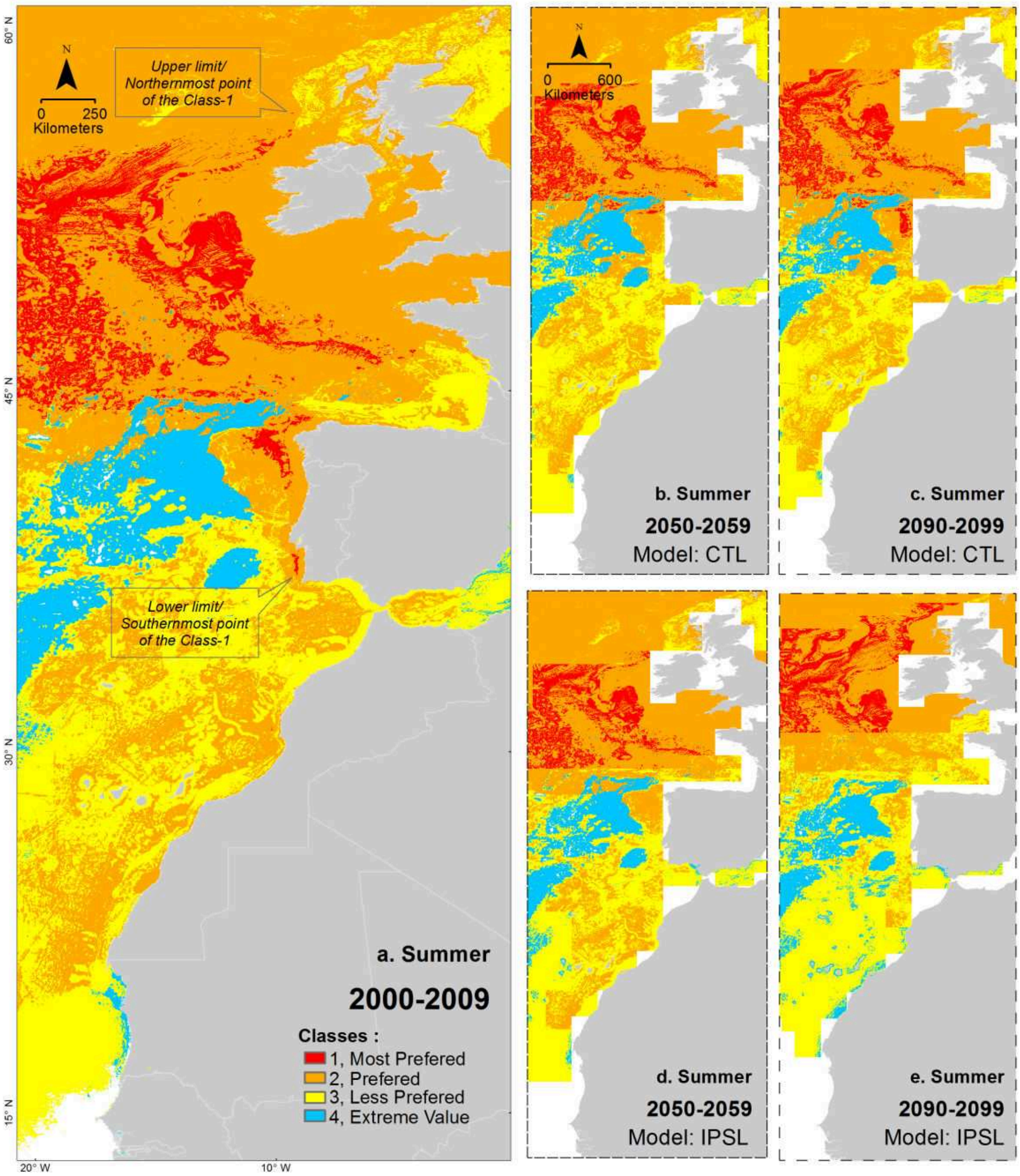


Figure 4-87: *M. punctatum* potential distribution in summer; a) Distribution in recent years (2000-2009). CTL model: distribution in (b) 2050-2059, and in (c) 2090-2099; IPSL model for (d) 2050-2059, and (e) 2090-2099.

Table 4-32: Evolution of the upper/northernmostand lower/southernmost limit of the *M. punctatum* most preferred zone (the Class-1), by season.

No	Season	Periods					
				CTL Model		IPSL Model	
		1990-1999	2000-2009	2050-2059	2090-2099	2050-2059	2090-2099
1.	Northermost limit (°N)						
	winter	41.25	41.57	45.34	48.72	43.1	43.1
	spring	46.55	46.97	47.59	50.96	46.47	46.47
	summer	54.63	56.52	55.45	61.01	54.32	55.45
	autumn	49.07	49.84	49.83	54.32	48.72	48.72
2.	Southernmost limit (°N)						
	winter	15.26	16.44	24.01	26.25	29.62	35.27
	spring	18.02	18.73	32.99	32.99	36.36	39.72
	summer	29.87	30.88	43.1	40.85	45.34	48.72
	autumn	30.53	30.20	36.36	35.32	37.49	40.85

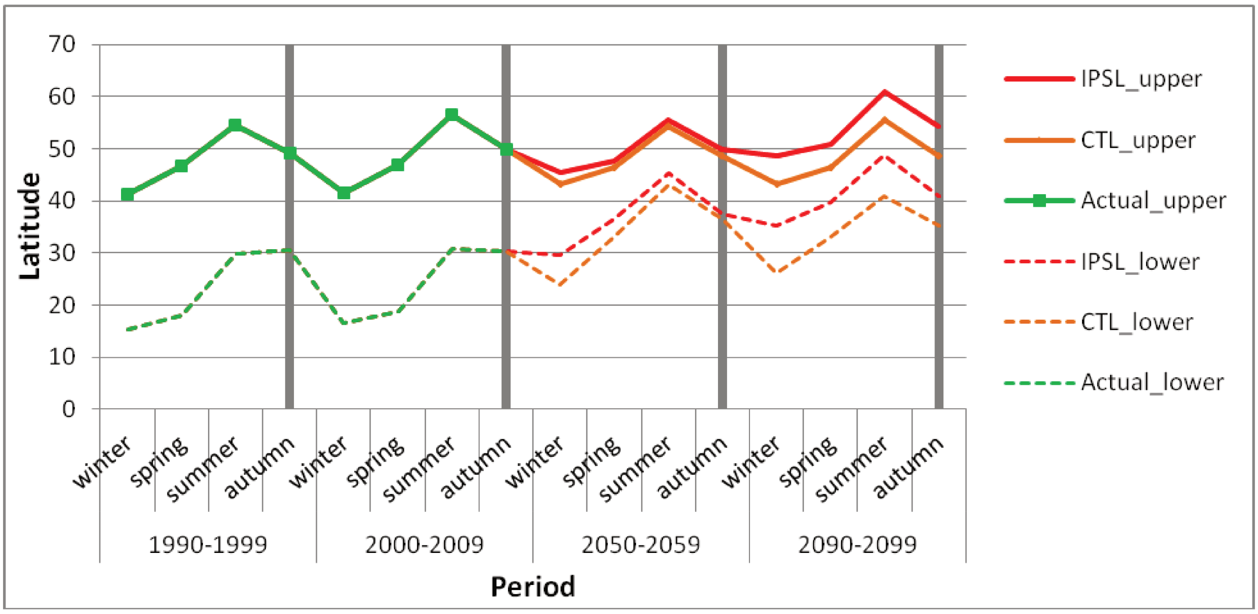


Figure 4-88: Seasonal evolution of northernmost-point of the preferred zone (the Class-1) of *M. punctatum*. Upper is the upper limit of the Class-1. Lower is the lower limit of the Class-1.

4.8.3 Discussion

Climate models attempt to simulate long-term change in the mean state of the ocean, over 50 to 100 years. Nicol et al. (2014) stated that the most advanced forecast climate models are the models that assimilate past observational data to capture historical conditions during the initialization. They mentioned that this inclusion has been completed for the IPSL and GFDL models.

A variability of prediction, discrepancies and uncertainties exist among the models. These impact the model of species distribution. The SST model of IPSL predicts a stronger increase of temperature than the CTL model (Figure 4-83). Unfortunately, these issues will not be discussed in this section because the subject is beyond the scope of this study.

Many assumptions and approximations were made in modelling, for both climate models and species distribution models, especially when projecting the shift of distribution over time. Synergistic effects between species, or anthropogenic factors such as fishing, are difficult to incorporate in modelling processes. The effect of ocean chemistry was also not incorporated. However, despite these uncertainties, our models agree with the results of other studies. This study can also be considered as the null hypothesis for future similar studies.

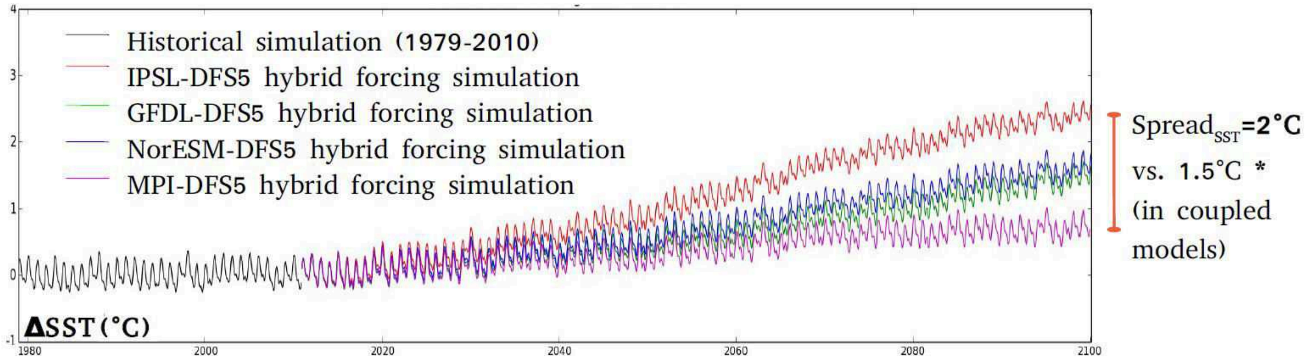


Figure 4-89: SST evolution in the coupled models and the forced simulation (Dessert et al. 2015).

The results of this study showed that the increase of temperature may lead the southern warm water species to migrate northwards. This phenomenon could potentially change the local species composition. Hiddink and Hofstede (2008) mentioned that the increase of fish species richness in the North Sea in the recent years was related to large-scale biogeographical patterns and climate change.

Marine species may have higher dispersal ability than terrestrial organisms, allowing them to find suitable habitats more easily as climate change. This study shows how temperature determines the past and future distribution of a species. This phenomenon may increase the negative impact of human disturbances on marine organisms. Bathymetry derivatives present how these distributions are limited by the availability of suitable habitats. Other informations from other studies show how geographical conditions may influence the intensity of climate change effects on species distribution.

Finally, availability of all environmental data or fishing pressure data at the scale of the area of study is scarce, especially when working with seasonal models that require consistent measurement over time. These data are considered to have important effects on species distribution, and are thus, promising for the next studies.

5 GENERAL DISCUSSION AND CONCLUSION

Our area of interest (AOI) encompasses a large range of climatic conditions. This area covers three linked large marine ecosystems: the Canary Current, the South European Atlantic Shelf and the Celtic Seas (Figure 4-1). The zoogeographic location of these latitudinal zones, especially the region in the central is important for studies of climate change effects on marine organisms: many species have their southern or northern distribution limits in this middle region. Thus, the AOI sensitivity for climate change studies is great.

The study area was extended to three adjacent ecosystems when working on species movement: the North Sea, the Western Mediterranean Sea, and the Guinea Current, because many studied species share their area of distribution with these adjacent ecosystems (Figure 4-1). The closeness among ecosystems was confirmed by the *Jaccard* similarity analysis conducted in this study (Figure 4-11).

The number of studied species varies by latitude. In the northern region, the number of species is generally lower than that in the southern region despite the large continental shelf area available or the higher number of scientific studies conducted in this region (Figure 4-13). It is well known that the tropical area is often more specious than the temperate area, but the cause is still under debate. Many factors influence the distribution of species and not merely the latitudinal variability. Temperature which is the main forcing factor analysed in this study, as well as the combined factors of over-exploitation, habitat loss, or physical and oceanographic conditions may lead to fish migrations and foster changes in species composition.

SST trends

The ongoing global climate change and its impacts on marine organisms have been extensively observed and broadly documented (Poloczanska et al. 2013). In the study area, the magnitude and trends of SST change differ among ecosystems, although all showed a consistent SST increase over time. The bathymetric conditions in the study area also vary across latitudinal areas. Thus, the impact of climate change on a marine organism differ geographically and seasonally following the natural geographic variations across these ranges of biogeographical scales, as well as temporal scales. These impacts are reflected by changes in the distribution patterns of marine species.

Increasing SST trends were observed in the three ecosystems studied as mentioned previously. It appeared clearly in the Celtic Seas (Figure 4-4) and Canary Current (Figure 4-6), by 0.85 °C, and 0.87°C respectively during the study period. The SST increased slightly over time in the South European Atlantic Shelf (Figure 4-8), by 0.55°C.

Temperature is one of the main drivers and a good proxy of the ecological niche, due to its crucial role in almost all aspect of the biochemistry, physiology and behaviour of a fish (Helaouët and Beaugrand, 2009; Fry, 1947). This parameter correlates well with other factors, such as oxygen and nutrient concentration and to a lesser extent chlorophyll concentration (Helaouët and Beaugrand 2009).

The vast majority of fish species do not have the ability to regulate their body temperature, and because there exists a range of temperature below or above which a given species cannot survive, their capability to avoid or select environmental temperature is one of the more critical components of their behavioural repertoire (Fry 1947). The rise in sea temperature could then cause physiological stress for marine species, especially for species already close to their tolerance limit (Occhipinti-Ambrogi 2007). Each species may have a temporal or seasonal niche that causes differences in growth rate, patterns of mortality, timing, duration and magnitude of reproductive output (Occhipinti-Ambrogi 2007). The fastest warming rate in winter and spring might bring forward physiological events, such as the start of growing seasons and the timing of reproduction (Poloczanska et al. 2013). Therefore, climate change is considered one of the major drivers of biodiversity change (Otero et al. 2013).

Species distributions

While the sea surface temperature increased consistently over time in all observed ecosystems, the changes in the number of species differed among ecosystems (Figure 4-12). The number of species in the middle regions, such as the South European Atlantic Shelf and the Western Mediterranean Sea, tended to increase over time. These regions received many species from the lower or the upper latitudes according to season.

The results of our study present the effect of climate change on fish species distributions. It confirms and shows how species respond to climate change by shifting their area of distribution and increasing their depth range. Many southern species extended their area of distribution into the middle region of the South European Atlantic Shelf and the Western Mediterranean Sea (Figure 4-14), highlighting the importance of these areas as a transition zones. Among the species studied, at least 7 species from the Canary Current tended to be found in the Western Mediterranean Sea, and 6 species from these two regions extended their area of distribution to the South European Atlantic Shelf when the temperature become suitable. As for the northern species, the responses to the environmental changes noticeable through the extension of their depth area range (see Figure 4-18 and Figure 4-19 for the case of *A. tobianus*). Other species move among ecosystems according to seasons.

Observational studies mentioned that the presence of tropical species in Atlantic European waters has been reported since the 1960s (Quero et al. 1997) with rapid increase in number and biomasse over time (Bañón 2004), and was predicted to be more rapid in the 21st century (Fernandes et al. 2013).

The common characteristics among marine organisms, such as high rates of propagule production and dispersal by ocean currents, might lead to faster expansions in distribution than those observed for plants and animals on land (Poloczanska et al. 2013). Sorte et al. (2010) stated that the rate of leading-edge expansions from 1960 to 2009 in highly mobile or dispersive pelagic organisms were 469.9±115.3 km·dec^{-1} for phytoplankton, 277.5±76.9 km· dec^{-1} for bony fish, and 142.1± 27.8 km-·dec^{-1} for invertebrate zooplankton. Poloczanska et al. (2013) added that the variation in individual species responses to environmental changes in a community are probably the result of interacting factors, such as population size, dispersal capability, dependence on habitat or prey availability, resource competition, migratory strategy, latitudinal gradient of light regime and fisheries impacts. Hence, the impacts of climate change on shifting species movement also vary depending on the biological characteristics and the sensitivity of the species.

Physical Barriers for species distribution

Demersal fish distributions are strongly influenced by seafloor characteristics, such as depth (Moore et al. 2011) and benthic characteristics. For shallow waters, the benthic characteristics could also influence the water column where the pelagic species live. In the Celtic Seas, the region is dominated by flat areas and the ruggedness of the terrain is higher near the coast. The other two ecosystems have less flat areas than the Celtic Seas and their ruggedness is also higher near the coast. Several studies associate ruggedness with high biodiversity (Wright 2011; Wright et al. 2013).

Terrain features and oceanographic processes may promote species movement. At the same time, they may also act as potential barriers for dispersal and survival of fish eggs and larval stages. Coastal embayments may have a role in eggs and larvae retention, because they can be effective at retaining water and reducing alongshore flow (e.g., Monteiro and Largier, 1999). Mason et al. (2005) explained in detail that a shallow bottom and coastline irregularities slow the flows alongshore. He also added that in the proximity of solid coastal walls, the cross-shore flows are inhibited. These weak currents are associated with a weak dispersion of propagules such as fish eggs and larvae, whose tendency for near-shore retention engenders what is called “sticky water” by Wolanski (1994). Some physical features such as front and eddies, in certain study areas may also act as potential barriers to planktonic dispersal and adult migration (Mason et al. 2005).

The topographic features on the seabed often play an important role in the formation of several physical phenomena, including upwelling zones. The South European Atlantic Shelf is dominated by slope and crest terrain. It has also the smallest flat area among the studied ecosystems. The terrain conditions in this ecosystem could become one of the barriers to northward migration for southern species. Many submarine canyons were found in this area. However, Mason et al. (2005) mentioned that the complicated topography of this ecosystem which has a strong meridional orientation is favourable for a number of upwelling processes that extend offshore from capes and headlands in this area. Upwelling-related circulations redistribute nutrients. Thus, they enhance primary production in the region where they occur and affect high trophic levels through food chain-related processes (Stequert and Marsac 1991).

The presence of capes or promontories is often associated with intensified coastal upwellings. Therefore, these features may have an impact on the life cycles of various fish species for which retention of eggs and larvae are important (Mason et al. 2005). An upwelling situation that transports particles away from the coast could be a source of dispersion (Stequert and Marsac 1991), as it can bring along passive particles such as eggs and larvae. However, a persistent upwelling could become a significant boundary for fish populations: The upwelling front may act as a barrier, retaining propagules near the coast (Mason et al. 2005).

Fishing pressure

Fishing activities may influence species distribution through bottom-up, top-down or wasp-waist controls (Cury 2000). These activities could remove or reduce the regional abundance of predators, allowing the population of the less predated species to increase, which furthermore could lead to the geographic expansion of these less exploited species (Summerson, Darbyshire, and Lawrence 2007; Garrison and Jason, 2000; Martins et al. 2012). High fishing pressure on small pelagic fish, as observed in the Canary Current can also lead to a reduced abundance of the higher trophic levels (Heileman and Tanstad 2008). Although fishing activities could be important in determining species distribution patterns, in this study, fishing effects were not considered as the major driver for species migrations. For instance, the increasing records of observations of tropical-Atlantic species, such as *S. senegalensis* and *D. vulgaris* in the central area of our study during autumn, is suggested to be probably linked to global warming (Bañón et al. 2010).

Ecological niche modelling

The emergence of large databases of species occurrences and the vast availability of environmental data have fostered ecological niche modelling studies (Peterson and Nakazawa 2007; Franklin 2009), and increased knowledge on many species geographical distributions.

A species ecological niche is the species environmental requirements within which the species can persist or a population can be established (Walker and Cocks, 1991). These niches along with the environmental variables control the limit of the species distribution (Pearson 2007; Phillips et al. 2004), required for modelling processes.

This study provides an alternative method for determining the realised niches of marine species, based on current occurrence records and raster environmental data at global scale using GIS. The realised niches were obtained by extracting environmental raster values at the locations of the species occurrences at the time of observation. The study uses only information on locations and the time of observation, allowing the utilisation of all occurrence records, and the method yields coherent results for most species observed. For pelagic species, such as *P. saltatrix*, the maximum SST found in this study was 30 to 33°C during the day and 29 to 30°C at night, depending on the instrument used. The values are near the maximum temperature determined in AquaMaps (31.78°C), as well as in experimental or observational studies, in which they range from 30 to 34°C (Olla et al. 1975; Fahay et al. 1999; Ballenger 2014). The minimum SST for this species was between 5.59 and 6.35°C, which differs from the value determined by AquaMaps (0.67°C) but matches the values from experimental or observational studies, that range from 6 to 13°C (Gilmore et al. 1978). The results of this method also agreed with the observational studies for demersal species such as *B. capriscus* and *S. senegalensis*.

The approach that we have presented here illustrated the capabilities of GIS technique to generate species realised niches using only occurrence location, along with satellite data and other environmental raster data. The method showed effective, robust and reliable results since they were in agreement with the results of observational or experimental studies.

The use of GIS provides new, improved techniques to deal with the issue of sample size and to handle a large quantity of spatial and temporal scale for both species occurrence records and environmental data (Soberón et al. 2002; Beck et al. 2014). With the establishment of ecological niches, in terms of niche modelling, our study opens a way for predicting species distribution. The availability of global, daily, systematic, high resolution images obtained from satellites has been a major data source for elucidating the relationships between exploited marine organisms and their habitat (Chassot et al. 2011). The results can now be used to improve modelling as well as projections for guiding future model or surveys.

In the case of *M. punctatum*, despite the small number of occurrence records in the study area, the method, using the occurrences at a global scale, was capable of depicting the species potential distribution following the seasonal variations. This result demonstrates the capabilities of the GIS technique in species distribution modelling, especially for poorly-known species and modelling in data-poor areas (Figure 4-69).

The different life stages of the fish species studies were not taken into account in the modelling process but we encourage doing so in future studies, to gain additional insights on the species seasonal movement across large spatial extents. Distribution of larvae and juveniles fish may be strongly influenced by oceanic currents, while the distribution of adult fish may be controlled by a seasonal switch between feeding and spawning habitat (Nicol et al. 2014).

Species Northward Movement

The models of species distribution produced in this study showed, in general, a north-bound trend of movement. This demonstrates how species have responded in their latitudinal distribution to long-term and seasonal environmental changes.

Newly recorded tropical species in the South European Atlantic Shelf (ID CWS in Figure 4-14) have confirmed the effect of climate change on shifting species distributions. However, the absence of survey data in the earlier period prevents us to make sure that it is the cause of this phenomenon.

Nevertheless, the steady increase of SST observed in all regions (Annex 8) may promote species migration, especially in the intermediate regions. Thus, their distribution range is expected to expand, as also stated by Kristin Kaschner et al. (2011). Furthermore, Bañón et al. (2010) suggested that the presence of tropical species of African origin in the central region of the study area was influenced by natural changes rather than the result of an increased sampling effort.

In the South European Atlantic Shelf, during warmer periods, six species originating from the Canary Current and the Western Mediterranean Sea extend their distributions to this area (Figure 4-14 and Figure 4-17). Bañón et al. (2010) stated that the arrival of numerous tropical fish in the South European Atlantic Shelf, such as *S. senegalensis* and *D. vulgaris*, seems to have altered the traditional species distribution pattern in this area, and they link this phenomenon to global warming. During warmer seasons, the difference of mean SST between the middle and the southern ecosystems was reduced (see Figure 4-15). This condition could allow the southern tropical species to migrate to the central region (without taking into account other limiting factors). However, low records of species occurrence in earlier period in this region limit our view on the analysis of the effect of global warming. In the earlier periods, the low richness of the studied species was strongly influenced by the poor availability of observations. Nevertheless, many studies suggest the increasing temperature was the major cause of the presence of tropical species as mentioned previously. As the SST continuously increase in all regions (Annex 8), the distribution range of many observed species are expectedto expand further still.

The records of tropical-Atlantic species occurrence in the Mediterranean Sea seem to be more confident than those in the South European Atlantic Shelf. In this study, 7 new species from the Canary Current tended to be found in the Western Mediterranean Sea. Deidun, Castriota, and Arrigo (2011) already noted 33 exotic fish of Atlantic-origin present in the Mediterranean Sea. Zenetos et al. (2010) point at the increasing number of alien fish species in this region, with a parallel increase in the number of migrant fish species from Atlantic. Many of these species are already well established and have expanded their distribution in the entire basin, suggesting also an eastward movement (CIESM 2002).

Many studies identified the temperature as the dominant environmental factor in limiting species distribution. Temperature controls the reproduction, growth and availability of food (Summerson, Darbyshire, and Lawrence 2007). Although the temperature is not the only forcing parameter, Cheung et al. (2009) stated that the response of marine species to environmental changes, such as ocean warming, is expressed by a shifting of their latitudinal or depth range and changes in the pattern of species richness.

The presence of tropical-Atlantic species in the central region confirms the phenomenon of "tropicalisation" of both pelagic and demersal species (Zenetos et al. 2010), with increasing frequency and biomass (Deidun, Castriota, and Arrigo 2011). This trend is also confirmed by the findings of this study, which suggest the northwards route of species movement.

Model of richness of the studied species

The available measurements of species biodiversity are mostly analyzed using expert knowledge or regional observations which cannot be used directly to investigate the potential shift in their distributions under different environmental conditions. Most of existing empirical attempts to measure species biodiversity are based on occurrence records, and thus are strongly influenced by the availability of species occurrences data. This type of data is scarce, especially for marine species because it may not be possible to sample the whole range of environmental variation (Araujo 2002).

Field surveys at sea and inventory of species occurrence records are expensive and limited by time. Quantifying patterns of biodiversity requires costly and challenging efforts, particularly in the oceans where the species cannot easily be seen and many of whom are highly mobile, with large areas of distribution that extend far into the open oceans (Tittensor et al. 2010). The lack of data in many places and the fact that the analyses were restricted in taxonomic and spatial coverage reduced the quality of predictions (Whitehead et al. 2010).

The modelling method used in this study allowed modelling of richness of the studied species, by superposing all models of individual species distribution at a given time. The model of richness presents the distribution of the areas that are potentially most occupied by the species (hotspot areas). The model changes seasonally over time from winter 1982 to autumn 2013. This could be essential to understand the seasonal evolution of species richness and can be used to assess the effectiveness of MPA location in relation to hotspot areas and climate change.

Marine Protected Area and Species Future Distribution

The flexibility of GIS allowed study in species distribution modelling related to the hotspot areas and MPAs' locations. In France, the localisation of the MPA Iroise is very important in terms of frequency of intersection and mean area intersecting the hotspot zones. This MPA was intersected by the hotspot zone in almost every season. The surface area intersected was also higher compared to the other MPAs.

The localisation of MPAs on the coast of Portugal are very important because all MPAs studied were always intersecting the hotspot zone in all seasons, except for the *Esposende* MPA (Figure 4-81), and the intersected areas were large. The north-ward movement of some tropical species in this area gives an important role to these MPAs.

The increase of temperature has led southern warm water species to migrate northwards. This phenomenon could potentially change the species composition. The summer northernmost point of *A. thori*'s suitable area resulting from the SST CTL model moved from 50.59 °N (2000-2009) to 48.72 °N (2050-2059) and to 49.83 °N in the last future period (2090-2099) reaching the English Channel. This movement is more evident with the SST IPSL model where the northernmost point moved from 50.59 °N (2000-2009) to 49.83 °N (2050-2059) and to 52.08 °N in the last future period (2090-2099), reaching the coast of Ireland. A similar pattern was found for *M. punctatum*.

Finaly, our study can provide valuable information to evaluate not only climate change effects on species biodiversity, but also the localisation of marine protected areas. This study provides information allowing an effective effort management to areas that are expected to be more impacted. The technique is especially useful for mapping and studying species distribution patterns over time, or identifying the geographical areas occupied by most species as a potential targets for conservation.

Our dynamic seasonal models offer an alternative predictive view of species distribution and richness as baseline knowledge to understand species movements related to seasonal environmental changes. Such information is scarce and direct observation through fieldwork can be costly, time consuming and limited to relatively shallow waters (Moore et al. 2011). These models will enhance the prediction models available today, and furthermore lead to a better understanding of species movement or biodiversity changes, enabling the identification of present and future high biodiversity areas.

Further study is needed to gain additional insights on species seasonal movements across large spatial extents. Species distribution modelling based on species environmental niches is promising, as the results could be used to predict the number of species occupying an area, and to target for protection the area occupied by most species.

The methods developed in this study could be an alternative or a complementary approach to the limitation in data availability when working at a large scale. The approaches could be applied for a wide range of organisms, especially for poorly-known species, both pelagic and demersal. The technique used could also be adapted for application in data-poor area and to terrestrial species.

Well-designed and effectively managed marine protected areas networks could be an alternative tool to reduce the threat climate change poses to marine ecosystems, and furthermore contribute to achieve multiple objectives such as fisheries management, biodiversity conservation and adaptation to changes in climate and ocean chemistry. We hope that this study will contribute to the comprehension of species distribution as well as to improve management and conservation strategies.

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ANNEXES

Annex 1: SST statistics per ecosystem: first decade = 1982-1991.

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
1982	1	2.53	12.64	9.38	1.39	6.10	17.54	13.10	1.74	14.08	25.46	19.83	1.97
1982	2	3.13	12.80	9.27	1.44	6.76	17.15	12.61	1.85	12.68	23.89	18.41	1.44
1982	3	3.57	12.12	9.25	1.23	7.95	16.81	12.74	1.52	13.48	24.85	17.87	1.55
1982	4	4.48	12.42	9.64	1.19	9.67	17.60	13.27	1.69	13.09	24.98	18.56	1.36
1982	5	5.67	13.46	10.30	1.22	10.47	20.04	14.20	1.80	14.78	25.85	19.06	1.28
1982	6	6.27	16.87	12.41	1.65	9.15	22.19	16.33	1.49	15.35	26.25	19.84	1.82
1982	7	6.65	19.05	14.22	2.08	13.88	22.10	18.13	1.20	15.76	28.49	21.30	2.09
1982	8	6.58	19.77	14.39	1.82	13.01	23.03	18.74	1.54	16.38	28.45	21.94	1.97
1982	9	7.73	19.72	13.61	1.68	12.00	24.07	18.63	1.79	16.97	29.10	22.70	2.08
1982	10	7.66	16.62	12.25	1.42	11.14	21.25	16.46	1.89	14.42	30.35	22.58	2.74
1982	11	6.11	14.76	11.12	1.16	9.24	19.76	15.34	2.03	14.72	28.43	21.80	2.68
1982	12	5.52	12.88	9.70	0.97	7.43	18.83	13.37	1.84	13.08	28.71	19.57	2.21
1983	1	4.08	12.34	8.94	1.14	6.82	16.11	12.17	1.59	13.55	23.73	17.88	1.72
1983	2	3.80	11.58	8.12	1.22	6.06	16.62	11.91	2.42	13.83	25.80	18.23	2.08
1983	3	3.34	11.51	8.41	1.42	7.02	16.33	11.95	1.93	13.56	25.86	18.35	2.08
1983	4	5.23	12.07	8.69	1.20	8.97	16.54	12.29	1.56	13.80	25.69	18.51	1.79
1983	5	5.24	12.99	9.73	1.12	9.52	18.28	13.35	1.58	14.04	27.53	18.54	1.84
1983	6	6.80	15.35	11.18	1.69	9.98	21.03	15.85	1.31	14.02	27.76	19.96	1.86
1983	7	6.48	21.15	13.37	2.33	11.84	22.93	18.41	1.91	16.28	29.14	21.74	2.42
1983	8	7.14	19.64	14.59	2.75	13.22	22.49	18.90	1.48	16.42	28.77	21.85	2.19
1983	9	8.57	19.05	13.74	1.37	12.26	22.97	17.89	1.77	16.16	30.16	22.63	2.23
1983	10	5.60	17.21	12.19	2.01	12.87	22.08	17.57	1.96	16.55	29.54	23.44	2.46
1983	11	5.48	14.52	11.16	1.49	9.16	20.56	16.11	2.07	16.89	29.31	22.75	2.59
1983	12	5.73	13.82	10.55	1.10	6.98	19.33	14.37	2.17	15.71	29.93	21.02	2.34
1984	1	2.32	12.56	9.12	1.40	5.88	17.58	13.75	2.19	13.76	23.28	18.72	1.51
1984	2	3.47	11.76	8.87	1.35	6.81	16.33	12.20	1.76	12.31	23.47	17.51	1.54
1984	3	0.20	11.59	8.69	1.47	6.84	15.62	11.65	1.72	13.41	26.57	18.13	1.78
1984	4	4.11	12.45	8.99	1.28	8.72	17.19	12.90	1.94	14.72	24.72	18.77	1.49
1984	5	6.14	13.05	10.38	1.22	10.15	18.02	13.77	1.68	14.96	27.63	19.28	1.60
1984	6	5.87	16.85	11.04	1.88	11.31	20.00	15.43	1.33	14.72	27.70	19.61	2.45
1984	7	5.63	17.95	13.12	2.18	12.58	23.10	17.35	1.25	15.79	28.35	20.44	2.16
1984	8	7.32	19.50	15.09	1.80	12.80	23.84	19.03	1.52	16.55	29.27	21.85	2.25
1984	9	6.23	19.77	14.49	2.09	11.32	24.13	19.21	1.67	16.24	28.63	22.43	1.87
1984	10	7.34	16.37	12.47	1.39	10.09	21.12	15.98	1.91	15.01	28.65	22.14	2.63
1984	11	7.26	14.48	10.93	1.29	10.96	19.05	15.00	1.53	15.04	28.34	21.34	2.57
1984	12	3.34	13.27	10.02	1.19	8.47	18.17	14.21	1.71	15.23	27.48	19.89	1.86
1985	1	3.32	12.14	9.62	1.13	6.43	17.54	13.06	1.87	14.51	23.54	18.52	1.40
1985	2	1.48	11.62	8.84	1.58	6.15	16.48	12.51	1.69	13.71	22.41	17.85	1.38
1985	3	3.28	11.37	8.74	1.36	7.19	16.05	12.23	1.83	14.01	24.55	17.51	1.31
1985	4	4.85	12.35	9.29	1.24	9.36	17.45	12.97	1.45	13.35	24.00	17.90	1.27
1985	5	6.10	13.40	10.07	1.19	10.40	17.89	13.55	1.47	14.39	23.65	18.44	1.16
1985	6	6.39	15.20	11.36	1.24	10.20	21.81	16.27	1.68	14.55	26.30	19.96	1.30
1985	7	7.60	18.83	13.18	1.61	13.04	24.02	18.09	1.49	16.66	27.28	21.21	2.03
1985	8	6.74	18.03	13.28	1.15	13.77	23.32	18.36	1.56	16.66	28.80	21.92	2.43
1985	9	6.67	17.97	12.99	1.67	14.18	23.06	18.71	1.62	16.56	28.39	22.81	2.38
1985	10	7.18	17.99	12.45	1.76	14.28	23.19	18.18	1.74	16.24	28.81	22.97	2.42
1985	11	7.55	15.20	11.79	1.57	11.38	21.49	16.33	1.96	16.55	29.61	23.12	2.57
1985	12	5.90	13.65	10.41	1.28	9.02	18.97	14.40	1.90	15.78	28.60	20.63	1.91
1986	1	3.81	12.21	9.35	1.15	7.37	17.37	13.22	1.87	14.49	22.88	18.46	1.36
1986	2	1.54	11.30	8.32	1.46	6.19	16.25	12.39	2.06	13.79	23.65	17.78	1.37
1986	3	1.49	11.07	8.08	1.46	6.46	16.20	12.04	1.85	13.46	25.81	17.45	1.15
1986	4	4.47	11.08	8.37	1.21	7.68	16.04	11.91	1.86	13.52	25.78	17.86	1.57
1986	5	5.65	12.44	9.19	1.04	9.22	19.32	13.35	1.67	13.57	26.46	18.27	1.83
1986	6	6.50	16.05	10.97	1.21	10.55	20.61	15.30	1.46	15.34	27.07	19.63	2.04
1986	7	8.28	18.12	13.14	1.61	13.46	23.14	17.53	1.54	16.00	28.68	21.03	2.79
1986	8	10.57	18.45	13.18	1.04	13.09	22.85	18.69	1.73	17.17	28.80	21.82	2.33

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
1986	9	7.08	16.62	12.89	1.26	12.80	22.81	18.10	1.94	17.13	28.85	23.28	2.38
1986	10	7.30	16.04	12.71	1.49	13.13	22.09	17.78	1.91	15.80	29.30	23.22	2.88
1986	11	6.78	14.54	10.60	1.19	9.76	20.23	15.07	1.96	14.74	29.55	21.36	2.88
1986	12	5.82	13.26	9.85	1.14	8.48	18.28	14.19	1.60	14.67	25.90	19.45	2.08
1987	1	2.84	11.80	8.88	1.18	7.70	17.14	13.01	1.92	14.40	24.66	18.63	1.83
1987	2	2.79	11.85	8.60	1.27	4.48	16.59	12.52	2.09	13.77	24.20	18.10	1.48
1987	3	3.28	12.01	8.77	1.35	6.31	17.03	12.52	2.20	14.62	25.41	18.91	1.54
1987	4	4.41	12.32	9.06	1.32	8.30	17.70	13.21	1.84	14.96	24.94	18.97	1.69
1987	5	5.03	13.50	9.99	1.40	9.86	19.49	14.61	1.86	15.37	26.71	19.66	1.57
1987	6	7.43	18.04	11.70	1.37	11.14	21.73	16.25	1.57	15.84	28.51	20.49	1.77
1987	7	5.80	18.84	13.56	1.87	14.15	22.95	18.38	1.57	16.80	28.82	21.97	2.24
1987	8	8.24	18.94	14.84	1.66	14.14	23.54	18.79	1.39	16.91	29.80	22.82	2.31
1987	9	8.77	18.86	13.64	1.87	14.99	24.14	19.33	1.56	18.07	29.42	23.56	2.02
1987	10	7.83	16.80	12.12	1.47	12.56	23.41	17.07	2.12	17.05	29.30	23.76	2.02
1987	11	6.24	14.66	11.00	1.37	10.11	20.12	15.75	1.76	16.26	29.11	22.23	2.69
1987	12	5.69	12.83	9.93	1.07	9.14	18.38	14.12	1.74	16.37	27.40	21.03	2.40
1988	1	5.35	11.88	9.46	0.98	8.54	17.92	13.64	1.84	14.98	24.72	19.22	1.51
1988	2	4.16	11.47	8.83	1.10	7.77	16.74	12.70	1.65	14.15	22.87	17.38	1.30
1988	3	3.86	10.84	8.55	1.30	7.25	16.25	12.44	2.12	13.50	23.23	17.85	1.72
1988	4	5.54	11.89	9.25	1.10	9.26	17.32	13.07	1.62	14.16	25.23	18.56	1.83
1988	5	6.39	13.28	10.30	1.07	11.03	18.99	14.58	1.57	14.42	27.17	19.33	1.55
1988	6	6.85	14.93	11.23	1.44	12.05	19.43	15.40	1.53	14.59	27.55	20.09	1.77
1988	7	8.12	17.75	12.78	1.33	13.07	21.90	17.69	1.58	16.58	28.63	20.93	2.03
1988	8	9.46	18.36	13.69	1.27	13.92	24.08	19.01	1.56	17.39	28.04	21.87	2.05
1988	9	8.15	17.67	13.14	1.46	13.28	22.91	18.20	1.84	17.19	28.71	22.96	2.10
1988	10	6.26	15.87	12.06	1.34	12.27	21.32	16.86	1.82	15.83	30.01	22.78	2.40
1988	11	6.34	15.28	11.28	1.23	11.27	20.63	16.09	1.73	16.58	29.84	22.02	2.42
1988	12	6.18	13.17	10.48	1.12	8.54	18.33	14.27	1.92	15.64	26.89	20.09	2.11
1989	1	5.72	12.85	9.99	1.04	8.14	16.82	13.51	1.69	13.99	23.55	18.40	1.60
1989	2	4.38	12.21	9.84	1.15	7.50	16.08	13.18	1.58	13.81	23.71	17.57	1.57
1989	3	5.39	11.73	9.24	1.11	8.14	16.37	12.81	1.62	14.37	24.77	17.65	1.52
1989	4	5.19	12.09	9.31	1.16	9.95	16.38	12.85	1.45	13.80	25.81	17.68	1.43
1989	5	6.39	14.84	10.60	1.49	11.30	18.04	15.01	1.09	14.09	26.53	19.03	1.54
1989	6	8.18	17.66	12.56	1.92	13.71	23.08	17.94	1.45	15.39	27.81	20.63	1.96
1989	7	7.36	19.63	14.34	2.52	14.42	23.87	19.36	1.45	16.76	28.55	22.05	2.03
1989	8	8.00	20.05	14.93	2.33	14.85	25.25	20.39	1.50	17.87	28.94	23.42	2.04
1989	9	8.97	19.30	13.93	2.22	13.49	23.26	18.92	1.68	17.50	28.53	23.35	2.10
1989	10	7.32	17.75	12.57	1.91	13.10	23.42	17.60	2.03	17.67	28.76	23.58	2.05
1989	11	7.09	15.21	11.36	1.32	12.10	21.46	15.90	2.11	16.20	29.30	22.41	2.56
1989	12	5.74	13.56	10.41	1.13	7.95	18.53	14.48	1.70	16.25	27.52	20.97	2.22
1990	1	5.06	12.45	9.90	1.15	8.18	16.77	13.85	1.55	14.76	26.09	19.27	2.04
1990	2	3.80	11.83	9.24	1.15	8.06	16.21	13.34	1.38	14.03	25.13	18.27	1.56
1990	3	5.63	11.85	9.23	1.21	8.70	16.72	13.22	1.55	14.29	25.40	18.28	1.49
1990	4	4.92	11.85	9.32	1.12	9.92	16.83	13.41	1.80	14.72	24.82	18.87	1.52
1990	5	6.27	13.95	10.80	1.37	11.95	19.96	15.18	1.21	14.96	26.47	19.20	1.40
1990	6	7.76	15.86	12.27	1.23	12.37	21.94	16.93	1.50	15.32	27.75	20.20	1.52
1990	7	6.51	18.85	14.15	1.45	13.02	23.53	18.82	1.47	16.18	27.69	21.60	1.71
1990	8	9.97	20.94	15.20	2.31	15.24	25.30	20.18	1.50	17.79	28.39	23.11	2.01
1990	9	8.19	19.27	14.14	1.97	13.38	24.53	19.13	1.64	18.10	29.84	23.69	2.09
1990	10	7.25	17.33	12.61	1.77	12.88	22.74	18.11	1.78	17.37	29.63	23.81	2.50
1990	11	7.18	15.04	11.41	1.36	10.57	20.38	15.91	1.75	16.41	30.16	22.73	2.68
1990	12	5.34	13.02	9.98	1.31	8.46	18.75	13.99	1.52	15.61	27.77	20.83	2.27
1991	1	3.53	12.01	9.04	1.13	7.69	17.06	12.87	1.83	15.14	24.51	18.82	1.59
1991	2	2.57	11.19	8.56	1.37	6.34	16.23	12.23	1.73	13.80	24.57	17.84	1.57
1991	3	4.65	11.39	8.72	1.21	7.18	16.29	12.23	1.55	14.24	23.80	17.63	1.28
1991	4	5.74	11.13	8.97	1.06	8.90	16.34	12.45	1.58	13.93	25.49	18.04	1.49
1991	5	5.34	14.88	10.15	1.54	10.29	17.82	13.90	1.21	13.00	25.04	18.01	1.51
1991	6	6.01	15.55	11.67	1.08	12.33	23.33	15.85	1.53	14.91	26.18	19.30	1.86
1991	7	8.98	18.45	13.78	1.06	12.71	24.05	17.86	1.64	15.84	28.63	20.93	2.15
1991	8	9.46	19.76	15.09	1.46	14.28	24.52	19.34	1.53	16.55	27.59	22.02	1.73

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
1991	9	9.26	19.79	15.41	1.88	15.82	24.27	20.80	1.45	17.94	29.20	23.45	2.09
1991	10	6.93	17.55	12.08	1.91	12.02	21.77	17.50	1.76	16.47	29.28	22.88	2.28
1991	11	6.52	14.33	10.57	1.18	10.47	20.23	14.83	1.99	15.10	29.24	21.90	2.69
1991	12	5.38	12.89	9.96	1.18	8.01	17.91	13.82	1.71	15.50	26.32	20.34	2.26

Annex 2: SST statistics per ecosystem: second decade = 1992-2001.

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
1992	1	4.98	12.34	9.27	1.03	6.24	16.85	13.00	1.79	15.03	24.96	18.87	1.94
1992	2	4.15	11.78	8.84	1.05	6.44	16.78	12.67	1.89	14.38	24.52	18.59	1.89
1992	3	4.87	12.19	8.95	1.07	6.70	16.76	12.59	1.93	14.46	23.38	17.94	1.31
1992	4	5.54	11.93	8.80	0.90	8.04	17.80	12.60	1.80	13.62	25.18	17.87	1.48
1992	5	5.14	13.69	9.91	1.18	9.76	18.99	14.04	1.54	14.15	25.37	18.80	1.63
1992	6	6.42	17.82	12.70	1.27	13.33	20.96	16.35	1.32	15.36	27.48	20.33	1.85
1992	7	8.00	19.34	13.81	1.90	13.79	22.75	18.21	1.40	16.58	27.76	20.83	1.89
1992	8	8.52	20.49	14.03	1.77	14.38	25.40	19.77	1.45	17.08	28.11	22.28	2.10
1992	9	7.01	17.24	12.48	1.57	13.34	22.66	18.61	1.65	17.02	28.59	22.67	2.64
1992	10	6.64	15.95	11.82	1.48	11.32	21.65	16.11	1.97	16.39	29.60	22.69	2.47
1992	11	6.88	13.93	10.07	1.19	9.68	19.35	14.94	1.78	15.28	28.92	20.95	2.29
1992	12	5.32	13.00	9.59	1.09	9.03	18.58	13.95	1.67	15.09	26.72	20.08	2.27
1993	1	1.94	12.14	9.17	1.22	8.09	17.38	13.40	1.70	14.98	23.69	18.38	1.61
1993	2	1.49	12.10	8.92	1.25	8.01	16.47	13.10	1.51	14.27	24.27	18.06	1.65
1993	3	4.37	11.81	8.57	1.25	7.71	16.77	12.71	1.64	14.28	24.25	18.07	1.34
1993	4	5.49	11.94	8.75	0.99	9.35	16.94	13.36	1.66	14.10	24.86	18.31	1.84
1993	5	6.26	13.08	9.91	1.10	11.32	18.33	14.03	1.59	15.12	26.08	18.96	1.39
1993	6	6.82	17.25	12.29	1.66	13.54	20.89	16.77	1.40	14.96	28.77	20.31	1.94
1993	7	6.59	17.70	13.03	1.88	12.86	23.75	17.79	1.62	16.33	28.29	21.29	2.39
1993	8	7.97	19.11	13.65	1.88	13.98	23.82	18.71	1.62	17.39	28.92	22.33	2.31
1993	9	7.95	17.64	13.74	1.66	13.60	22.59	18.03	1.54	16.37	28.93	22.77	1.93
1993	10	7.84	15.89	12.23	1.04	12.03	20.31	15.88	1.65	16.20	29.80	22.25	2.72
1993	11	5.91	13.57	10.62	1.04	10.21	18.44	14.39	1.63	15.73	28.60	20.86	2.48
1993	12	4.80	12.05	9.30	0.93	8.00	17.57	13.65	2.13	14.41	25.21	18.96	1.91
1994	1	2.72	11.07	8.85	1.02	7.07	16.28	12.34	1.60	13.92	22.86	17.75	1.62
1994	2	2.60	11.08	8.72	1.12	7.17	16.18	11.93	1.69	14.02	21.81	17.22	1.32
1994	3	3.42	11.51	8.49	1.34	7.14	16.17	12.52	1.69	13.48	24.81	17.39	1.54
1994	4	4.56	11.26	8.50	1.20	8.27	16.71	12.35	1.84	13.92	25.95	18.14	1.67
1994	5	6.27	13.01	9.47	0.94	9.56	18.75	13.91	1.36	13.95	26.58	18.69	1.54
1994	6	6.93	18.77	11.45	1.52	12.96	21.53	16.66	1.65	15.47	27.90	19.98	1.82
1994	7	7.75	19.07	13.20	1.67	12.58	23.60	18.37	1.65	17.34	28.32	21.16	1.87
1994	8	9.48	19.89	14.18	1.52	12.81	23.87	19.33	1.75	16.46	27.67	22.47	2.07
1994	9	9.43	18.31	13.73	1.37	13.43	21.98	18.13	1.92	16.91	29.04	22.56	2.26
1994	10	8.61	15.73	12.66	1.13	12.94	21.42	16.84	1.75	17.45	29.41	23.04	2.51
1994	11	7.60	14.91	11.50	0.96	11.67	20.04	15.63	1.93	17.98	29.38	22.29	2.39
1994	12	6.87	14.22	10.71	1.22	10.89	19.45	15.21	1.90	16.24	28.57	21.20	2.22
1995	1	5.14	12.25	9.80	1.09	9.50	17.99	14.19	1.82	15.38	25.35	19.51	1.83
1995	2	4.92	11.59	9.50	1.15	9.16	17.70	13.47	2.11	15.05	25.85	19.38	2.08
1995	3	4.15	11.46	9.15	1.22	8.11	16.84	12.92	1.89	13.58	25.44	18.31	1.64
1995	4	4.69	11.85	9.11	1.18	8.61	18.17	13.33	2.19	14.59	25.89	19.04	1.47
1995	5	5.74	14.25	10.75	1.36	10.21	20.02	15.54	1.51	16.17	27.54	20.68	1.97
1995	6	7.53	18.50	12.30	1.84	12.13	22.40	16.53	1.63	17.16	28.16	21.78	1.68
1995	7	8.85	20.03	14.58	1.84	14.21	22.64	18.90	1.44	18.11	28.86	23.09	2.07
1995	8	10.25	20.92	16.45	1.92	15.00	24.51	20.31	1.53	18.79	28.55	23.71	1.83
1995	9	9.31	19.75	14.98	1.49	13.56	23.87	18.58	1.68	16.94	29.72	23.76	2.11
1995	10	7.81	17.20	13.50	1.65	13.48	21.89	17.82	1.59	16.98	29.10	23.83	2.65
1995	11	6.10	16.10	12.51	1.42	11.86	21.41	16.78	1.97	17.82	29.58	23.46	2.51
1995	12	5.52	13.76	10.61	1.37	8.89	20.32	14.98	1.94	15.59	28.68	21.77	2.35
1996	1	4.02	12.71	10.00	1.16	7.43	18.76	13.88	1.85	15.05	25.43	20.51	1.86
1996	2	1.00	11.97	9.12	1.25	6.73	16.49	13.40	1.77	14.77	25.11	18.79	1.65
1996	3	3.88	11.36	8.86	1.18	7.84	16.93	12.80	1.82	15.25	26.80	18.69	1.46
1996	4	4.71	11.62	9.11	1.12	8.27	18.11	13.49	2.14	14.24	27.06	19.05	1.72

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
1996	5	6.02	12.46	10.01	1.04	10.80	21.17	14.52	2.07	16.43	27.09	20.12	1.61
1996	6	6.72	16.47	11.84	1.37	11.14	21.85	16.92	1.58	16.08	27.68	20.91	2.10
1996	7	7.75	19.38	14.03	1.94	12.70	23.82	18.85	1.73	16.84	28.62	21.81	2.04
1996	8	9.26	20.21	14.34	1.81	14.31	23.58	19.24	1.46	17.29	28.75	22.93	2.12
1996	9	10.47	18.80	14.50	1.43	13.12	22.82	18.44	1.51	16.74	29.20	23.33	2.31
1996	10	7.94	16.22	12.72	1.51	13.41	21.48	16.90	1.55	16.42	29.92	23.23	2.73
1996	11	6.23	15.11	11.46	1.38	11.15	20.86	16.21	2.00	16.44	29.84	22.48	2.73
1996	12	5.39	12.79	10.16	1.14	8.38	19.25	13.85	1.90	15.47	27.66	20.93	2.57
1997	1	3.49	11.96	9.33	1.18	6.89	16.86	12.85	1.77	15.13	25.53	19.68	1.95
1997	2	4.12	11.76	9.18	1.22	7.26	16.60	12.70	1.86	14.25	25.15	19.01	1.82
1997	3	4.90	11.85	9.22	1.14	8.55	17.40	13.50	1.87	14.62	25.67	19.07	1.36
1997	4	5.73	12.63	10.02	1.13	10.13	19.33	14.32	2.04	14.76	24.85	19.65	1.34
1997	5	6.07	13.47	10.94	1.35	11.65	19.24	14.96	1.94	14.98	26.07	20.04	1.46
1997	6	8.35	16.40	12.42	1.37	12.81	21.03	16.99	1.65	15.99	27.85	21.36	1.58
1997	7	7.73	19.03	13.97	1.46	13.01	23.19	18.23	1.25	16.87	28.52	21.96	2.06
1997	8	10.51	20.26	15.36	1.61	15.62	24.81	20.19	1.46	16.71	28.74	22.61	1.86
1997	9	8.70	18.78	14.13	1.57	14.97	23.64	19.48	1.56	17.77	29.80	23.42	2.17
1997	10	7.81	18.07	13.64	1.77	14.09	23.19	19.50	1.49	18.18	29.35	23.70	2.16
1997	11	8.16	16.55	12.32	1.31	11.41	20.99	16.84	1.71	16.60	30.03	23.14	2.87
1997	12	6.32	13.84	11.12	1.00	9.21	19.29	15.04	1.73	16.10	28.50	21.37	2.22
1998	1	5.31	12.60	10.05	0.91	7.97	17.84	13.82	1.72	15.54	25.23	20.01	1.87
1998	2	5.07	12.25	9.82	1.07	7.39	17.10	13.49	1.91	15.17	25.45	19.62	1.92
1998	3	6.28	11.92	9.88	1.04	7.66	17.20	13.50	1.82	15.47	25.73	19.40	1.68
1998	4	6.33	11.73	9.62	0.84	9.55	17.61	13.58	2.03	14.89	25.72	19.22	1.55
1998	5	6.43	14.96	11.18	1.38	11.16	18.64	15.07	1.10	14.31	27.09	19.57	1.76
1998	6	7.61	16.74	12.20	1.14	12.22	21.38	16.88	1.24	16.32	27.68	20.39	1.50
1998	7	7.18	17.78	13.72	1.32	11.98	24.01	18.28	1.63	15.97	28.22	21.16	1.99
1998	8	7.95	19.35	14.69	1.66	14.42	24.47	19.22	1.62	17.17	28.54	22.44	2.30
1998	9	9.42	18.23	14.60	1.52	13.93	23.50	18.75	1.51	17.16	28.97	22.85	2.30
1998	10	7.06	17.36	13.25	1.44	12.63	21.27	17.03	1.51	16.30	29.27	23.07	3.00
1998	11	6.00	14.93	11.20	1.35	11.43	20.20	15.89	1.78	15.89	30.10	22.76	3.04
1998	12	5.81	13.78	10.53	1.18	8.68	18.82	14.34	1.85	14.82	28.18	20.68	2.58
1999	1	5.16	12.70	9.64	1.08	8.77	17.43	13.48	1.56	14.74	23.55	18.77	1.56
1999	2	4.56	12.21	9.53	1.26	7.73	16.55	12.85	1.71	14.67	23.29	17.65	1.38
1999	3	5.18	11.97	9.19	1.13	8.03	16.55	12.77	1.60	14.70	25.23	17.55	1.25
1999	4	5.89	12.08	9.46	1.01	8.46	17.60	13.24	1.72	14.01	24.75	18.00	1.18
1999	5	7.01	15.74	10.63	1.06	11.41	20.51	14.98	1.56	14.68	27.57	19.40	1.70
1999	6	6.66	17.35	11.94	1.82	12.50	23.19	16.70	1.52	15.41	28.48	20.30	2.32
1999	7	8.18	19.99	13.87	1.99	14.44	24.73	18.85	1.37	16.36	28.05	21.56	2.12
1999	8	10.49	20.08	15.05	1.46	14.93	23.28	19.99	1.43	16.29	27.53	22.44	1.84
1999	9	7.30	19.88	14.29	1.91	14.95	23.75	20.20	1.54	17.21	28.86	23.63	2.10
1999	10	8.25	16.45	12.97	1.40	13.38	22.30	17.43	1.81	17.14	29.80	23.47	2.48
1999	11	7.35	15.34	11.47	1.35	10.70	20.52	15.74	1.83	15.69	29.47	22.45	2.76
1999	12	6.32	13.72	10.39	1.11	8.21	18.04	14.24	1.81	15.14	28.69	20.64	2.75
2000	1	4.61	12.48	9.48	1.12	7.60	16.81	13.02	1.69	14.97	25.38	18.72	1.99
2000	2	5.10	11.77	9.32	1.05	7.81	16.53	12.89	1.88	13.94	25.17	18.24	1.56
2000	3	5.11	12.01	9.44	1.09	8.77	16.83	12.95	1.80	14.93	25.76	18.59	1.82
2000	4	5.47	11.94	9.35	1.07	9.71	17.30	12.81	1.82	14.77	26.65	18.96	1.70
2000	5	7.01	13.27	10.64	0.92	9.18	20.04	15.04	1.65	15.39	28.48	19.45	1.52
2000	6	8.38	16.92	11.69	1.19	9.53	22.02	16.68	1.92	15.29	27.43	20.31	2.01
2000	7	6.93	19.17	14.42	1.77	14.02	23.56	18.35	1.51	16.20	28.68	21.50	2.11
2000	8	7.65	19.03	14.92	1.63	14.46	24.24	19.48	1.53	16.70	28.32	22.65	2.16
2000	9	9.05	19.47	14.79	1.63	14.50	23.43	19.78	1.36	17.22	29.18	23.53	2.34
2000	10	8.14	17.33	12.32	1.32	12.55	21.74	17.34	1.92	15.69	29.85	23.15	2.89
2000	11	7.76	14.14	10.49	0.96	10.29	20.14	15.07	1.82	15.20	29.86	21.50	3.14
2000	12	5.98	13.20	10.06	0.87	9.73	18.86	13.91	1.83	15.33	27.76	20.66	2.59
2001	1	3.98	12.25	9.33	1.05	7.89	16.92	13.15	1.70	14.25	25.25	19.29	1.82
2001	2	3.24	11.89	9.04	1.23	7.13	16.41	12.69	1.67	14.47	24.68	18.29	1.55
2001	3	3.97	11.79	8.94	1.36	8.11	16.81	12.76	1.87	14.66	26.16	18.93	1.66
2001	4	5.73	12.29	9.25	1.23	9.90	17.45	13.40	1.70	13.84	26.88	18.55	1.71

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
2001	5	6.69	14.42	10.67	1.12	11.34	20.96	14.44	1.52	13.93	27.65	19.55	2.11
2001	6	8.09	18.07	12.81	1.66	12.46	22.30	17.21	1.35	15.95	27.66	20.72	2.15
2001	7	7.70	19.73	14.27	1.56	13.95	23.33	18.56	1.22	15.83	27.91	21.41	2.37
2001	8	7.90	20.20	15.22	1.53	14.72	23.58	19.43	1.29	16.54	29.33	23.23	2.48
2001	9	10.31	17.93	14.56	1.58	13.26	23.12	18.88	1.74	17.21	29.51	24.06	2.19
2001	10	7.86	16.62	13.47	1.16	13.41	22.40	17.65	1.76	17.78	30.59	24.26	2.74
2001	11	7.02	15.92	12.40	1.40	10.51	20.21	16.12	1.55	15.32	30.18	23.32	3.36
2001	12	6.96	14.17	11.17	1.08	8.68	18.87	14.30	1.68	15.50	28.98	21.99	3.14

Annex 3: SST statistics per ecosystem: third decade = 2002-2011.

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
2002	1	4.97	12.55	9.99	1.05	7.26	17.95	13.10	2.10	16.09	26.17	20.45	2.27
2002	2	5.52	12.31	9.69	1.04	7.42	17.63	13.22	2.14	14.54	26.11	19.85	1.99
2002	3	5.14	12.63	9.53	1.08	7.84	17.54	13.16	1.89	14.87	26.08	19.05	1.47
2002	4	6.54	12.87	9.99	0.96	9.47	18.17	13.67	1.84	14.69	26.33	18.68	1.43
2002	5	7.30	14.12	10.64	0.93	11.32	18.47	14.44	1.52	14.01	26.93	19.30	1.55
2002	6	8.34	17.13	12.01	0.99	12.12	22.00	16.42	1.46	14.85	26.99	20.19	1.91
2002	7	9.63	18.13	13.54	1.41	12.51	23.28	17.48	1.40	16.08	29.15	21.28	2.30
2002	8	11.28	19.97	14.87	1.44	13.46	24.54	18.75	1.44	16.33	29.09	22.64	2.60
2002	9	10.59	18.97	14.65	1.50	14.25	23.42	18.80	1.33	16.51	29.65	23.44	2.43
2002	10	9.65	17.41	13.99	1.48	13.39	21.97	17.89	1.69	17.80	29.77	23.81	2.40
2002	11	8.26	15.05	11.91	1.02	11.86	21.35	16.25	2.22	16.62	29.42	22.88	2.43
2002	12	6.54	13.37	10.94	0.92	9.66	19.08	14.80	1.77	15.22	27.21	21.16	2.32
2003	1	4.48	12.67	10.22	0.94	7.21	17.41	13.41	1.64	15.07	26.11	19.57	1.85
2003	2	3.69	12.13	9.69	1.13	7.27	16.97	12.59	1.55	13.88	24.94	18.13	1.43
2003	3	5.18	12.25	9.63	1.13	8.83	16.74	12.92	1.50	14.25	26.03	18.66	1.56
2003	4	6.76	12.61	10.37	0.96	9.25	19.39	13.65	1.59	14.47	26.47	19.20	1.40
2003	5	7.89	15.46	10.72	0.93	10.93	20.82	15.00	1.48	14.60	27.23	19.81	1.64
2003	6	9.21	18.25	12.89	1.46	13.32	23.15	18.01	1.60	16.08	27.44	21.11	1.71
2003	7	11.20	20.03	14.98	1.35	14.51	23.98	19.51	1.44	16.16	27.97	21.91	2.04
2003	8	11.22	20.88	15.87	1.54	16.36	25.61	21.21	1.81	17.71	28.60	24.16	1.94
2003	9	9.86	20.40	15.17	1.67	15.65	23.54	20.03	1.42	17.12	30.10	23.96	2.33
2003	10	8.80	17.44	13.58	1.57	12.56	23.10	18.18	1.90	17.26	30.06	24.14	2.53
2003	11	8.02	15.22	12.18	1.17	11.26	20.00	15.67	1.53	16.14	29.22	22.71	2.67
2003	12	6.39	13.60	11.07	1.09	9.25	18.17	14.23	1.54	16.09	27.66	21.00	2.67
2004	1	4.96	12.70	10.20	1.01	8.15	17.35	13.42	1.77	15.68	25.49	19.74	2.07
2004	2	5.27	12.71	9.96	1.05	7.39	17.33	13.00	1.79	15.31	24.47	19.23	1.68
2004	3	3.86	12.22	9.69	1.11	7.56	16.68	12.68	1.86	15.24	25.35	18.75	1.58
2004	4	6.49	13.02	10.11	0.97	9.53	17.03	13.16	1.58	15.05	25.80	19.31	1.75
2004	5	7.57	14.62	11.48	1.15	11.43	19.50	14.63	1.34	14.50	26.69	19.65	1.53
2004	6	9.36	18.53	13.90	1.76	13.20	23.20	17.81	1.55	15.05	27.36	20.88	1.67
2004	7	11.13	19.38	14.52	1.34	13.61	25.32	19.00	1.48	16.21	28.81	22.34	1.85
2004	8	11.61	20.10	15.37	1.48	15.23	24.23	20.31	1.48	16.92	29.36	23.95	1.71
2004	9	10.06	19.47	14.85	1.36	15.00	23.56	19.75	1.60	17.33	29.88	24.03	2.29
2004	10	9.02	16.80	12.80	1.22	13.26	23.07	17.57	2.00	16.83	29.79	24.08	2.42
2004	11	7.23	15.26	11.57	1.03	11.47	20.69	15.82	1.79	15.85	29.58	22.95	2.74
2004	12	6.28	13.75	10.91	0.99	8.99	18.46	14.38	1.53	15.91	27.87	20.87	2.51
2005	1	5.56	12.71	10.14	1.03	8.47	16.95	13.32	1.47	13.85	25.28	18.97	2.07
2005	2	5.27	12.34	9.47	1.12	7.18	15.83	12.66	1.51	13.33	24.67	18.13	1.86
2005	3	4.74	12.35	9.63	1.22	6.21	16.16	12.27	1.56	13.72	26.29	18.98	1.58
2005	4	6.83	12.84	10.17	0.98	9.97	18.06	13.31	1.68	14.08	28.09	19.54	1.99
2005	5	7.22	13.59	10.90	0.91	10.91	19.73	14.95	1.73	15.06	28.53	20.03	2.10
2005	6	7.67	17.59	12.75	1.59	12.76	22.57	17.38	1.56	16.58	28.64	21.79	2.14
2005	7	8.90	19.11	14.61	2.22	14.29	24.10	19.38	1.43	15.81	28.98	22.40	2.17
2005	8	10.40	19.84	15.37	1.74	13.75	24.48	19.92	1.60	17.31	28.90	23.09	1.95
2005	9	7.34	20.23	14.82	1.94	13.84	22.87	19.38	1.41	17.36	29.46	23.97	2.47
2005	10	6.53	17.35	13.34	1.57	13.38	22.75	18.06	1.66	17.70	29.97	24.03	2.68
2005	11	7.61	15.88	12.31	1.12	12.89	20.81	16.35	1.76	16.23	30.19	23.11	3.08
2005	12	6.39	13.75	11.11	0.99	8.86	18.76	14.16	1.84	16.17	28.85	21.90	3.07

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**
2006	1	4.86	12.55	10.21	0.96	6.56	16.98	12.98	1.81	15.21	27.69	19.57	2.31
2006	2	4.85	12.67	9.84	1.05	5.59	15.90	12.49	1.81	14.35	24.95	18.35	1.75
2006	3	4.19	12.18	9.36	1.28	6.20	16.08	12.23	1.84	14.55	25.81	18.25	1.63
2006	4	5.76	12.41	9.76	1.10	8.78	18.10	13.36	1.84	14.94	26.27	19.16	1.69
2006	5	6.23	13.42	10.46	0.88	10.79	20.04	15.02	1.76	14.97	26.81	19.81	1.66
2006	6	8.33	16.17	12.74	1.35	11.92	22.08	17.09	1.76	16.29	28.28	21.04	1.54
2006	7	9.75	20.19	14.36	1.99	15.20	24.59	20.10	1.65	17.25	28.23	21.80	1.89
2006	8	8.72	20.00	15.52	1.86	14.56	24.96	20.26	1.77	18.15	28.52	23.58	1.99
2006	9	9.64	19.17	14.83	1.58	14.96	25.39	19.87	1.52	18.47	28.52	24.44	1.92
2006	10	9.10	17.46	13.86	1.41	14.30	23.05	18.78	1.64	18.09	30.00	24.22	2.28
2006	11	8.18	17.09	12.52	1.42	12.66	21.88	17.28	1.96	18.20	30.66	23.78	2.70
2006	12	6.52	14.01	10.82	0.98	9.95	19.50	14.90	1.65	15.66	27.42	20.90	2.36
2007	1	5.91	12.89	10.30	0.97	8.60	17.84	14.03	1.67	14.93	25.23	19.37	1.80
2007	2	5.65	12.40	9.94	0.97	8.30	16.88	13.29	1.53	14.80	25.02	18.97	1.70
2007	3	5.72	11.84	9.78	0.93	9.73	16.89	13.25	1.52	14.30	25.14	18.46	1.53
2007	4	6.18	13.31	10.45	0.89	9.85	17.21	13.80	1.33	14.61	26.52	18.74	1.58
2007	5	7.72	15.45	11.44	1.06	11.88	18.60	14.94	1.32	14.64	26.32	19.72	1.58
2007	6	8.23	17.16	12.62	1.30	12.70	21.41	16.70	1.61	15.80	26.86	20.62	1.46
2007	7	7.92	18.24	14.45	1.08	12.97	23.79	18.17	1.57	15.78	27.65	21.02	1.81
2007	8	9.55	19.54	14.67	1.58	12.86	23.69	18.96	1.57	16.38	28.07	22.42	2.00
2007	9	6.34	18.22	15.01	1.96	12.60	23.39	18.67	1.72	16.16	29.06	23.39	2.34
2007	10	7.58	17.40	13.84	1.59	13.36	22.55	17.92	1.78	16.64	30.30	23.49	2.54
2007	11	7.94	16.18	12.77	1.50	10.64	20.75	16.16	2.08	15.94	29.92	22.75	2.59
2007	12	5.94	14.67	11.16	1.00	8.42	18.87	14.33	2.02	16.33	27.51	20.89	2.19
2008	1	4.97	13.15	10.42	1.06	7.35	17.78	13.56	1.92	15.95	25.27	19.50	1.78
2008	2	4.15	12.77	10.15	1.05	7.92	17.41	13.37	1.83	15.10	25.81	19.51	1.90
2008	3	5.65	12.26	9.65	1.06	8.38	17.41	13.37	2.03	15.37	27.06	19.42	1.88
2008	4	6.11	12.50	9.87	0.98	9.48	17.61	13.46	1.76	14.78	25.95	19.17	1.79
2008	5	6.74	14.89	11.68	1.01	11.17	18.83	15.38	1.44	14.63	27.27	20.25	1.92
2008	6	6.70	17.51	13.13	1.23	13.32	22.04	17.66	1.33	14.92	28.42	20.99	1.96
2008	7	6.18	19.46	13.70	1.55	13.75	23.75	18.81	1.54	16.20	28.53	21.92	1.90
2008	8	9.79	20.05	14.61	1.39	14.09	24.24	19.21	1.72	15.81	29.65	22.70	2.30
2008	9	9.80	17.36	14.11	1.11	13.52	23.11	18.62	1.71	17.30	29.50	23.76	2.47
2008	10	8.10	16.29	13.02	1.24	13.25	21.64	17.44	1.78	15.80	29.71	23.20	2.82
2008	11	7.60	14.56	11.49	1.10	10.97	19.85	15.40	1.91	15.63	29.76	21.73	2.92
2008	12	5.99	12.79	10.47	0.90	8.00	17.56	13.29	1.58	14.61	28.19	19.86	2.78
2009	1	3.87	12.66	9.83	1.07	5.00	16.68	12.64	1.74	14.14	25.57	18.39	1.72
2009	2	3.34	11.92	9.37	1.28	6.64	15.62	12.09	1.71	14.20	22.84	17.65	1.46
2009	3	5.23	12.21	9.67	1.17	8.02	16.11	12.63	1.61	14.12	24.73	18.01	1.30
2009	4	6.44	12.60	9.94	0.90	9.72	17.30	13.01	1.56	14.46	25.87	18.39	1.44
2009	5	7.34	14.41	10.57	0.79	10.93	18.02	14.00	1.51	14.44	26.77	19.18	1.59
2009	6	7.82	18.25	12.97	1.24	13.23	23.55	17.56	1.67	15.06	27.67	21.39	1.64
2009	7	7.93	18.79	14.52	1.06	13.88	23.63	19.16	1.60	16.15	28.60	22.52	1.95
2009	8	8.66	20.56	14.46	1.27	13.43	25.13	19.70	1.75	16.72	29.22	23.63	2.31
2009	9	7.58	18.12	14.17	1.28	13.42	24.77	19.05	1.79	16.96	29.52	23.92	2.38
2009	10	8.65	17.20	13.28	1.56	12.90	22.78	18.42	1.96	16.79	30.39	24.63	2.59
2009	11	8.52	15.76	11.89	1.00	10.79	21.61	16.01	2.12	15.54	30.65	23.17	2.90
2009	12	5.73	13.34	10.79	0.81	7.99	19.88	14.58	2.24	15.61	27.36	21.84	2.17
2010	1	3.26	12.09	9.85	1.05	6.10	17.89	13.18	2.10	16.15	26.48	20.74	1.97
2010	2	3.40	12.03	9.48	1.36	6.09	17.66	12.78	2.13	15.49	26.19	20.32	1.95
2010	3	2.98	11.72	9.34	1.33	5.78	16.93	12.47	2.10	15.37	26.69	20.11	1.93
2010	4	5.19	12.08	9.64	1.17	9.07	19.67	13.33	2.03	15.06	27.23	20.18	1.83
2010	5	5.91	14.56	10.90	1.29	10.51	19.09	15.06	1.73	15.28	27.72	20.17	1.70
2010	6	8.12	17.91	13.29	1.51	12.82	22.89	17.37	1.19	15.24	29.04	21.37	2.09
2010	7	10.35	19.24	14.29	1.55	14.09	24.02	19.11	1.52	16.43	28.99	22.19	2.31
2010	8	8.35	19.24	15.04	1.38	13.24	26.31	19.82	1.94	18.12	29.25	23.69	1.93
2010	9	8.00	18.94	14.99	1.54	13.98	25.81	19.63	1.61	16.76	30.17	24.43	2.52
2010	10	9.14	17.61	13.88	1.36	13.81	22.14	18.04	1.57	16.50	29.94	24.31	2.41
2010	11	7.02	16.13	11.75	1.25	10.72	21.03	16.24	1.92	16.67	29.97	23.44	2.93
2010	12	4.75	13.17	10.29	0.94	7.22	18.97	14.24	2.10	16.84	29.44	22.49	2.73

Year	Month	Celtic Seas # E				South Europe # G				Canary Current # 27			
		Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
2011	1	2.41	12.16	9.60	1.14	6.93	17.76	13.16	2.08	15.47	27.23	20.90	2.32
2011	2	3.55	12.23	9.51	1.17	6.01	16.79	12.82	2.01	14.74	24.01	19.17	1.68
2011	3	4.61	12.05	9.46	1.22	7.69	16.81	12.70	1.82	14.77	25.22	18.65	1.67
2011	4	5.28	13.07	9.98	1.16	10.58	17.75	14.10	1.58	14.54	25.50	19.01	1.49
2011	5	7.35	15.30	11.17	1.16	12.68	20.98	16.31	1.63	15.31	27.30	20.33	1.12
2011	6	6.34	17.53	11.84	1.41	11.80	22.51	17.50	1.80	15.95	27.92	21.49	1.61
2011	7	8.39	18.00	13.61	1.39	12.70	24.13	17.92	1.75	16.50	28.60	21.93	2.09
2011	8	7.39	19.05	14.16	1.33	14.07	24.94	18.84	1.62	16.40	29.14	22.47	2.12
2011	9	6.49	18.51	13.62	1.30	14.54	23.98	18.95	1.63	16.23	29.44	23.47	2.50
2011	10	8.17	18.38	12.88	1.56	14.04	22.65	18.85	1.55	16.55	30.27	23.85	2.84
2011	11	6.92	15.91	12.03	1.25	12.64	20.11	16.34	1.36	16.32	30.54	22.28	2.92
2011	12	5.45	14.34	10.51	1.06	9.21	18.39	14.74	1.68	15.09	28.35	20.78	2.87

Annex 4: Checklist of the selected species. Bañón et al. (2010) was one of the main sources used in this study, to identify the species in the focused study area, the central zone of the Eastern Atlantic waters. The occurrences were observed in the period of 1982-2012.

No	Species	Cepnames[a]	Affinity[b]	H. Use[b]	Sources	Occurrences number in each ecosystems						
						N[c]	C[c]	S[c]	W[c]	Cn[c]	G[c]	Total
1	*Acanthurus monroviae*	Acanmonr	Tropical	3	CIESM 2002, Zenetos et al. 2010	0	0	0	0	251	2038	2289
2	*Alosa fallax*	Alosfall	Temperate	3	Bañón et al. 2010	734	322	48	38	9	0	1151
3	*Ammodytes tobianus*	Ammotobi	Temperate	5	Bañón et al. 2010	1962	810	113	3	4	0	2892
4	*Anthias anthias*	Anthanth	Sub-Tropical	4	Bañón et al. 2010	0	0	3	196	123	1426	1748
5	*Argentina sphyraena*	Argesphy	Temp-Subtropical	3	Bañón et al. 2010	97	35	23	66	24	0	245
6	*Argyrosomus regius*	Argyregi	Sub-Tropical	4	Bañón et al. 2010	0	2	83	4	258	21	368
7	*Arius parkii*	Ariupark	Tropical	4	CIESM 2002, Zenetos et al. 2010	0	0	0	0	157	768	925
8	*Arnoglossus imperialis*	Arnoimpe	All	4	Bañón et al. 2010	35	3623	2264	96	283	1455	7756
9	*Arnoglossus laterna*	Arnolate	Temperate	0	Bañón et al. 2010	18639	6599	1037	250	31	26	26582
10	*Arnoglossus thori*	Arnothor	Temp-Subtropical	3	Bañón et al. 2010	2	29	39	407	43	7	527
11	*Atherina presbyter*	Athepres	Temp-Subtropical	2	Bañón et al. 2010	41	41	40	15	31	0	168
12	*Balistes capriscus*	Balicapr	All	4	Quero et al. 1986	21	174	70	29	64	3901	4259
13	*Bathysolea profundicola*	Bathprof	Sub-Tropical	4	Bañón et al. 2010	0	9	17	71	112	17	226
14	*Belone belone*	Belobelo	Temp-Subtropical	4	Bañón et al. 2010	643	68	16	30	25	0	782
15	*Blennius ocellaris*	Blenocel	Temp-Subtropical	3	Bañón et al. 2010	40	245	26	96	13	2	422
16	*Boops boops*	Boopboop	All	5	Quero et al. 2009	7	17	25	423	778	1388	2638
17	*Buglossidium luteum*	Bugllute	Temp-Subtropical	3	Bañón et al. 2010	864	566	14	22	17	2	1485
18	*Callionymus lyra*	Calllyra	Temperate	3	Bañón et al. 2010	53782	33135	3166	14	35	0	90132
19	*Callionymus maculatus*	Callmacu	Temperate	2	Bañón et al. 2010	140	350	24	67	2	1	584
20	*Campogramma glaycos*	Campglay	Sub-Tropical	3	Bañón et al. 2010	2	7	2	9	98	3	121
21	*Capros aper*	Capraper	Temp-Subtropical	0	Bañón et al. 2010	94	9559	3212	496	283	0	13644
22	*Caranx crysos*	Caracrys	Sub-Tropical	3	Quero et al. 1994, Quero et al. 2005	0	0	0	5	89	3819	3913
23	*Cephalopholis taeniops*	Cephtaen	Tropical	3	Brito et al. 2011, Deidun et al. 2011	0	0	0	0	159	1992	2151
24	*Chelidonichthys lucerna*	Chelluce	All	4	Bañón et al. 2010	304	492	40	101	243	1954	3134
25	*Chlorophthalmus agassizi*	Chloagas	Sub-Tropical	3	Quero et al. 2003, Quero et al. 1999	0	0	9	225	631	1531	2396
26	*Ciliata mustela*	Cilimust	Temperate	4	Bañón et al. 2010	3414	394	32	0	0	0	3840

No	Species	Cepnames^{a}	Affinity^{b}	H. Use^{b}	Sources	Occurrences number in each ecosystems						
						N^{c}	C^{c}	S^{c}	W^{c}	Cn^{c}	G^{c}	Total
27	*Citharus linguatula*	Cithling	Sub-Tropical	3	Bañón et al. 2010	0	0	16	88	797	2170	3071
28	*Coelorinchus caelorhincus*	Coelcael	All	3	Bañón et al. 2010	4	36	3	123	294	1236	1696
29	*Conger conger*	Congcong	Temp-Subtropical	4	Bañón et al. 2010	267	2759	1247	478	161	8	4920
30	*Coris julis*	Corijuli	Sub-Tropical	3	Bañón et al. 2010	2	8	11	374	87	1383	1865
31	*Dactylopterus volitans*	Dactvoli	Sub-Tropical	3	Quero et al. 2004	1	10	3	59	738	2471	3282
32	*Dentex macrophthalmus*	Dentmacr	Sub-Tropical	4	Bañón et al. 2010	0	0	5	13	452	519	989
33	*Dicentrarchus labrax*	Dicelabr	Temperate	4	Bañón et al. 2010	702	683	362	68	21	1	1837
34	*Dicologlossa cuneata*	Dicocune	Sub-Tropical	4	Bañón et al. 2010	5	0	193	25	231	1382	1836
35	*Diplodus vulgaris*	Diplvulg	Sub-Tropical	4	Bañón et al. 2010	0	0	15	515	157	2	689
36	*Dipturus batis*	Diptbati	Temperate	3	Bañón et al. 2010	276	967	17	14	13	0	1287
37	*Echeneis naucrates*	Echenauc	Tropical	3	Quero et al. 2005	0	0	6	7	99	767	879
38	*Echiichthys vipera*	Echivipe	Temperate	3	Bañón et al. 2010	614	488	32	32	8	0	1174
39	*Engraulis encrasicolus*	Engrencr	All	5	Bañón et al. 2010	6133	417	1366	595	175	1414	10100
40	*Ephippion guttifer*	Ephigutt	Tropical	4	Oral 2010	0	0	0	0	196	2761	2957
41	*Epinephelus marginatus*	Epinmarg	Sub-Tropical	5	Bañón et al. 2010	0	2	0	129	102	1343	1576
42	*Fistularia petimba*	Fistpeti	Tropical	2	CIESM 2002, Zenetos et al. 2010	0	0	0	0	346	960	1306
43	*Gaidropsarus macrophthalmus*	Gaidmacr	Temperate	2	Bañón et al. 2010	0	106	16	0	0	0	122
44	*Gaidropsarus mediterraneus*	Gaidmedi	Temp-Subtropical	3	Bañón et al. 2010	8	127	19	37	2	0	193
45	*Galeoides decadactylus*	Galedeca	Tropical	4	Oral 2010	0	0	0	0	909	2694	3603
46	*Galeus melastomus*	Galemela	Temp-Subtropical	3	Bañón et al. 2010	144	1745	3105	510	72	6	5582
47	*Gephyroberyx darwinii*	Gephdarw	Tropical	4	CIESM 2002, Zenetos et al. 2010	0	0	0	0	211	1359	1570
48	*Halosaurus ovenii*	Halooven	Sub-Tropical	0	CIESM 2002, Quero et al. 1994	0	0	0	0	346	2012	2358
49	*Hoplostethus cadenati*	Hoplcade	Tropical	4	Quero et al. 1997b, Quero et al. 1997c, Quero et al. 1994	0	0	0	0	312	37	349
50	*Hymenocephalus italicus*	Hymeital	All	0	Quero et al. 2000	0	9	4	261	261	1406	1941
51	*Labrus mixtus*	Labrmixt	Temperate	2	Bañón et al. 2010	621	7456	43	32	8	1	8161
52	*Lepidorhombus whiffiagonis*	Lepiwhif	Temperate	5	Bañón et al. 2010	11166	28561	2577	200	7	0	42511
53	*Lithognathus mormyrus*	Lithmorm	Sub-Tropical	3	Bañón et al. 2010	0	0	18	75	110	15	218
54	*Liza ramada*	Lizarama	Temp-Subtropical	4	Bañón et al. 2010	26	19	180	70	9	3	307
55	*Merluccius merluccius*	Merlmerl	Temp-Subtropical	5	Bañón et al. 2010	24962	46324	14095	2448	64	1	87894
56	*Mugil cephalus*	Mugiceph	All	5	Bañón et al. 2010	8	1	3	82	65	7	166
57	*Mustelus mustelus*	Mustmust	All	5	Bañón et al. 2010	26	42	11	37	528	880	1524
58	*Mycteroperca rubra*	Myctrubr	Sub-Tropical	3	Oral 2010	0	0	3	23	187	35	248
59	*Myctophum punctatum*	Myctpunc	Temp-Subtropical	0	Bañón et al. 2010	9	130	125	301	84	0	649
60	*Notacanthus bonaparte*	Notabona	Subtropical	0	Bañón et al. 2010	0	22	1	47	17	0	87
61	*Pagrus caeruleostictus*	Pagrcaer	Sub-Tropical	4	Bañón et al. 2010	0	0	3	10	788	2032	2833
62	*Parapristipoma octolineatum*	Paraocto	Tropical	4	Oral 2010	0	0	0	14	231	11	256
63	*Pegusa lascaris*	Pegulasc	All	3	Bañón et al. 2010	56	89	26	20	88	754	1033

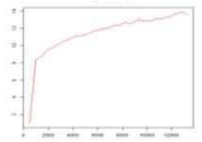
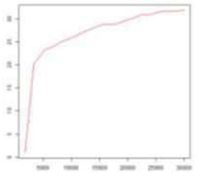
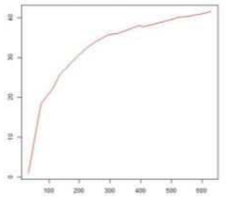
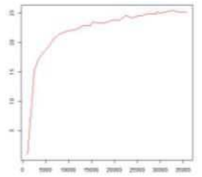
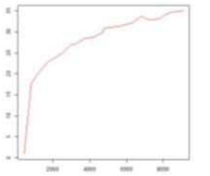
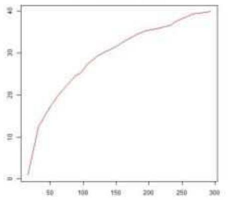
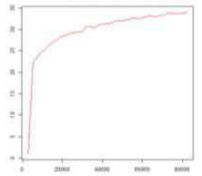
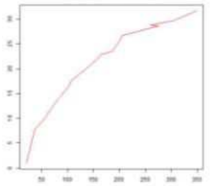
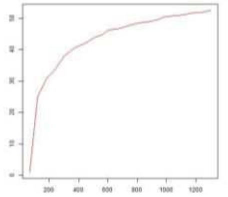
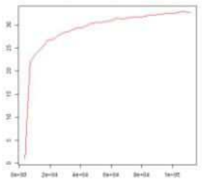
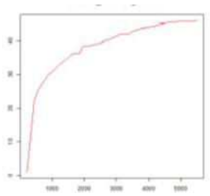
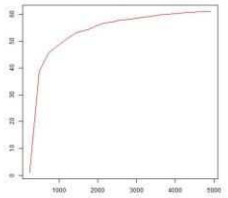
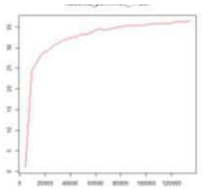
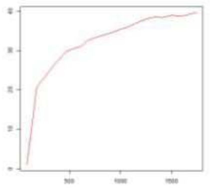
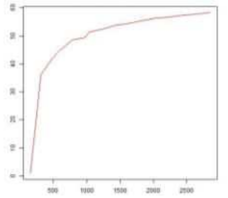
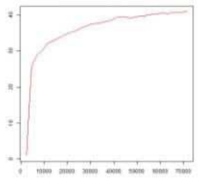
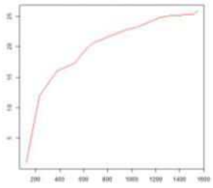
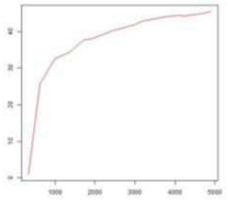
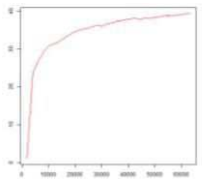
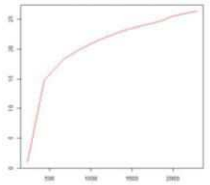
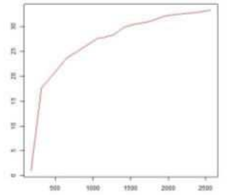
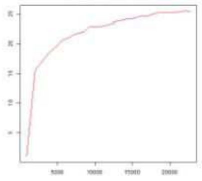
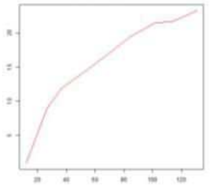
No	Species	Cepnames[a]	Affinity[b]	H. Use[b]	Sources	Occurrences number in each ecosystems						
						N[c]	C[c]	S[c]	W[c]	Cn[c]	G[c]	Total
64	*Peristedion cataphractum*	Pericata	Sub-Tropical	4	Bañón et al. 2010	1	0	0	106	323	2083	2513
65	*Pisodonophis semicinctus*	Pisosemi	Tropical	4	Bilecenoglu et al. 2009,	0	0	1	0	51	97	149
66	*Pomatomus saltatrix*	Pomasalt	Sub-Tropical	5	Quero et al. 1997b, Quero et al. 1997c	0	0	2	38	232	1336	1608
67	*Pontinus kuhlii*	Pontkuhl	Sub-Tropical	4	Oral 2010	0	0	5	5	510	969	1489
68	*Raja miraletus*	Rajamira	Sub-Tropical	4	Bañón et al. 2010	0	1	2	267	120	1448	1838
69	*Rhinobatos cemiculus*	Rhincemi	Sub-Tropical	3	Bañón et al. 2010	0	1	0	15	362	2061	2439
70	*Rhinobatos rhinobatos*	Rhinrhin	Tropical	4	Bañón et al. 2010	0	0	0	1	377	1759	2137
71	*Salmo salar*	Salmsala	Temperate	5	Bañón et al. 2010	2963	433	99	291	0	0	3786
72	*Sarda sarda*	Sardsard	All	5	Quero et al. 1991	14	21	32	43	114	1358	1582
73	*Sardina pilchardus*	Sardpilc	Temp-Subtropical	5	Bañón et al. 2010	2094	712	2703	383	141	0	6033
74	*Scomber scombrus*	Scomscom	Temp-Subtropical	5	Bañón et al. 2010	50225	16957	4296	90	24	4	71596
75	*Scophthalmus rhombus*	Scoprhom	Temp-Subtropical	4	Bañón et al. 2010	5604	1158	36	43	9	0	6850
76	*Scorpaena scrofa*	Scorscro	All	4	Bañón et al. 2010	29	18	18	795	94	1365	2319
77	*Scyliorhinus stellaris*	Scylstel	All	3	Bañón et al. 2010	68	385	16	37	142	1331	1979
78	*Solea senegalensis*	Solesene	Sub-Tropical	4	Oral 2010, Zenetos et al. 2010	0	0	12	17	316	7	352
79	*Sphoeroides pachygaster*	Sphopach	Sub-Tropical	4	Peristeraki et al. 2006	1	4	3	1	256	790	1055
80	*Sphyraena sphyraena*	Sphysphy	Sub-Tropical	3	Bañón et al. 2010	0	0	0	86	130	41	257
81	*Spondyliosoma cantharus*	Sponcant	All	4	Bañón et al. 2010	530	217	400	305	329	26	1807
82	*Sprattus sprattus*	Spraspra	Temperate	5	Bañón et al. 2010	148726	14708	271	11	0	2	163718
83	*Stromateus fiatola*	Strofiat	Sub-Tropical	3	Quero et al. 1991	0	0	1	35	309	2013	2358
84	*Torpedo marmorata*	Torpmarm	All	0	Bañón et al. 2010	11	19	79	166	306	1521	2102
85	*Trachurus trachurus*	Tractrac	All	5	Bañón et al. 2010	41871	17963	9367	1590	253	3	71047
86	*Trachyrincus scabrus*	Tracscab	All	3	Bañón et al. 2010	0	115	17	51	73	0	256
87	*Trichiurus lepturus*	Triclept	Tropical	5	Bañón et al. 2010	0	4	4	0	200	1332	1540
88	*Trigla lyra*	Triglyra	Sub-Tropical	3	Bañón et al. 2010	8	49	28	72	187	1997	2341
89	*Umbrina canariensis*	Umbrcana	Sub-Tropical	4	Oral 2010	2	1	8	23	638	1200	1872

[a] The column of *Cepnames* holds the eight-characters of the species Zoological Latin names, generated by *Cepnames* function of *Vegan* package in *R* software (https://cran.r-project.org/web/packages/rich/rich.pdf).

[b] The values of affinity and human use (H. Use) were obtained from a global information on fishes (http://fishbase.org); 5 = Highly commercial (hc); 4 = Commercial (c); 3 = Minor commercial (mc); 2 = Subsistence fisheries (sf); 1 = Potential interest (pi); 0 = no interest (ni) or no data.

[c] N = North Sea; C = Celtic Sea; S = South European Atlantic Shelf; W = Western Mediterranean Sea; Cn = Canary Current; G = Guinea Current.

Annex 5: Rarefaction graph species “specific” richness per 2° latitude.

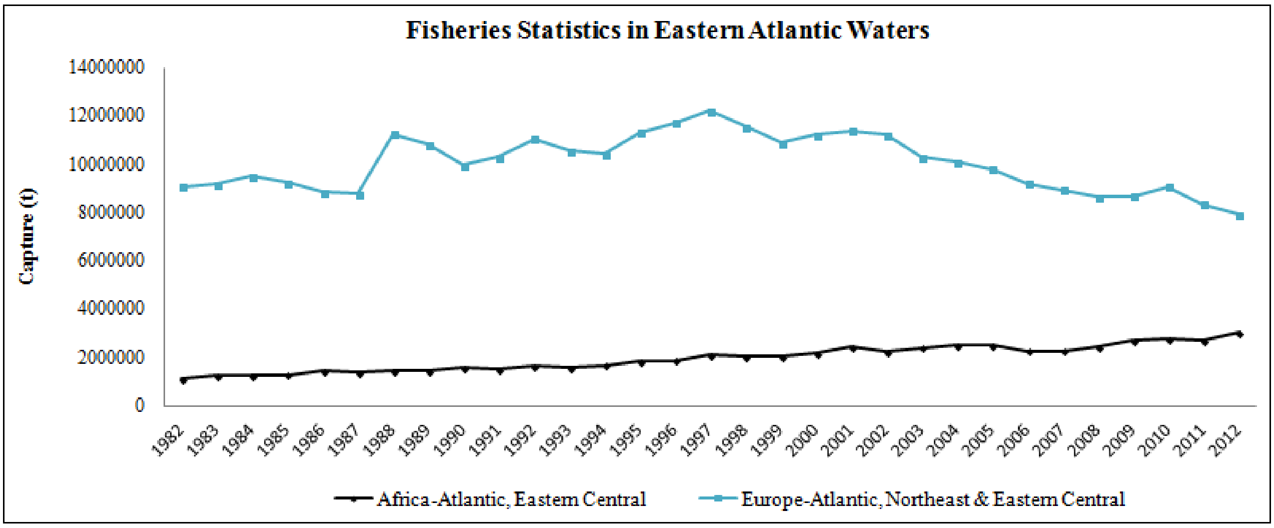
No	Lat. (°N)	Rarefaction	No	Lat. (°N)	Rarefaction	No	Lat. (°N)	Rarefaction
1	62 - 64		9	46 - 48		22	20 - 22	
2	60 - 62		10	44 - 46		23	18 - 20	
3	58 - 60		11	42 - 44		24	16 - 18	
4	56 - 58		12	40 - 42		25	14 - 16	
5	54 - 56		13	38 - 40		26	12 - 14	
6	52 - 54		14	36 - 38		27	10 - 12	
7	50 - 52		15	34 - 36		28	8 - 10	
8	48 - 50		18	28 - 30				

Annex 6: SST statistics by season in each ecosystem (1982 to 2012).

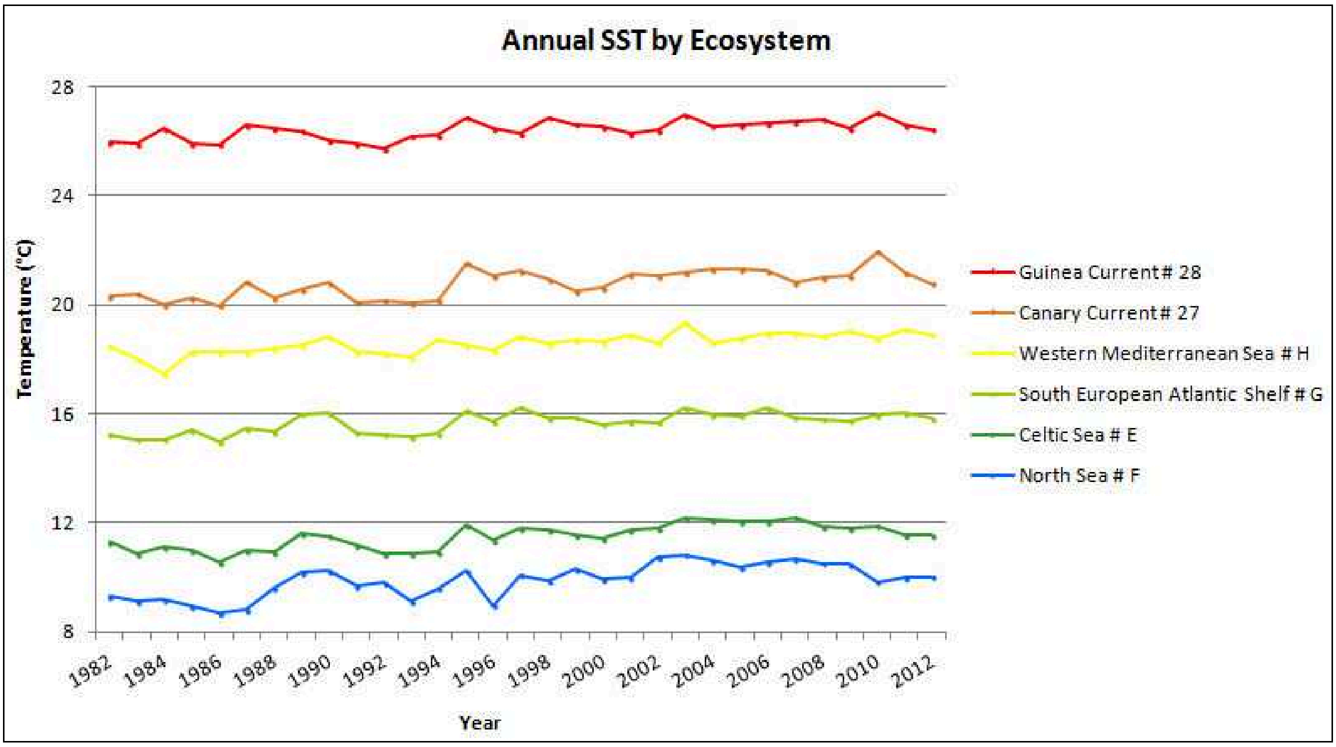
No	Seasons	Stat.	Ecosystems					
			North S.	Celtic S.	South Europ.	Western Medit.	Canary C.	Guinea C.
1	Winter	Mean	5.916	9.357	12.915	14.011	18.66	26.93
		STD	0.759	0.454	0.389	0.357	0.686	0.455
		Slope	0.038	0.037	0.013	0.014	0.037	0.027
		P value	0.009	2.70E-06	0.087	0.053	0.005	0.002
2	Spring	Mean	9	10.726	14.844	17.577	19.561	26.934
		STD	0.839	0.544	0.547	0.681	0.57	0.374
		Slope	0.063	0.044	0.042	0.057	0.04	0.012
		P value	2.40E-05	2.40E-06	1.60E-05	8.20E-07	0.00014	0.125
3	Summer	Mean	14.581	14.274	19	24.17	22.595	24.909
		STD	0.899	0.599	0.56	0.613	0.545	0.483
		Slope	0.055	0.031	0.028	0.037	0.039	0.025
		P value	0.001	0.008	0.009	0.001	9.70E-05	0.006
4	Autumn	Mean	10.03	11.607	15.904	18.567	22.256	26.867
		STD	0.56	0.557	0.557	0.494	0.678	0.468
		Slope	0.035	0.037	0.027	0.02	0.042	0.035
		P value	0.001	0.00031	0.012	0.047	0.001	1.80E-05

North S. = North Sea; Celtic S. = the Celtic Sea; South Europ = the South European Shelf; Western Medit. = the Western Mediterranean Sea; ; Canary C. = the Canary Current; Guinea C. = the Guinea Current.

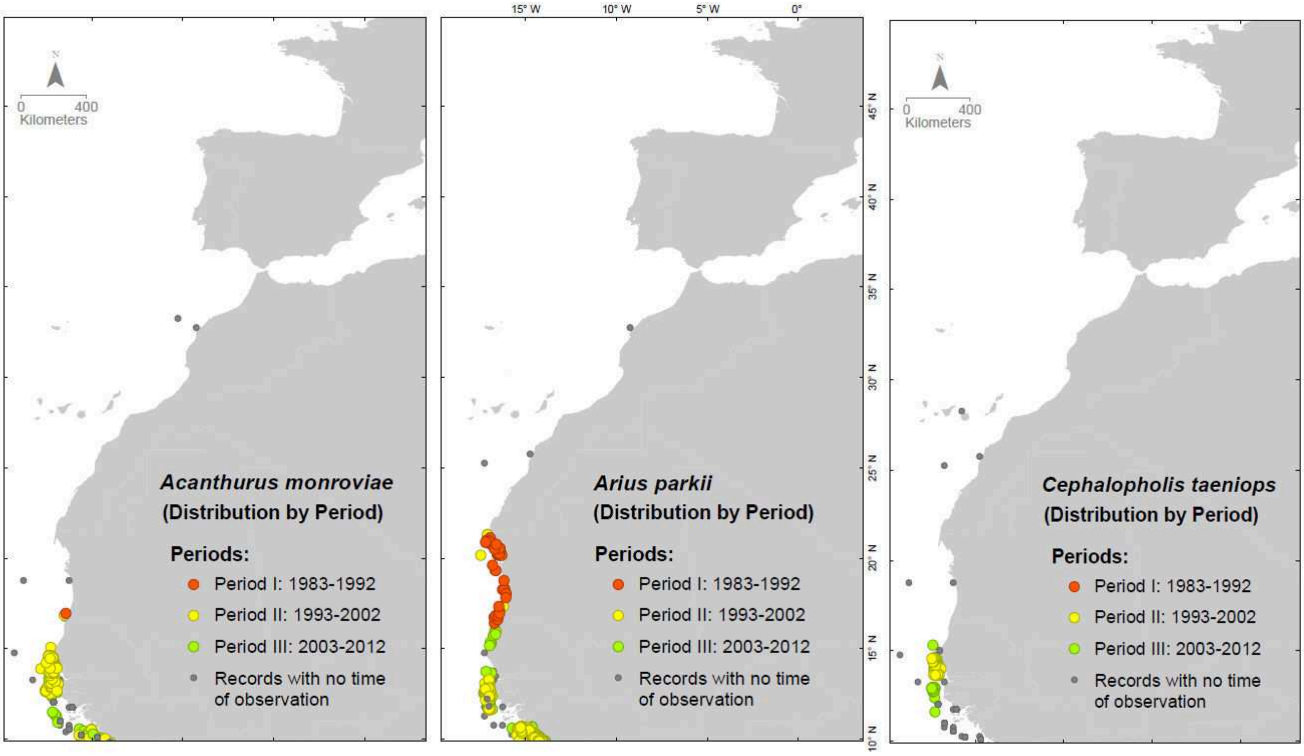
Annex 7: Capture production from 1982-2012 (FAO 2016).

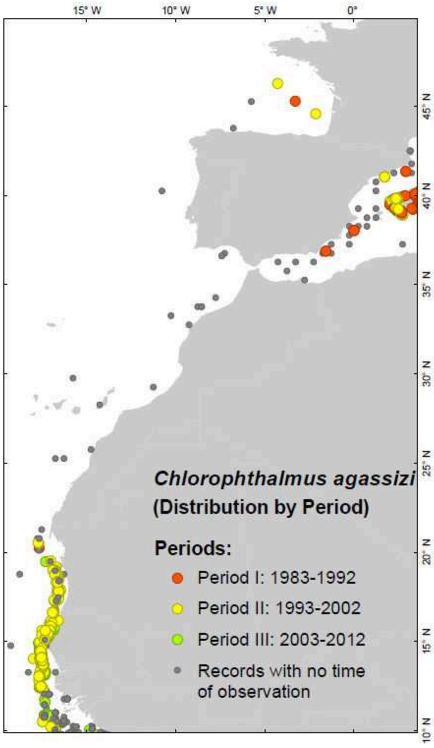


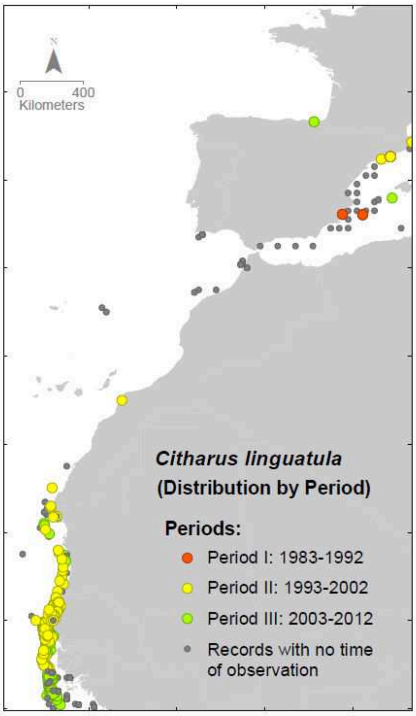
Annex 8: Mean annual SST by ecosystem represented by different colors.

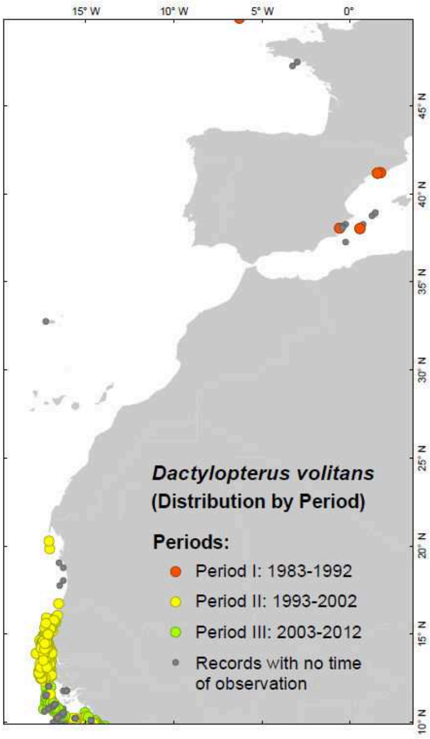


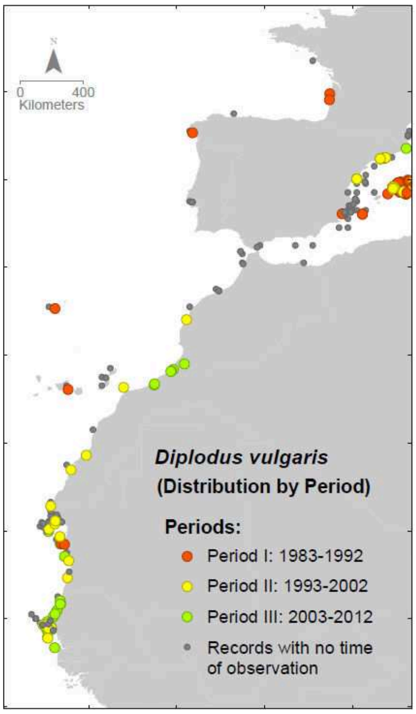
Annex 9: Occurrence distributions of species with north-bound trend.

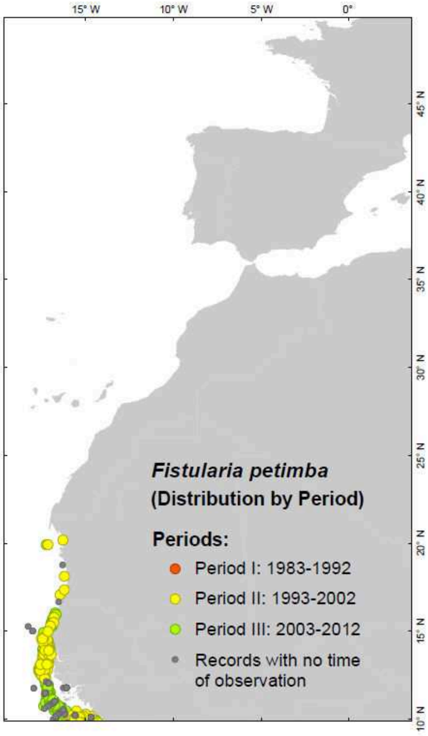


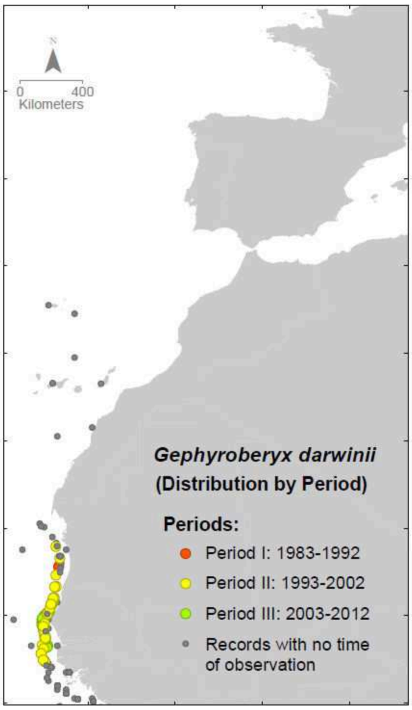

15° W
10° W
5° W
0°
45° N
40° N
35° N
30° N
25° N
20° N
15° N
10° N
Chlorophthalmus agassizi
(Distribution by Period)
Periods:
Period I: 1983-1992
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation


N
0 400
Kilometers
Citharus linguatula
(Distribution by Period)
Periods:
Period I: 1983-1992
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation


15° W
10° W
5° W
0°
45° N
40° N
35° N
30° N
25° N
20° N
15° N
10° N
Dactylopterus volitans
(Distribution by Period)
Periods:
Period I: 1983-1992
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation


N
0 400
Kilometers
Diplodus vulgaris
(Distribution by Period)
Periods:
Period I: 1983-1992
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation


15° W
10° W
5° W
0°
45° N
40° N
35° N
30° N
25° N
20° N
15° N
10° N
Fistularia petimba
(Distribution by Period)
Periods:
Period I: 1983-1992
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation


N
0 400
Kilometers
Gephyroberyx darwinii
(Distribution by Period)
Periods:
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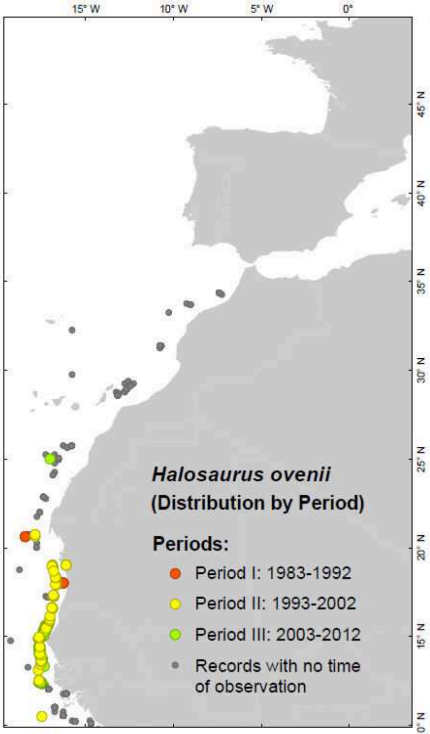
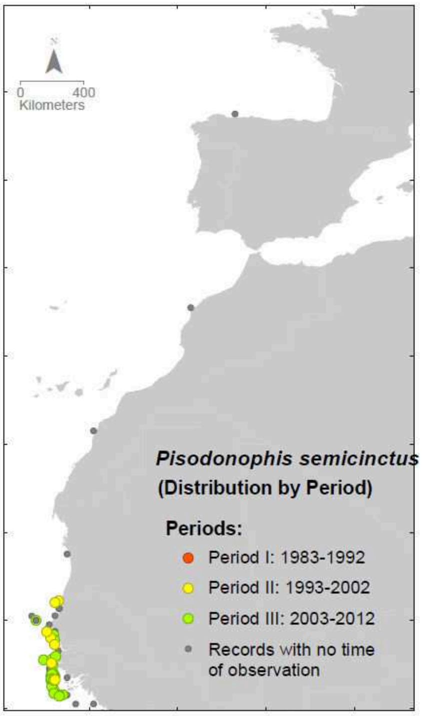
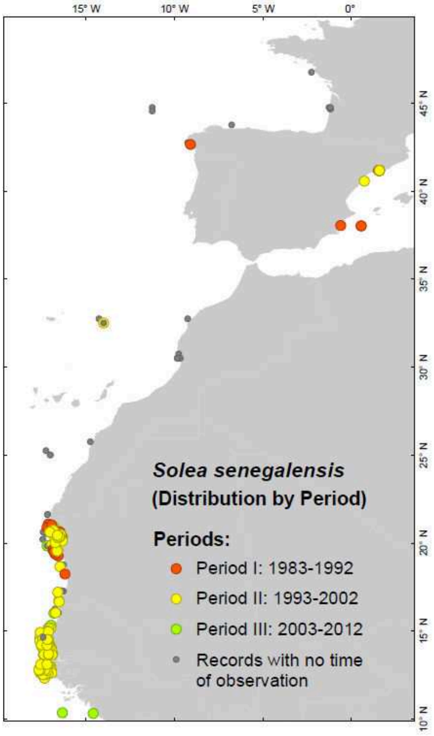
Period II: 1993-2002
Period III: 2003-2012
Records with no time of observation

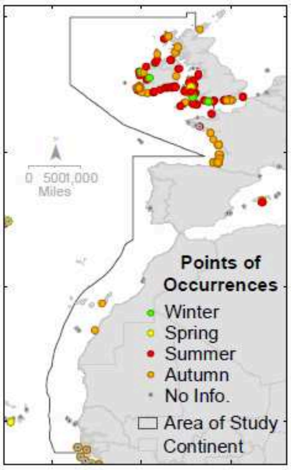






Annex 10: *B. capriscus*'s environmental values of all variables taking into account.

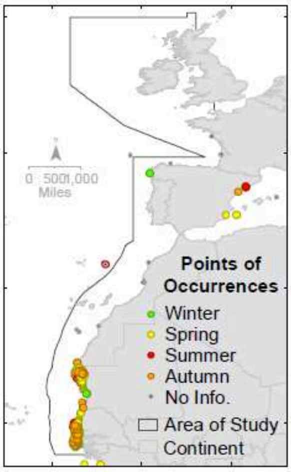
	SstAvD	SstAvN	SstMoD	SstMoN	ChlorMo	CdomMo	PicMo	KdMo	PocMo	ParMo	IparMo	Depth-Area	Slope	Vrm	BenZon
All Seasons															
Min	10.16	9.58	8.51	7.43	0.089	0.843	0.00007	0.025	36.48	6.12	0.00076	2	0.122	0	3
LowWhis	19.43	18.73	22.21	19.05	0.089	0.843	0.00007	0.025	36.48	23.5	0.00118	2	0.122	0	4
5th	19.24	18.35	16.43	15.58	0.089	0.903	0.0001	0.029	36.48	23.64	0.00121	12	0.272	0.003	1
10th	21.97	21.46	17.78	17.21	0.089	0.903	0.0001	0.029	36.48	28.34	0.00133	17	0.384	0.005	2
25th	24.66	24.01	26.01	24.41	0.149	1.371	0.00012	0.041	50.2	35.97	0.00159	29	0.926	0.016	
75th	28.19	27.6	28.58	28.09	1.871	2.116	0.00131	0.155	271.95	44.63	0.00187	4191	11.15	0.397	
90th	28.91	28.14	28.98	28.49	3.564	4.378	0.0059	0.251	417.2	47.19	0.00191	4981	22.554	0.61	
95th	29.13	28.39	29.21	28.6	4.597	6.216	0.01172	0.312	486.88	47.19	0.00191	5113	37.081	0.755	
UpWhis	31.57	30.09	30.6	29	3.939	3.219	0.00306	0.318	531.82	54.58	0.00199	5913	26.245	0.967	
Max	31.57	30.09	30.6	29	11.562	9.987	0.05576	0.86	2978.62	54.58	0.00199	5913	80.01	0.979	
Winter-Spring															
Min	10.86	10.12	8.62	7.99	0.097	0.843	0.00012	0.03	38.73	6.12	0.0016				
LowW	18.59	18.32	24.65	25.49	0.15	1.446	0.00012	0.041	50.2	31.53	0.00185				
5th	19.32	19.39	26.01	25.95	0.149	0.903	0.00012	0.041	50.2	35.18	0.00178				
10th	21.46	21.32	26.01	25.95	0.149	0.903	0.00012	0.041	50.2	35.97	0.00187				
25th	23.76	23.42	26.79	27.02	0.15	1.446	0.00012	0.041	50.2	39.49	0.00187				
75th	27.22	26.89	28.23	28.09	0.15	1.446	0.00026	0.041	51.16	44.88	0.0019				
90th	27.85	27.44	28.81	28.17	0.196	1.446	0.00026	0.046	60.75	47.19	0.00191				
95th	27.85	27.44	29.33	28.62	0.694	2.276	0.00059	0.079	126.1	47.19	0.00191				
UpW	30.54	29.09	29.79	29	0.15	1.446	0.00042	0.041	51.16	52.82	0.00192				
Max	30.54	29.09	29.79	29	11.472	6.97	0.00725	0.807	2719.27	52.82	0.00197				
Summer-Autumn															
Min	10.16	9.58	8.51	7.43	0.089	0.933	0.00007	0.025	36.48	10.4	0.00076				
LowW	22.36	22.59	8.51	7.43	0.089	0.933	0.00007	0.025	36.48	19.93	0.00083				
5th	18.49	17.73	15.4	14.54	0.089	1.292	0.0001	0.025	36.48	19.93	0.00106				
10th	22.82	21.64	16.42	15.55	0.089	1.343	0.0001	0.029	36.48	23.62	0.00123				
25th	26.18	25.79	18.03	17.66	0.089	1.371	0.0001	0.029	36.48	32.99	0.00138				
75th	28.74	27.98	28.58	28.01	2.987	3.188	0.00433	0.218	363.09	41.79	0.00175				
90th	29.07	28.33	29.21	28.6	3.928	5.974	0.01049	0.276	480.1	44.09	0.00186				
95th	29.3	28.57	29.21	28.6	5.527	6.722	0.01392	0.399	530.95	44.86	0.00189				
UpW	31.57	30.09	30.6	28.87	7.131	5.871	0.01049	0.429	848.75	54.58	0.00199				
Max	31.57	30.09	30.6	28.87	11.562	9.987	0.05576	0.86	2978.62	54.58	0.00199				



*See legend in Figure 4-22

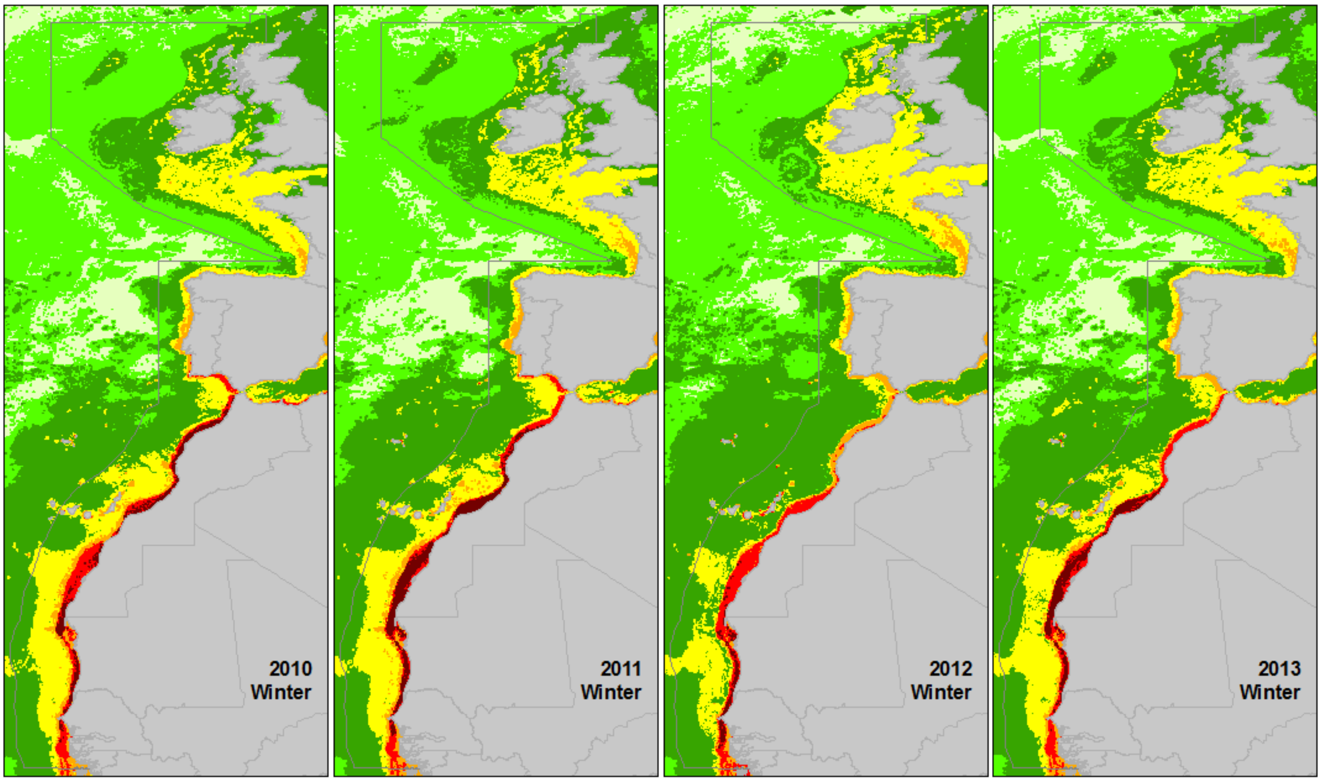
Annex 11: *S. senegalensis*'s environmental values of all variables.

	SstAvD	SstAvN	SstMoD	SstMoN	ChlorMo	CdomMo	PicMo	KdMo	PocMo	ParMo	IparMo	Depth-Area	Slope	Vrm	BenZon
All Seasons															
Min	12.31	12.5	11.63	10.64	0.108	3.404	0.00009	0.028	40.88	16.98	0.00115	2	0.122	0.002	3
LowWhis	12.31	12.5	12.56	12.47	0.108	3.404	0.00009	0.028	40.88	34.28	0.00115	2	0.122	0.002	1
5th	17.74	16.98	13	13.32	0.118	3.775	0.0001	0.028	43.45	34.69	0.00126	3	0.344	0.009	4
10th	17.91	17.4	17.36	16.88	0.189	3.846	0.00013	0.037	59.7	38.58	0.00151	5	0.486	0.013	2
25th	18.96	18.81	19.77	19.18	2.279	4.376	0.00407	0.178	351.42	41.97	0.00156	13	0.876	0.055	
75th	25.93	25.24	24.62	24.35	9.32	7.082	0.01192	0.611	781.42	53.51	0.00191	48.5	3.262	0.452	
90th	27.85	27.37	26.12	25.89	15.016	7.942	0.01531	1.059	886.2	56.34	0.00196	87	6.944	0.673	
95th	29.26	27.65	26.39	26.22	16.194	8.782	0.01857	1.123	1087.74	57.62	0.00197	363.5	8.313	0.766	
UpWhis	30.27	28.16	26.59	26.48	18.764	9.103	0.02108	1.14	1367.82	58.47	0.00197	101	6.455	0.947	
Max	30.27	28.16	26.59	26.48	18.764	9.103	0.02618	1.405	1637.45	58.47	0.00197	4874	39.788	0.947	
Winter-Spring															
Min	12.31	12.5	11.63	10.64	0.108	3.902	0.00009	0.028	40.88	16.98	0.00115				
LowW	16.44	12.5	16.96	10.64	0.108	3.902	0.00009	0.028	40.88	41.64	0.00153				
5th	17.45	16.47	12.56	12.47	0.108	3.902	0.0001	0.028	40.88	16.98	0.00115				
10th	17.78	17.09	13	12.89	0.12	3.902	0.0001	0.028	43.87	34.28	0.00123				
25th	18.12	17.68	18.7	17.04	0.189	4.876	0.00013	0.037	59.7	48.91	0.00169				
75th	22	22.54	22.52	21.99	4.947	6.996	0.0089	0.334	511.63	56.34	0.00196				
90th	24.44	23.31	23.97	23.24	7.892	6.996	0.00958	0.525	633.4	57.76	0.00197				
95th	24.66	23.65	24.07	23.36	8.181	8.049	0.01002	0.545	727.15	58.47	0.00197				
UpW	26.99	26.73	24.07	23.48	8.199	9.103	0.01097	0.549	827.21	58.47	0.00197				
Max	26.99	26.73	24.07	23.48	8.199	9.103	0.01097	0.549	827.21	58.47	0.00197				
Summer-Autumn															
Min	20.13	18.31	20.98	21.48	4.236	3.404	0.00407	0.29	521.4	38.37	0.00151				
LowW	21.36	21.28	20.98	21.48	4.236	3.404	0.00407	0.29	521.4	38.37	0.00151				
5th	21.58	21.53	21.97	22.13	4.679	3.64	0.00417	0.321	552.63	38.57	0.00151				
10th	22.55	22.18	22.07	22.19	4.887	3.779	0.00509	0.335	567.48	38.6	0.00151				
25th	25.12	24.92	22.65	23.09	6.265	4.356	0.00717	0.417	601.33	41.94	0.00153				
75th	27.75	27.36	25.96	25.47	14.988	7.252	0.01501	1.046	872.7	48.72	0.0017				
90th	29.58	27.66	26.4	26.22	16.262	8.051	0.0194	1.129	1181.1	53.59	0.00176				
95th	29.8	27.7	26.4	26.31	17.109	8.553	0.02261	1.219	1448.71	54.29	0.00177				
UpW	30.27	28.16	26.59	26.48	18.764	8.883	0.02618	1.405	901.02	55.07	0.00177				
Max	30.27	28.16	26.59	26.48	18.764	8.883	0.02618	1.405	1637.45	55.07	0.00177				

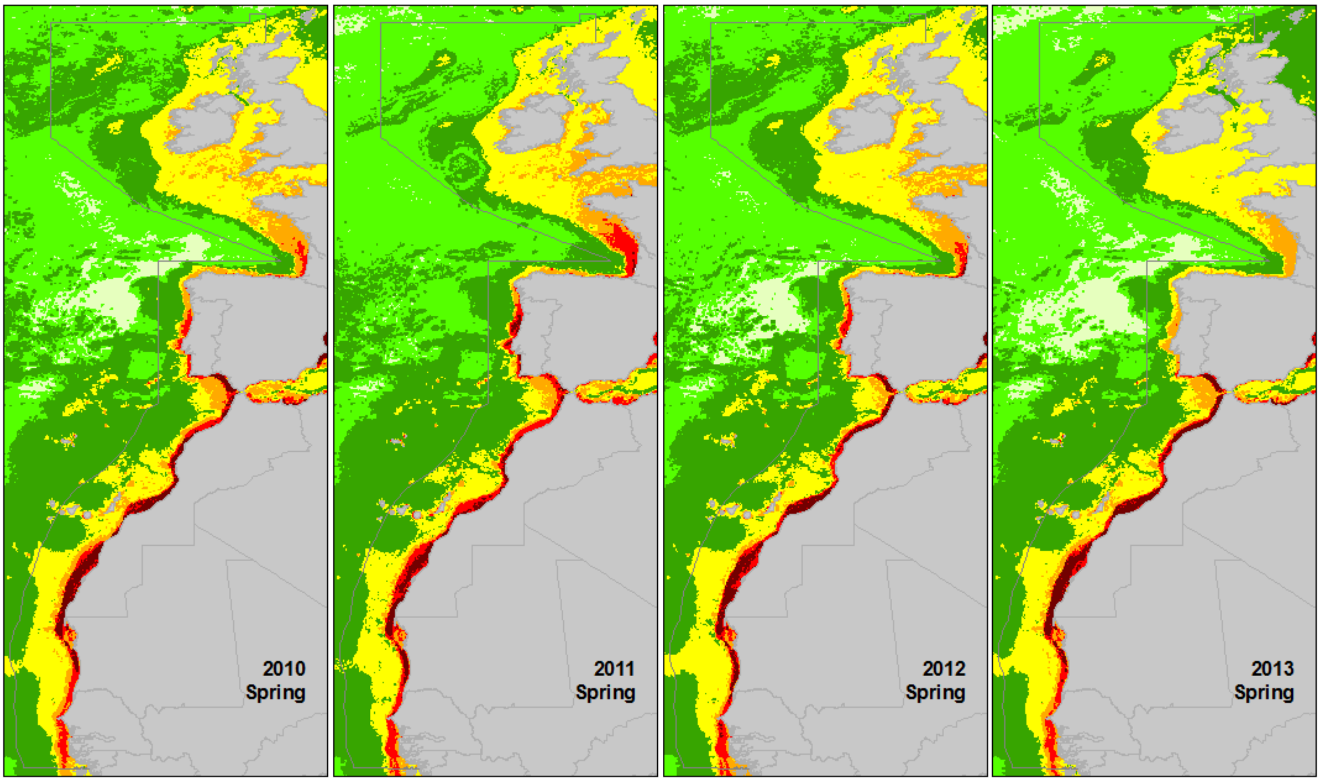


*See legend in Figure 4-22

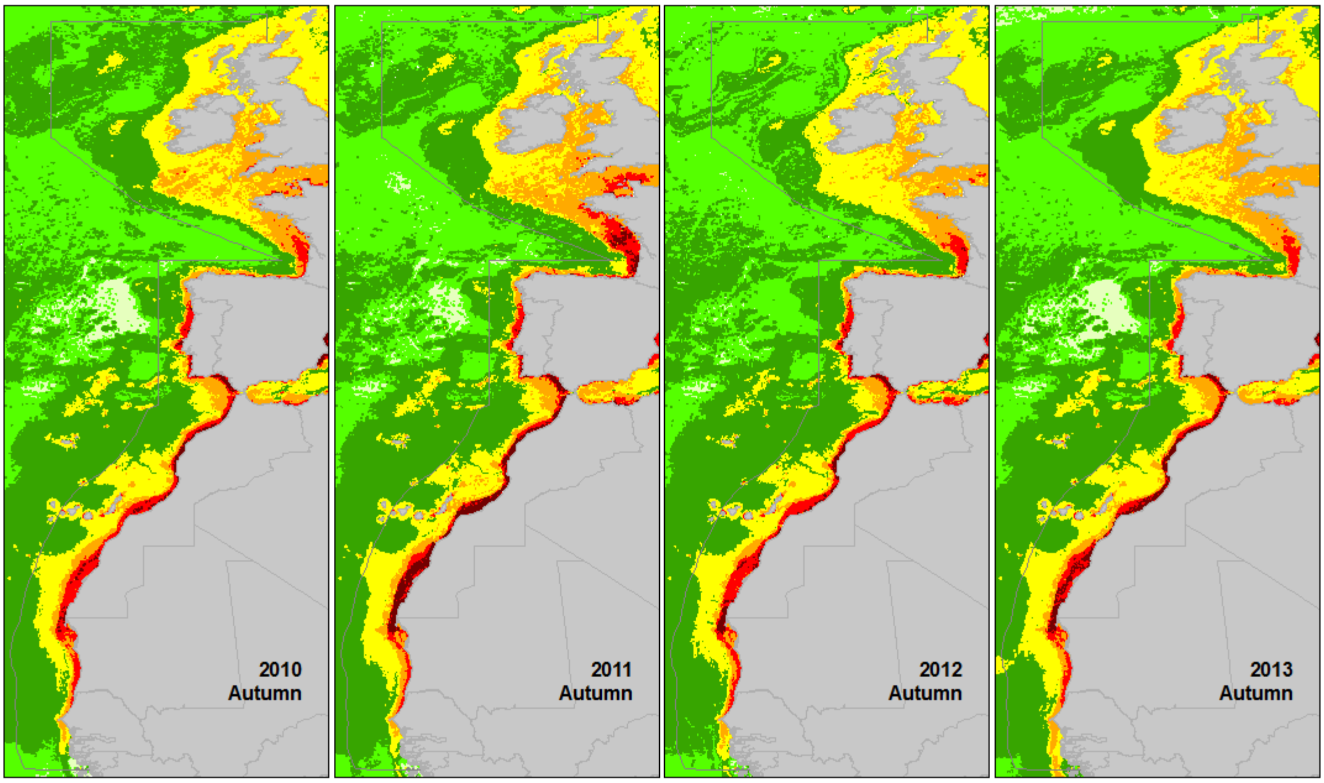
Annex 12: Winter evolution of richness of the studied species from 2010 to 2013.



Annex 13: Spring evolution of richness of the studied species from 2010 to 2013.



Annex 14: Autumn evolution of richness of the studied species from 2010 to 2013.



Version française de l'introduction et des discussions/conclusions des chapitres

Il ne s'agit pas d'un travail original mais de la traduction du document en anglais

Introduction

L'effet de serre croissant que subit l'atmosphère terrestre induit le réchauffement climatique, et entraîne donc un changement climatique à l'échelle globale (IPCC 2007). Ces phénomènes, largement reconnus dans la communauté scientifique, sont devenus, au cours des dernières décennies et des dernières années particulièrement, des problématiques essentielles, étant donné que leurs effets ont été largement observés et documentés.

Les océans ont la capacité d'absorber la chaleur et ralentissent l'augmentation de la température globale. En dépit de cette propriété, le réchauffement de l'océan a des effets immédiats sur l'environnement marin, et entraîne notamment des impacts significatifs sur la biodiversité marine (Poloczanska et al. 2013).

L'un des effets du réchauffement climatique est de faciliter l'introduction d'organismes dans des zones situées hors de leur aire de répartition naturelle. Quelques-uns de ces organismes seront en mesure d'établir une population viable et de devenirs invasifs (Secrétariat de NOBANIS 2012). Les espèces invasives sont considérées comme la deuxième cause majeure de perte de biodiversité, après la destruction de l'habitat, accélérant le déclin de communautés autochtones déjà soumises à un stress environnemental (Streftaris et Zenetos 2006), puis entrainant une modification de la richesse spécifique aux niveaux local ou régional (Hiddink et Hofstede 2008). La présence d'espèces de poissons d'origine tropicale dans les eaux européennes est rapportée depuis 1960 (Quero et al., 1997), et leur nombre augmente rapidement au cours du temps, aussi bien pour des espèces pélagiques et côtières que pour des poissons d'eau profonde (Bañón 2004). Par conséquent, le changement climatique est considéré comme un facteur majeur de modification de la biodiversité (Otero et al. 2013).

Le climat connaît des variations naturelles dans l'espace et le temps. De ce fait, les changements climatiques diffèrent géographiquement et saisonnièrement, ce qui se traduit par des changements dans la distribution des espèces marines (Cheung et al 2009; Margules et Pressey 2000). Les impacts dépendent aussi des caractéristiques biologiques et des sensibilités des espèces.De nombreuses études des effets des changements climatiques sur les organismes marins ont été menéess (Poloczanska et al. 2013). Cependant, il s'agit principalement d'études à l'échelle mondiale ou portant sur une zone de dimension limitée (e.g., Cheung et al. 2009 et ter Hofstede et al., 2010). Il existe peu d'études sur les effets des changements climatiques à l'échelle de régions liées qui couvrent l'ensemble de l'aire de distribution latitudinale des espèces.

La prise de conscience de la nécessité de protéger les milieux marins et ses ressources a mis en évidence le besoin de disposer les informations de base au niveau de l'écosystème, afin d'en réaliser un suivi à long terme et d'estimer l'étendue géographique des habitats critiques (Lundblad et al., 2006). L'accélération de la perte de la biodiversité stimule le développement de techniques d'évaluation et de surveillance de la biodiversité qui permettent d'aborder les questions écologiques à grande échelle (Chiarucci et al., 2011).

Dans le cadre de cette étude, nous avons développé plusieurs techniques de mesure du changement climatique (à l'aide des données de température de surface de la mer), et de ses impacts sur la richesse spécifique et la distribution des espèces. Nous avons pour cela fait appel à des bases de données environnementales alimentées principalement par des observations satellitaires, et à un grand nombre de données d'occurrence d'espèces provenant de bases de données librement accessibles à en ligne ainsi que de bases de données non publiées. Nous avons déterminé les niches fondamentales des espèces, puis tenté de modéliser leurs distributions saisonnières en fonction de ces niches. Tous ces modèles de distribution ont été utilisés pour créer un modèle simple de richesse spécifique. Ce modèle de richesse a ensuite été utilisé pour évaluer l’efficacité du placement des AMPs dans la zone d'étude. À la dernière étape de cette étude, nous avons proposé une prédiction de la distribution future des espèces étudiées en utilisant un modèle projeté de la température de surface de la mer (Figure 1).

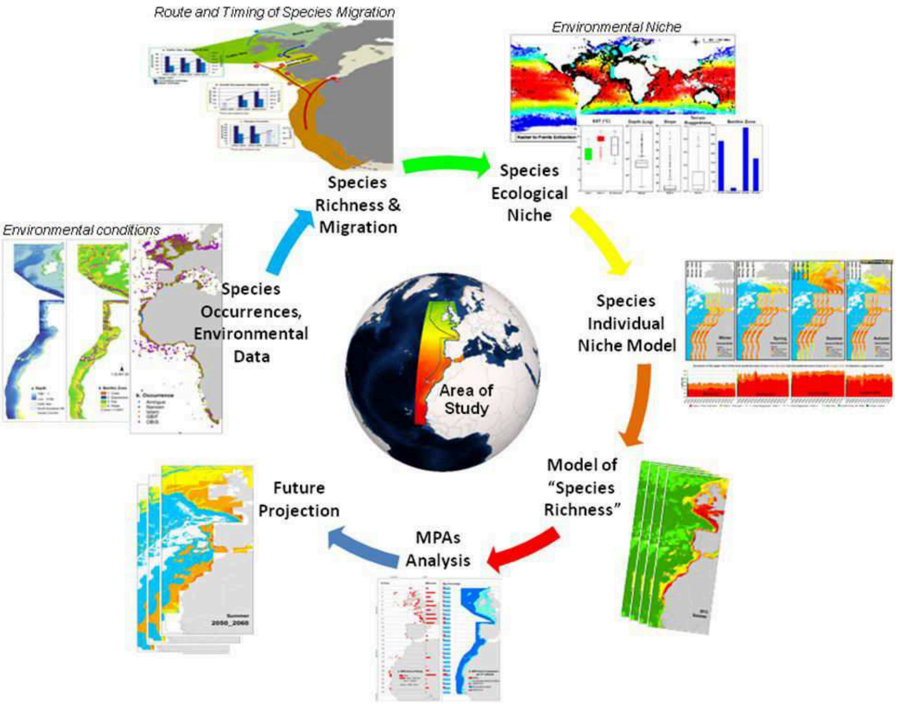


Figure 1: Illustration décrivant les principaux travails de cette étude.

Ce travail de thèse a treize objectifs :

(1) Détermination de la zone d'intérêt (AOI) où l’on peut détecter les impacts du changement climatique sur la distribution des espèces.

(2) Sélection des espèces de poissons étudiées (espèces notées comme rares ou « alien » dans la zone d'intérêt).

(3) Collecte des données d'occurrence des espèces sélectionnées à partir de plusieurs bases de données.

(4) Récupération des données environnementales : données bathymétriques et d’autres paramètres océanographiques issues des observations satellitaires.

(5) Évaluation du changement climatique à travers l’étude de l’évolution de la température de surface de la mer.

(6) Calcul des modifications du nombre d'espèces étudiées par écosystème par périodes décennales.

(7) Détermination des niches écologiques des espèces étudiées.

(8) Modélisation par SIG des distributions des espèces étudiées en fonction de leurs niches écologiques.

(9) Suivi de l'évolution saisonnière des zones de répartition des espèces étudiées au fil du temps.

(10) Identification des zones d’occupation préférentielle des espèces étudiées (*hotspots*), à partir de modèles de répartition des espèces.

(11) Analyse de superficies des aires marines protégées (AMP) présentes dans la zone d'intérêt.

(12) Évaluation de l'efficacité des AMP selon leur localisation par rapport aux zones de *hotspots*.

(13) Prédiction des distributions futures des espèces étudiées, en faisant appel à des modèles de prévision des températures de surface de la mer.

Dans la première phase de cette étude, nous allons déterminer l'aire d'intérêt de l'étude (*Area of Interest*, ou AOI) dans les eaux de l'Atlantique est (Figure 2). Cette zone d'étude couvre trois grands écosystèmes marins : le Courant des Canaries, le plateau plateau atlantique sud-européen et les mers celtiques. Ces zones, en particulier la région centrale, représentent la zone de transition entre les eaux chaudes tropicales et les eaux froides tempérées, et sont donc d'une grande importance sur le plan zoogéographique. De nombreuses espèces provenant du sud ou du nord de l'AOI ont leurs limites de distribution dans cette région, ce qui en fait une zone d'une grande sensibilité pour la détection des changements climatiques. De nombreux rapports indiquent la tendance à l'augmentation de la présence de poissons tropicaux dans la région centrale (Teixeira et al. 2014). Malheureusement, l'itinéraire et la chronologie de l'introduction d'espèces dans cette région sont mal connus (Johnston et Purkis 2011). C'est l'une des raisons pour lesquelles nous avons choisi cette zone d'étude. En outre, les études de la distribution des espèces dans cette région sont rares par rapport aux zones adjacentes, comme les eaux fermées de la mer Méditerranée.

Dans la deuxième phase de l'étude, nous allons exploiter les données environnementales disponibles, telles que la température de surface de la mer (SST), afin de déterminer l'état actuel du réchauffement de la mer dans la zone d'intérêt. L'observation par des satellites qui mesurent différents types d'énergie rayonnés par la Terre est le seul moyen de recueillir de telles données à l'échelle mondiale. L'observation par satellite a permis de travailler avec des séries temporelles exhaustives de données océanographiques physiques. Nous allons assembler les 30 ans de données de SST provenant du satellite NOAA, et les 11 ans de données des autres paramètres océaniques obtenues par le satellite MODIS-AQUA. Ces données environnementales constituent les données d'entrée clé pour de nombreuses applications.

Dans la troisième phase de l'étude, nous allons créer plusieurs cartes de distribution de la profondeur, de la pente, de la rugosité et des zones benthiques de la zone d'étude (AOI), afin de comprendre la relation entre le type de fond et la biodiversité des poissons. Ces cartes seront utilisées dans le processus de modélisation de la distribution des espèces. Les données bathymétriques utilisées proviennent de la base de données SRTM30_PLUS, tandis que les données dérivatives bathymétriques seront générées dans cette étude.

Dans la quatrième phase de l'étude, nous allons sélectionner 89 des 465 espèces de poissons rares / exotiques identifiées dans la zone d'intérêt. Les distributions des ces espèces sont en train de s'étendre car elles ont déjà été observées en dehors de leurs distributions connues. Nous allons rassembler les données d'occurrence disponibles de ces espèces sélectionnées à l'échelle mondiale à partir de plusieurs bases de données. L'énorme quantité de données d'occurrences disponibles nous permettra d'étudier l'évolution décennale de la richesse "spécifique" au niveau des écosystèmes et par 2° de latitude, et d'étudier la migration des espèces en réponse aux changements environnementaux.

Dans la cinquième phase de l'étude, les données dérivées de la bathymétriques ainsi que les données satellitaires seront utilisées pour déterminer les niches fondamentales de chaque espèce. Nous allons calculer ces niches en extrayant les valeurs environnementales au point d'occurrence au moment de l'observation. Ce processus va utiliser toutes les occurrences d'espèces disponibles à l'échelle mondiale. Ainsi, il permettra de minimiser les problèmes issus d'échantillons de petite taille. Un script écrit en langage de programmation *Python* sera utilisé pour automatiser le processus.

Dans la sixième phase de l'étude, nous allons modéliser la distribution de chaque espèce étudiée en projetant leurs niches fondamentales sur une série chronologique des données environnementales. Le modèle utilisé est un modèle de SIG. Les capacités et la flexibilité de la technique du SIG (Système d'Information Géographique), couplée à l'intégration du langage de programmation Python et à l'utilisation des données environnementales à long terme, nous ont permis de montrer l'évolution potentielle de la répartition de chaque espèce sur trois périodes décennales, de 1982 à 2013, ainsi que de montrer comment la distribution des poissons est modifiée/se décale en réponse au réchauffement des océans.

Dans la septième phase de l'étude, nous allons superposer tous les modèles d'espèces en fonction du temps pour modéliser la richesse spécifique au fil du temps. Le modèle calcule simplement le nombre d'espèces trouvées dans une zone (zone de chevauchement) à un moment donné. Ce modèle de richesse sera ensuite analysé dans la prochaine phase de l'étude pour démontrer l'importance de l'emplacement des aires marines protégées.

Dans la dernière phase de l'étude, nous allons proposer une prédiction de la répartition des espèces en utilisant le modèle futur de la température de surface de la mer. Nous allons également calculer le décalage des aires de distribution des espèces durant les la périodes 1990-1999, 2000-2009, 2050-2059 et 2090-2099.

Enfin, cette étude présente différente approches qui pourraient être mises en oeuvre pour générer des niches écologiques et des distributions potentielles des espèces, en particulier pour les espèces peu connues. La technique utilisée est également prometteuse pour modéliser la richesse spécifique dans les zones pauvres en données. Ces modèles amélioreront les modèles de prévision disponibles aujourd'hui, et les résultats apporteront une meilleure compréhension des effets du changement climatique sur la répartition et la richesse spécifique.

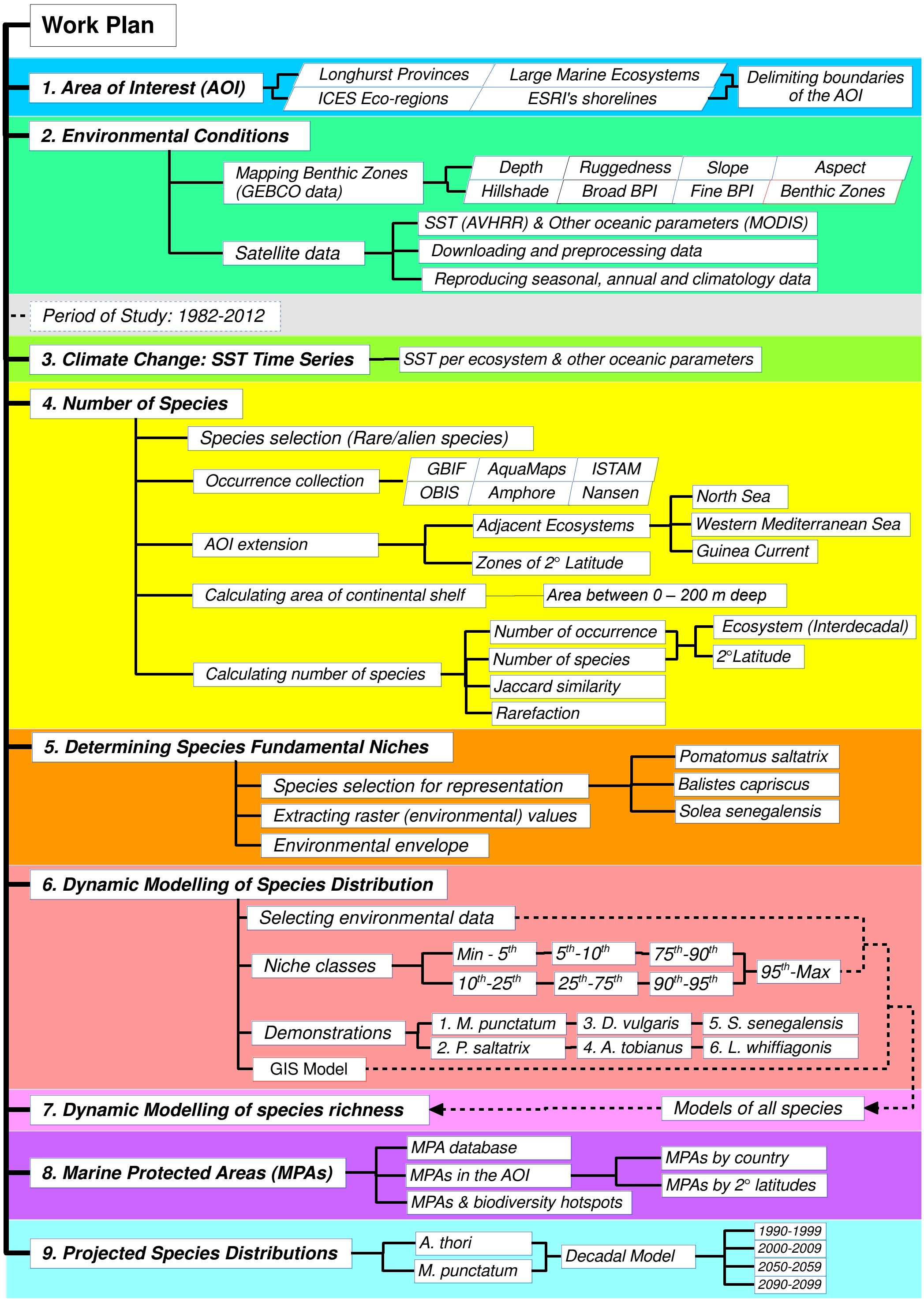


Figure 2: Plan de travail de la thèse.

4.1.3 Discussion : Conditions océanographiques dans l'AOI

Nous avons, au cours de cette étude, produit plusieurs cartes bathymétriques en appliquant une méthode de classification des eaux peu profondes à des zones plus larges et plus profondes. La classification des zones benthiques repose principalement sur l'analyse et l'interprétation de données bathymétriques multifaisceaux couplée à des données d'enquêtes visuelles (par exemple : vidéo, photos, échantillons, etc.), permettant de faire des inférences qualitatives et / ou quantitatives.

La précision des cartes de zones benthiques produites dans cette étude n'a pas été testée en raison de la grande échelle de notre analyse. Des enquêtes de terrain doivent être menées dans de futures études pour acquérir la vérité terrain et établir une évaluation statistiquement robuste de nos cartes bathymétriques. Des observations de terrain sont nécessaires pour déterminer les types d'habitats dans les zones où il y a encore des incertitudes, où des gradients d'habitats existent ou là où la diversité de l'habitat est très hétérogène (Lundblad et al., 2006). Cette étude ne définit pas des classes de nature des fonds plus détaillées en raison du manque d'observations sur le terrain, mais encourage à le faire dans les études futures.

Greene et al. (1999) ont développé avec succès un système de classification pour les habitats de poissons au large des côtes de la Californie centrale. Ils ont également décrit de grandes catégories, telles que les méga-habitats (basés sur la profondeur et les limites physiographiques générales), les méso / macro-habitats (basés sur l'échelle), la pente des fonds marins, la complexité des fonds marins, et les unités géologiques. Lundblad et al. (2006) ont ajouté que ce schéma peut être adapté à des caractéristiques de l'habitat plus détaillées, telles que les micro-habitats (basés sur l’observation des caractéristiques du fond marin à petite échelle), la pente (estimée à partir des enquêtes *in situ*), et de la complexité des fonds marins (rugosité estimée) par observation directe ou ou interprétation de photo ou de vidéo.

Coyne et al. (2003) ont choisi la classification hiérarchique pour définir et délimiter les habitats marins. Cette classification hiérarchique utilise deux catégories de classes : les « zones » et les « habitats ». Lundblad et al. (2006) expliquent que les « zones » décrivent l'emplacement d'une communauté benthique, alors que les « habitats », qui existent au sein des zones, sont basés sur la structure géomorphologique et le type de couverture biologique. La structure et les éléments composant la couverture sont ensuite divisés en niveaux principaux et détaillés. Cette approche a été développée par le Conseil de gestion des pêches des Caraïbes (Coyne et al 2002b; Christensen et al., 2003) et par la suite retouchés pour une utilisation à Hawaii et dans les Territoires US du Pacifique (Lundblad et al., 2006).

Malgré la simplicité du système de classification employé dans cette étude, nous espérons que son utilisation pour classifier le terrain benthique à grande échelle peut conduire à une gestion plus efficace des réseaux des aires marines protégées, faciliter la tâche des gestionnaires, permettre à la recherche marine et côtière de progresser, et mener à des améliorations dans le domaine de la cartographie marine.

La section suivante présente une brève discussion sur les principaux processus et phénomènes physiques dans l’AOI, principalement basée sur Mason et al. (2005). Des informations détaillées peuvent être trouvées dans cet article. Cette brève discussion vise à mettre en évidence les processus physiques pertinents qui sont communs dans le système de l'Atlantique Est, et ont un effet potentiel sur les processus biologiques et donc sur la distribution des espèces.

4.1.3.1 Principaux courants

Les principaux courants à grande échelle dans l'AOI sont le courant de l'Atlantique Nord (NAC), le courant des Açores (AC) et le courant des Canaries (CaC) (Figure 3). Ces courants sont associés à la partie orientale des *gyres* anticycloniques subtropicaux de l’Atlantique Nord (Stramma, 2001). Une partie importante du NAC qui se dirige vers le nord-est devient la Dérive Nord-Atlantique (NADC), tandis que le reste continue vers l'est en direction de l'Europe du nord.

Le courant du Portugal (PoC), qui se dirige globalement vers le sud, permet les échanges entre le NAC et l'AC (Pérez et al., 2001) lesquels, avec le PoC qui passe autour de Madère, alimentent également le CaC vers l'est (Barton, 2001).

En été, le CaC est plus fort sur la côte africaine, tandis qu'en hiver, la partie la plus puissante du CaC se trouve à l'ouest des îles Canaries (l'archipel se trouve dans la zone de transition entre les eaux côtières et océaniques). Le CaC est constant saisonnièrement.

Dans la région de la péninsule ibérique (IP), il existe un courant de sub-surface orienté vers le Pôle Nord, le courant de la péninsule ibérique (IPC), entrainé par les gradients de densité. Ce courant se trouve le long des côtes européennes et au nord-ouest du plateau africain.

Dans le détroit de Gibraltar, la masse d'eau méditerranéenne (MW), dense et à forte salinité, passe au-dessous de 1000 m dans le golfe de Cadix. Le courant MW se caractérise par sa signature de température qui s'étend loin dans l'Atlantique Nord. Ce courant forme un courant de fond vers le Pôle Nord qui s'écoule le long de la pente de la péninsule ibérique.

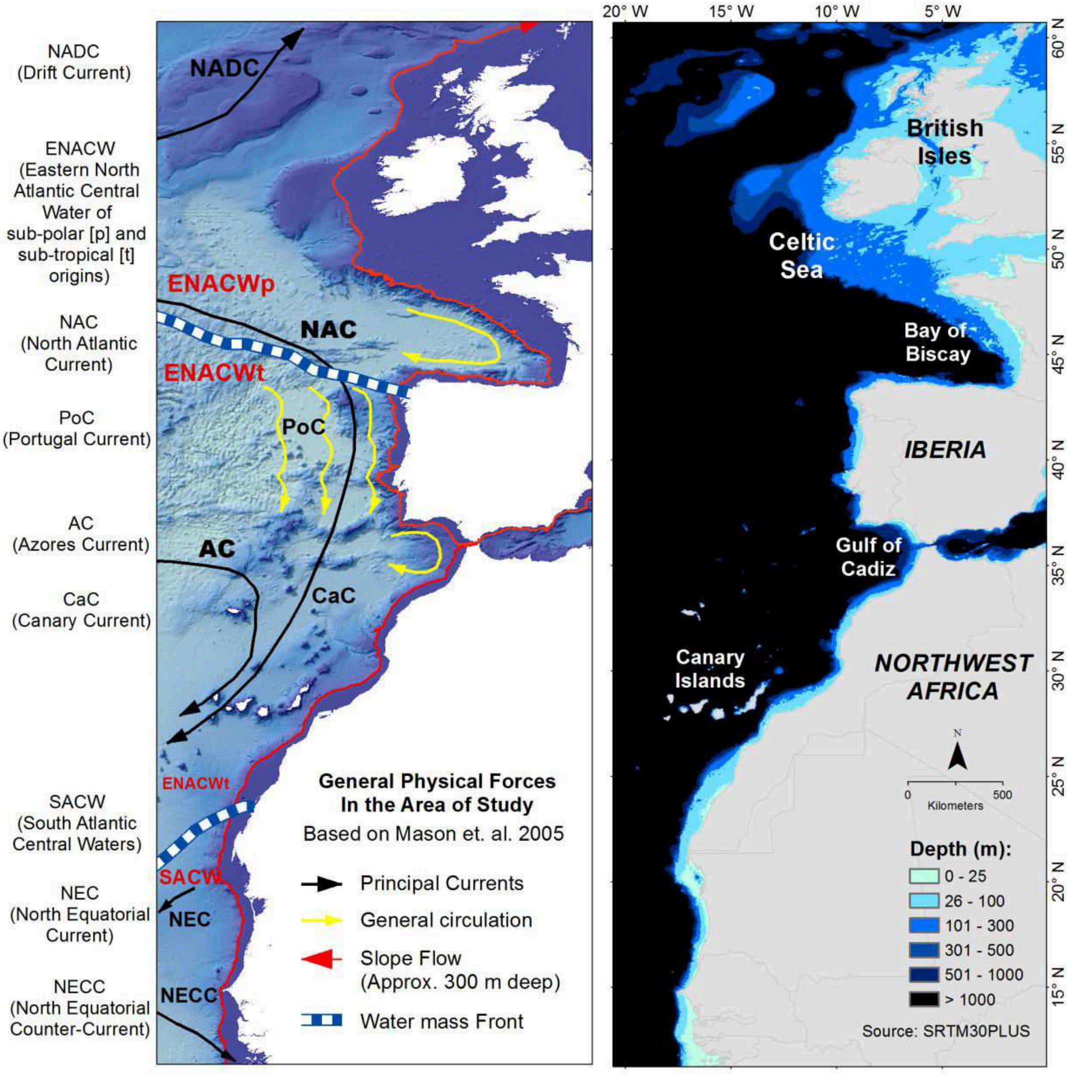


Figure 3: Les principaux courants de la zone d'étude. Le courant de l'Atlantique Nord (NAC), le courant des Açores (AC), le courant des Canaries (CaC) et le courant du Portugal (PoC) sont les courants de surface principaux à grande échelle dans l'AOI. Les eaux de l'Atlantique Nord-est central d'origine sub-polaire (ENACWp), d'origine sub-tropicale ($ENACW_T$) et les eaux de l'Atlantique Sud central (SACW) sont les principales masses d'eau dans la région. NADC est le courant de dérive de l'Atlantique Nord, tandis que NEC et NECC sont le Courant nord-équatorial et le contre-courant nord-équatorial. La circulation générale dans le golfe de Gascogne et le golfe de Cadix est indiquée (Adapté de Mason et al., 2005).

Les courants de pente (ligne rouge sur la carte de la Figure 3) sont, à ce qu'on pense, générés par une caractéristique topographique appelé l'effet conjoint de baroclinicité et de relief (JEBAR) (Huthnance, 1995; Hill et al., 1998) ; voir Trowbridge et al. (1998).

Le flux vers le Pôle Nord est persistant et lié à la pente continentale. Dans la zone de 300 m de profondeur, le courant de sub-surface circule avec une vitesse d'environ 0,1 m/s (Mason et al., 2005). À certains moments, l'écoulement vers le pôle s'étend jusqu'à la surface de la mer. Ce courant est typique des frontières orientales et des systèmes d'upwelling. L'eau des upwellings est souvent issue du courant sous-jacent vers le pôle. Les flux dirigés vers le pôle se situent généralement à des profondeurs de plus de 50 m, ils pourraient donc avoir des effets sur les premiers stades de vie des poissons pélagiques. Leur direction s'établit souvent contre les vents équatoriaux, indiquant l'influence de mécanismes de forçages non-locaux à plus grande échelle, ou d'un gradient de pression en mer (le niveau de la mer s'élève vers la côte). Cependant, le courant pourrait être aussi provoqué par un forçage local induit par la poussée hydrostatique; voir Neshyba et al. (1989).

Il existe également des courants côtiers de densité, résultant des sorties de fleuves. Aux latitudes plus élevées, ces courants sont plus étroits et plus intenses. Ils peuvent également être influencés par le vent et d'autres mécanismes de forçage, tels que la densité. Les vents favorables à l'upwelling ont tendance à diffuser des panaches flottants au large, tandis que les vents favorables aux downwellings font le contraire. Dans les grandes sorties de fleuves, où les panaches flottants sont importants et persistants, le panache agit potentiellement comme un obstacle aux transferts biologiques.

4.1.3.2 Les masses d'eau et les principales limites de Fronts

Il existe deux grandes masses d'eau océaniques dans le AOI (Mason et al., 2005) : l'eau centrale de l'Atlantique Nord (NACW), à forte salinité, domine dans la zone au-dessus de 600 m et, au sud, l'eau de l'Atlantique-sud centrale (SACW), moins salée et plus riche en éléments nutritifs ; voir la Figure 3. La NACW montre une variabilité latitudinale considérable : (1) entre les îles Canaries et la péninsule ibérique, il existe les eaux de l'Atlantique Nord-est central d'origine subtropicale ($ENACW_T$), qui s'écoulent généralement vers l'est et la péninsule ibérique, (2) l'ENACWp d'origine subpolaire, qui est constitué d'eau plus froide et plus douce. L'$ENACW_T$, légèrement plus chaude, est transportée vers le sud par le courant des Canaries (CaC). Des upwellings sont présents dans ces masses d'eau, par exemple au Cap Finisterre et au Cap Blanco (Fraga, 1981).

4.1.3.3 La limite côtière

Le fond peu profond et les irrégularités du littoral ralentissent les flux le long du rivage. Ces flux côtiers suivent généralement la ligne de côte. À proximité du mur côtier, les flux littoraux sont inhibés. La circulation verticale provoquée par les upwellings ou la circulation estuarienne pourrait favoriser la présence de flux *cross-shore* persistants bien que les flux restent faibles près du rivage. Ces courants faibles sont associés à une faible dispersion des propagules (œufs et larves de poissons), dont la tendance à la rétention près du rivage engendre ce que Wolanski (1994) appelle « sticky water » ou « l'eau collante ».

4.1.3.4 Fronts

Les fronts sont d'étroites zones de gradients renforcés qui séparent les masses d'eau. Ils persistent de plusieurs heures à plusieurs années. Les zones des fronts sont biologiquement plus productives, en raison de l'augmentation des concentrations de nutriments et de plancton, qui peuvent bénéficier aux poissons, des œufs et larves aux adultes. Les fronts sont des traits caractéristiques des frontières orientales des océans, qui agissent comme des obstacles à l'exportation de particules dans les eaux côtières recouvrant le plateau continental (par exemple, Bakun, 1996). Ainsi, ils agissent également comme des obstacles potentiels à la dispersion planctoniques et à la migration des adultes.

Il existe également un front de marée, qui est une discontinuité de la température des eaux de surface qui marque la transition d'une colonne d'eau mélangée par la marée à une colonne d'eau stratifiée verticalement. Il se produit de façon saisonnière dans des sites relativement stationnaires dans les mers celtiques et la Manche. La présence saisonnière de ce type de front est considérée comme ayant moins d'influence sur les structures des stocks de poissons que des processus plus permanents ; voir Mason et al., (2005). À l'inverse, il existe un front de rupture de pente qui sépare les eaux du plateau (habituellement moins salées) de celles de la pente et des eaux océaniques. Il se produit généralement tout au long de l'année, mais son impact sur les stocks de poissons du plateau est considéré comme relativement faible (détaillé dans Mason et al., 2005).

4.1.3.5 Ondes internes

Les ondes internes, qui peuvent se produire dans les mers celtiques et à l’ouest de la péninsule ibérique, ont généralement des amplitudes beaucoup plus grandes et des périodes plus longues (10-20 minutes à plusieurs heures) que les ondes de gravité de surface (plusieurs secondes ou minutes). Les marées internes sont des ondes internes avec la même période que la marée. L’onde interne amène des eaux plus riches en éléments nutritifs lorsqu’elle atteint le plateau ou des zones moins profondes, et a ainsi un impact biologique ; voir Ryan et al. (2005).

4.1.3.6 Tourbillons

Un tourbillon est généré à partir des flux d'eau qui se déplacent le long d'une côte incurvée ou irrégulière. La recirculation de l'eau dans les tourbillons peut retenir les propagules sur des échelles de temps importantes, améliorant le recrutement des œufs non-locaux et des larves. Ces échelles de temps pourraient être réduites par le frottement sur le fond et des courants plus forts, mais dans les baies semi-fermées, cette rétention reste importante (voir, Graham et Largier, 1997; Largier, 2003). Ainsi, les tourbillons peuvent être considérés comme des agents de dispersion autant que de rétention. Les échelles spatiales des tourbillons varient de 10 à 100 km. Dans l’AOI, les tourbillons peuvent être trouvés dans le golfe de Gascogne, au large de l'ouest de la péninsule ibérique, au large de l’Afrique du nord et au large des îles Canaries.

4.1.3.7 Upwelling

Les caractéristiques de l'océan mondial varient en raison de nombreux processus géologiques (Becker et al., 2009). Sur le fond, les caractéristiques topographiques jouent un rôle important dans la formation de plusieurs phénomènes physiques, y compris les upwellings et les zones d'ombre. La présence de caps ou de promontoires est souvent associée à une intensification des upwellings côtiers. La circulation locale peut être modifiée par la présence de canyons au large des côtes qui coupent la pente continentale, provoquant un upwelling renforcé. Par conséquent, ces phénomènes peuvent avoir un lien étroit avec les cycles de vie de différentes espèces de poissons, pour lesquelles la conservation des œufs et des larves sont importantes (Mason et al., 2005). À une plus petite échelle spatiale, les caractéristiques de l'habitat, comme le type du fond marin, influencent fortement les espèces. Hattab et al. (2014) ont mentionné que les modèles qui ne tiennent pas compte des relations espèces-habitat peuvent donner des prévisions irréalistes.

Un upwelling (ou downwelling) côtier se produit lorsque les vents équatoriaux (vers le pôle) induisent un transport d'*Ekman* de surface net vers le large (*à la côte*), ce qui entraîne une divergence (convergence) de transport près de la côte (Mason et al., 2005).

La circulation dans les upwellings et downwellings redistribue non seulement la chaleur et la salinité, mais aussi les éléments nutritifs. Ainsi, ils améliorent la production primaire dans la région concernée et affectent les niveaux trophiques élevés grâce à des processus liés à la chaîne alimentaire. Les impacts biologiques des upwellings et downwellings sont discutés dans Graham et Largier (1997) et Brink (1998).

L'une des principales caractéristiques d'une situation d'upwelling entièrement développé est que la couche de surface au large est transportée loin de la côte. Ce phénomène pourrait être une source de dispersion car il emporte des particules telles que les œufs et les larves. Cependant, un upwelling persistant et l'advection en mer qui en découle pourraient devenir une frontière importante pour les populations de poissons. Le front d'upwelling côtier peut agir comme barrière, conservant les propagules près de la côte.

Le processus de downwelling agit essentiellement comme l'upwelling, mais les flux sont inversés. Un downelling favorise le transport de propagules le long du rivage, bien que cela, en termes de production biologique, ait tendance à être défavorable.

Les régions du nord de l'AOI sont considérées comme des écosystèmes modérément productifs, tandis que les régions du sud sont considérées très productives (Heileman et Tanstad 2008).

La région mers celtiques est considérée comme un écosystème de classe II, modérément productif (150-300 $gCm^{-2}y^{-1}$) (Aquarone et al., 2008). Cette région subit un cycle climatique saisonnier qui affecte fortement l'écosystème pélagique par des facteurs de forçage. De nombreuses espèces de poissons de cette région partagent leur aire de distribution avec la mer du Nord et le plateau sud de l'Atlantique européenne.

La région du plateau atlantique sud-européen est considérée comme un écosystème modérément productif de classe II, soumis essentiellement au climat et à l'upwelling (Aquarone et al., 2008). Cet écosystème se caractérise par des conditions favorables à la production de clupéidés et d'autres petits poissons pélagiques. Le réchauffement dans cette région entraîne une restructuration importante des écosystèmes locaux, la pêche intensive étant la force motrice secondaire. De nombreuses espèces d'origine septentrionale de l'écosystème ont été trouvées en abondance dans les périodes plus froides, tandis que dans les périodes plus chaudes, la région est dominée par des espèces de poissons tropicaux du courant des Canaries ou de la mer Méditerranée occidentale. Ainsi, cet écosystème est connu comme étant la zone de transition entre les eaux froides de l'Atlantique Nord-est et les eaux chaudes de l'Atlantique Est (Teixeira et al. 2014).

L'AOI englobe des conditions climatiques allant du climat tropical à tempéré. La circulation près de la surface dans l'océan Atlantique Nord et du Sud est principalement sous l'influence du vent. Au niveau des côtes africaines, le vent est essentiellement dirigé vers l'équateur, ce qui est favorable à l'upwelling.

Le courant des Canaries est une région d'upwelling majeur située au large de la côte nord-ouest de l'Afrique, classée I, écosystème très productif (> 300 $gCm^{-2}y^{-1}$) (Heileman et Tanstad 2008). Les conditions hydrographiques et la variabilité climatique sont les principales forces motrices qui influent sur les variations de la biomasse et la distribution des petites espèces pélagiques. De nombreuses espèces endémiques et migratrices habitent dans cette région, ce qui fait du courant des Canaries un écosystème unique d'importance mondiale. De nombreuses espèces de poissons de cette région partagent leur aire de distribution avec le courant de Guinée au sud et avec la mer Méditerranée occidentale au nord. Plusieurs espèces du courant des Canaries sont observées sur le plateau atlantique sud-européen en été (Quero et al 1997; Bañón 2004).

4.2.3 Discussion : Évolution de la SST dans l'AOI

En général, les valeurs de SST observées au cours des périodes récentes sont plus élevées que durant les périodes précédentes, ce qui indique un réchauffement de la mer. Ces tendances croissantes sont observées dans les trois écosystèmes étudiés. Cela apparaît clairement dans les mers celtiques et le courant des Canaries, tandis que sur le plateau atlantique sud-européen, les valeurs de SST n'ont que légèrement augmenté au fil du temps (Table 1).

Tableau 1 *: Résumé des statistiques de la SST dans chaque écosystème par période décennale.*

Period	**Celtic Seas # E**				**South Europe # G**				**Canary Current # 27**			
	Min	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**	**Min**	**Max**	**Mean**	**Std**
I	0.20	21.15	11.10	2.02	4.48	25.30	15.38	2.49	12.31	30.35	20.35	1.97
II	1.00	20.92	11.42	2.10	6.24	25.40	15.67	2.43	13.48	30.59	20.74	1.92
III	2.41	20.88	11.95	1.98	5.00	26.31	15.93	2.59	13.33	30.66	21.22	1.95

* I = 1981-1990; II = 1991-2000; III = 2001-2012; South Europ. = South European Atlantic Shelf.

Le Tableau 4-1 présente les statistiques de la SST par période décennale : les moyennes, les valeurs maximales, minimales et les écarts types des observations quotidiennes de chacun des écosystèmes. Des informations plus détaillées sont présentées à l'Annexe 1, Annexe 2, et à l'Annexe 3.

Dans les mers celtiques, la température change de manière abrupte dans les deux premières décennies (1982-1991 et 1992-2001). La SST augmente de 11.10 °C à 11,42 °C, puis à 11,95 ° C dans la dernière décennie (2001-2011). Au total, la SST a augmenté de 0,85 °C (Tableau 4-2).Sur le plateau atlantique sud-européen, la SST moyenne montre une tendance à la hausse de 0,55 °C (Tableau 2) entre la première et la troisième période. Elle passe de 15,38 °C à 15,67 °C entre la première décennie (1982-1991) et la deuxième décennie (1992-2001), puis monte à 15,93 °C dans la dernière décennie (2002-2011).

Dans le courant des Canaries, la SST moyenne de la première décennie (1982-1991) était à 20,35 °C, et est montée à 20,74 °C au cours de la décennie suivante (1992-2001). La tendance à la hausse de la SST a persisté dans la dernière décennie (2002-2011), montant à 21,22 °C, soit une augmentation de 0,87 °C depuis la première décennie (Tableau 4-2). Le Tableau 4-2 contient les p-values du test apparié. Il présente l'évolution de la SST dans les trois régions pour les trois périodes étudiées.

Tableau 2*: Différence entre les moyens (P) - Test appariés.*

Period	**Celtic Seas**			**South European Atlantic Shelf**			**Canary Current**		
	I	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
I	-	0.32 (5.7e-06)	0.85 (2.2e-16)	-	0.29 (0.0001)	0.55 (1.2e-10)	-	0.39 (7.6e-07)	0.87 (2.2e-16)
II	0.32 (5.7e-06)	-	0.53 (1.3e-12)	0.29 (0.0001)	-	0.26 (0.0006)	0.39 (7.6e-07)	-	0.48 (6.5e-09)
III	0.85 (2.2e-16)	0.53 (1.3e-12)	-	0.55 (1.2e-10)	0.26 (0.0006)	-	0.87 (2.2e-16)	0.48 (6.5e-09)	-

*I = 1981-1990; II = 1991-2000; III = 2001-2012.

4.3.9 Discussion : Migration des espèces

4.3.9.1 Question des occurrences d’espèces

Un biais dans la distribution des occurrences d'espèces pourrait conduire à une vision déformée de la structure de répartition des espèces (Yang, Ma, et Kreft 2013). Plusieurs facteurs peuvent être à l'origine de ce biais, tels que l'échelle spatiale, la localisation de l'enquête, les techniques d'échantillonnage, les erreurs d’identification, et la mobilité des espèces.

Certaines sources de données présentent des problèmes de qualité, et le manque de transparence sur les données a été noté par de nombreux auteurs, et critiqué publiquement (Soberon, Arriaga, et Lara 2002; Graham et al 2007; Yesson et al., 2007), en particulier pour ce qui concerne les données provenant des musées d'histoire naturelle qui sont rarement collectées de manière optimale. De plus, l'information est parfois insuffisante pour des raisons politiques et/ou financières, c'est par exemple le cas dans les eaux du Portugal et les eaux marocaines. En revanche, de nombreuses données d'occurrences sont disponibles dans les pays développés, où les campagnes scientifiques sont bien financées, même si la densité réelle peut être plus élevée ailleurs (Beck et al. 2014). Dans un futur proche, il va être nécessaire de négocier pour avoir l'accès à plusieurs bases de données qui ne sont pas encore disponibles publiquement, comme le soulignent Yesson et al. (2007). Ainsi, la disparité des données dans certaines zones pourrait être comblée. Néanmoins, de nombreuses améliorations ont été apportées et de grandes quantités de données de bonne qualité sont déjà disponibles. Elles sont de plus en plus utilisées et cela peut encourager la recherche dans de nombreuses applications.

Dans cette étude, nous avons intégré plusieurs sources de données, des bases de données accessibles au public aussi bien que des bases de données non publiées. L'utilisation de ces bases de données permet l’étude des modes de répartition des espèces à de grandes échelles spatiales et temporelles, et donc de mieux comprendre le déplacement des espèces en réponse aux changements environnementaux.

Nous avons pris plusieurs mesures pour réduire le risque de biais : nous avons notamment utilisé exclusivement des données récentes (enregistrées après 1982 seulement), exclu de l'étude des occurrences sans temps d'observation, effectué une sélection rigoureuse des espèces étudiées et des enregistrements d'occurrence, et supprimé des occurrences suspectes.

4.3.9.2 Variation latitudinale

Afin d'obtenir une image complète de la distribution des espèces, notre étude couvre une large zone latitudinale (des eaux tropicales et subtropicales aux eaux tempérées). Malgré le nombre élevé de données d'occurrence (plus de 100.000 enregistrements) provenant de nombreuses campagnes scientifiques dans les régions tempérées (la mer du Nord et les mers celtiques), la diversité spécifique y est plus faible que celle observée dans les régions tropicales, où les observations scientifiques sont rares (moins de 7.000 occurrences). Le nombre d'espèces diminue avec l'augmentation de la latitude, la zone tropicale étant souvent deux ou trois fois plus riche (voire plus) en espèces que la zone tempérée (Gaston 2000); les causes de cet état de fait sont encore en débat (Clarke et Gaston 2006).

La variabilité latitudinale n’est pas le seul moteur de la diversité des espèces. D'autres facteurs limitatifs sont importants, tels que la surexploitation, la perte d'habitat, les effets saisonniers, le profil du fond marin, et les conditions océanographiques. La disponibilité des nutriments, la salinité et le taux de dispersion peuvent aussi influer sur la distribution des espèces et la composition spécifique. Tous ces facteurs combinés peuvent conduire à des migrations de poissons, en particulier des espèces très tolérantes et naturellement adaptables, et donc potentiellement invasives (Hiddink et Hofstede 2008).

4.3.9.3 Effets de la pêche

Les perturbations provoquées par des activités de pêche peuvent influer sur la distribution des espèces en réorganisant l'assemblage de poissons (Summerson, Darbyshire, et Lawrence 2007). Garrison et Jason (2000) ont mentionné que les effets spatiaux dans les taux d'exploitation peuvent modifier les distributions des espèces. Les activités de pêche réduisent l'abondance des espèces prédatrices, qui influencent les niveaux trophiques de base (Martins et al. 2012). Si l'abondance des espèces moins exploitées augmente, l'expansion de leur distribution est alors un effet indirect possible (Martins et al. 2012).

Un rapport de la FAO (FIGIS 2016) a montré une tendance décroissante des captures dans les régions de l'Atlantique européen, alors qu'une augmentation des captures a été observée dans l'Atlantique Centre-Est (Annex 5). Ce dernier est la source potentielle de nos espèces migratrices, et la tendance croissante observée dans les captures n'implique pas d'impact important des activités de pêche sur les peuplements de poissons. Dans la région centrale du plateau atlantique sud-européen, où on a observé une diminution globale des captures, Teixeira et al. (2014) ont mentionné que la capture des espèces marines provenant des eaux froides a diminué au cours des dernières décennies, alors que les captures d'espèces marines d'origine tropicale ou subtropicale ont considérablement augmenté.

Ainsi, bien que les activités de pêche puissent avoir une influence importante sur la distribution des espèces, les effets de la pêche ne sont pas considérés comme le principal moteur dans cette étude.

4.3.9.4 Effets du changement climatique

Les observations récentes d'espèces tropicales, comme *S. senegalensis* et *D. vulgaris*, dans la zone centrale (face à la zone côtière du Portugal), au cours de l'automne, suggèrent que l'aire de distribution de ces espèces s'est étendue vers le nord. Bañón et al. (2010) ont estimé que ces phénomènes étaient probablement liés au réchauffement climatique.

De nombreuses études ont identifié la température comme le facteur environnemental dominant limitant la répartition des espèces. La température contrôle la reproduction des espèces, ainsi que la croissance et la disponibilité de ses aliments (Summerson, Darbyshire, et Lawrence 2007). Bien que la température n'est pas le seul paramètre de forçage, Cheung et al. (2009) ont mentionné que la réponse des espèces marines aux changements environnementaux, tels que le réchauffement de l'océan, se traduit par un déplacement de leur gamme latitudinale ou de leur profondeur, et par des changements dans la structure de la richesse spécifique. Hiddink et Hofstede (2008) ont également noté que la biodiversité aux latitudes élevées, dans les eaux subtropicales et tempérées, semble être sensible au changement climatique. L'apparition d'espèces tropicales sur le plateau atlantique sud-européen (ID CWS) pourrait confirmer l'effet du changement climatique sur le déplacement des espèces. Cependant, l'absence de données portant sur la période antérieure nous empêche d'attribuer définitivement ce phénomène au réchauffement climatique. Néanmoins, l'augmentation constante de la SST observée dans toutes les régions (Annex 6) peut favoriser l'émigration des espèces, en particulier dans les régions intermédiaires. Ainsi, leur aire de répartition pourrait s'étendre, comme le dit aussi Kristin Kaschner et al. (2011). En outre, Bañón et al. (2010) ont suggéré que la présence d'espèces tropicales d'origine africaine dans la région centrale de la zone d'étude reflète les changements naturels réels plutôt que des efforts accrus d'échantillonnage. L'Annex 7 présente la répartition des espèces étudiées dont la distribution présente une tendance à se déplacer vers le nord.

4.3.9.5 Effets des forçages physiques

Le fort gradient de température nord-sud et la bathymétrie dans la région du plateau atlantique sud-européen pourraient restreindre la distribution de nombreuses espèces (Bañón et al., 2010); voir

Figure 4. Bakun (2006) a mentionné que le succès du recrutement des poissons est fortement influencé par trois catégories (connues sous le nom de la triade fondamentale) de processus océanographiques : l'enrichissement (comme les upwellings et le *run-off* des fleuves), la concentration (qui se produit dans des zones de fronts ou les panaches fluviaux) et la rétention (fronts, courants et modes de circulation).

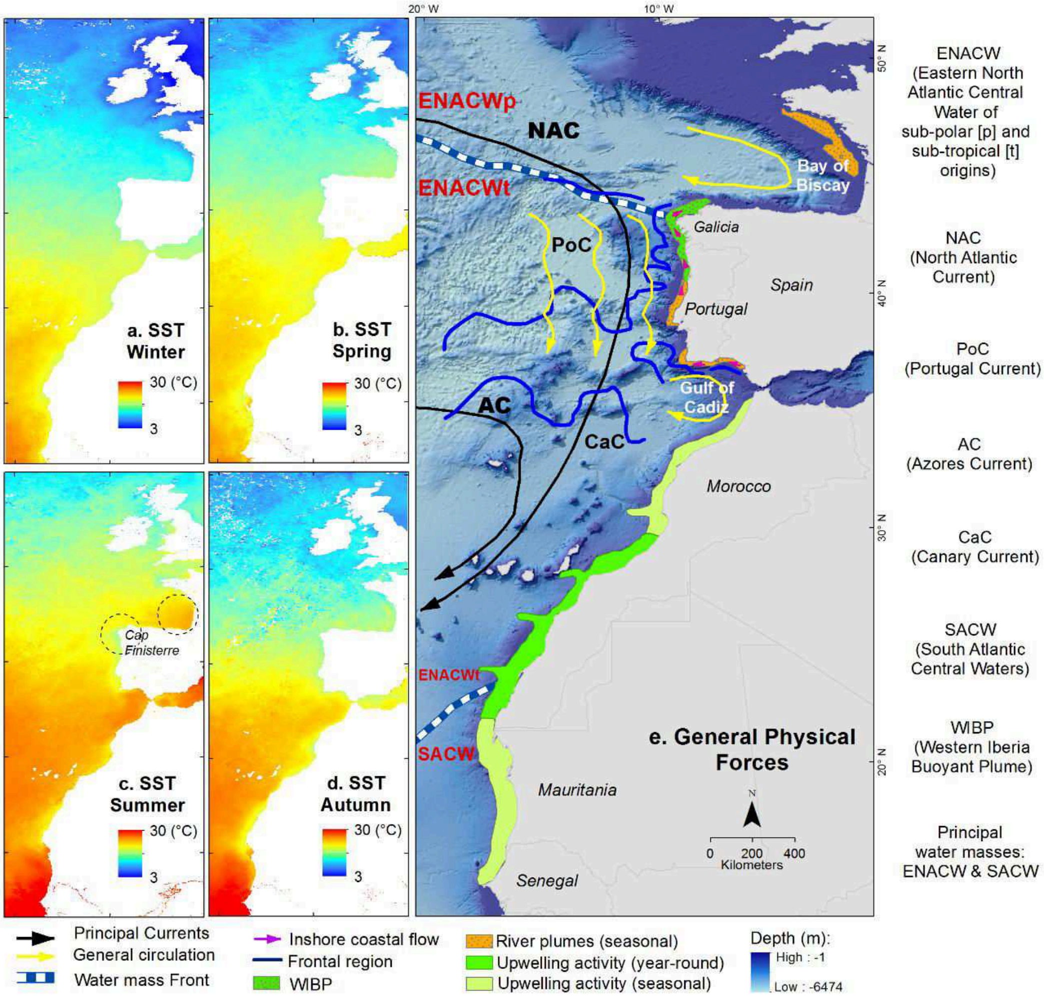


Figure 4: Climatologie saisonnière de la SST dans la zone d'étude, 1982-2012: a) l'hiver; b) le printemps; c) l'été; d) l'automne; et e) principales structures hydrologiques (voir la Figure 3).

Les fronts sont des zones frontalières étroites qui séparent les masses d'eau (Mason, Coombs, et Oliveira, 2005). Elles présentent des gradients forts de nombreux paramètres de l'eau et sont plus productives, avec des fortes concentrations en éléments nutritifs et plancton. Ces environnements peuvent bénéficier aux poissons adultes ainsi qu'aux larves et aux œufs. Ils sont omniprésents aux frontières orientales des océans et agissent comme des barrières qui réduisent l'exportation de particules dans les eaux côtières du plateau continental (Bakun 2006). Ainsi, ils agissent également comme des obstacles potentiels à la dispersion planctoniques et la migration des adultes (Figure 4e).

Les zones d'upwelling, avec leurs eaux riches en nutriments, augmentent la production primaire et par conséquent la nourriture pour les niveaux trophiques supérieurs, soutenant donc la production de poisson (Aggrey-Fynn 2007). Bañón et al. (2010) expliquent que l'upwelling présent au large du cap Finisterre de mars à octobre (Figure 4c) est probablement la raison de la présence d'espèces d'eau froide à cet endroit, alors qu'elles sont absentes ou rares dans le golfe de Gascogne. L'eau au cap Finisterre est nettement plus froide que sur la côte galicienne et dans le golfe de Gascogne. En revanche, les espèces d'eau chaude sont présentes dans le golfe de Gascogne et absentes ou rares au large du cap Finisterre.

4.3.9.6 Routes et calendrier de migration

Les déplacements de la distribution des espèces, présentés dans les résultats de cette étude, semblent être fortement corrélés avec les changements environnementaux saisonniers. *A. tobianus* ne se trouve que dans le plateau atlantique sud-européen en automne, tandis qu'au printemps et en été, il peut être trouvé en mer du Nord et en mers celtiques. Bien que la température ne soit pas le seul paramètre influençant la répartition des espèces, les SST moyennes au cours de cette saison sont proches dans ces deux régions ; en outre, la température automnale moyenne dans le plateau atlantique sud-européen est dans la même gamme que la température d'été dans les mers celtiques et la mer du Nord.

Dans les mers celtiques, en dépit de l'augmentation significative des données d'occurrences au fil du temps, la richesse spécifique montre une tendance à la baisse ; en revanche, dans la mer du Nord, cette richesse augmente. Une étude menée par Hiddink et Hofstede (2008) dans cette région a constaté que le nombre d'espèces dans la partie nord de la mer du Nord a augmenté au fil du temps. Ce résultat a été confirmé par Cheung et al. (2009). Cependant, notre étude a montré les effets importants de la profondeur préférentielle et la variation saisonnière. Certaines espèces ont pu être observées plus souvent dans la mer du Nord en certaines saisons, tandis que durant les autres saisons, elles étaient plus observées dans les mers celtiques ou sur le plateau atlantique sud-européen. Cette étude montre que 13 espèces se déplacent de façon saisonnière dans la mer du Nord, les mers celtiques et le plateau atlantique sud-européen. La zone nord de la mer du Nord a des eaux plus profondes que la zone sud. En conséquence, les espèces ayant une profondeur préférentielle de 100-200 m, tels que *Lepidorhombus whiffiagonis*, sont plus à l'aise dans la partie nord de la région, tandis que les espèces dont la profondeur préférentielle est de moins de 50 m, comme *A. tobianus*, sont beaucoup plus souvent présentes dans la partie sud de la région. Par conséquent, si la température d'hiver ou de printemps augmente, *L. whiffiagonis* migrerait vers le nord, alors que *A. tobianus* peut migrer vers l'est plutôt que vers le nord étant donnée sa gamme de profondeur. Sur le plateau atlantique sud-européen, au cours des périodes plus chaudes, six espèces provenant du courant des Canaries et de la mer Méditerranée occidentale étendent leurs distributions dans cette région. Bañón et al. (2010) ont mentionné que l'arrivée de nombreux poissons tropicaux dans le plateau atlantique sud-européen semble avoir modifié le modèle traditionnel de distribution des espèces dans cette région, et ils ont avancé que ce phénomène est probablement lié au réchauffement climatique. Pendant les saisons plus chaudes, la différence de SST moyenne entre les écosystèmes du centre et du sud a diminué (allant de 15,9 °C en été à 22,5 °C en hiver; voir le Table 4-11). Cette condition pourrait permettre aux espèces tropicales du sud de migrer vers la région centrale (d'autres facteurs limitant ne sont pas pris en compte). Cependant, la faible disponibilité de données d'occurrence dans cette région pour la période antérieure limite notre point de vue et notre analyse de l'effet du réchauffement climatique. Durant la première période, la faiblesse de la richesse est fortement liée à la faible disponibilité des observations. Néanmoins, de nombreuses études ont suggéré que l'augmentation des températures était la principale cause de la présence d'espèces tropicales comme mentionné précédemment. Comme la SST continue d'augmenter dans toutes les régions (Annexe 6), on peut s'attendre à ce que de nombreuses espèces continuent d'élargir leur aire de distribution.

Nous sommes un peu plus confiants dans l'enregistrement de la présence d'espèces tropicales de l'Atlantique en la mer Méditerranée que sur le plateau atlantique sud-européen. Dans cette étude, 7 espèces du courant des Canaries ont été trouvées en Méditerranée occidentale. Deidun, Castriota et Arrigo (2011) ont noté l'observation de 33 espèces de poissons exotiques d'origine Atlantique présents dans la mer Méditerranée. Zenetos et al. (2010) ont noté le nombre croissant d'espèces de poissons exotiques dans cette région, avec une augmentation parallèle du nombre des espèces de poissons migrants depuis l'Atlantique. Beaucoup de ces espèces sont déjà établies et ont élargi leur distribution à l'ensemble du bassin, ce qui suggère également un mouvement vers l'est (CIESM 2002).

La présence d'espèces tropicales de l'Atlantique dans la région centrale confirme le phénomène de « tropicalisation » à la fois des espèces pélagiques et demersales (Zenetos et al., 2010), pour lesquelles on observe une augmentation de la fréquence et de la biomasse (Deidun, Castriota et Arrigo 2011). Cette tendance est également confirmée par les résultats de cette étude, qui suggèrent une route de migration orientée vers le nord.

Enfin, une étude plus approfondie est nécessaire pour acquérir des connaissances supplémentaires sur les migrations saisonnières des espèces. La modélisation de la distribution des espèces en fonction de leur niche écologique est prometteuse, car les résultats pourraient être utilisés pour prédire leur aire de distribution et la richesse spécifique dans une région donnée. L'utilisation de ces modèles pourrait être une alternative ou une approche complémentaire à la limitation de la disponibilité des données à grande échelle, et conduirait à une meilleure compréhension des changements de la biodiversité et permettrait l'identification des zones à forte biodiversité actuelles et futures.

4.4.5 Discussion : niche écologique

Le manque de données limite notre compréhension de la dynamique des populations de poissons, ce qui influence la précision de la décision en matière de conservation. Les informations requises sur la distribution spatiale des espèces et leurs caractéristiques environnementales ne sont disponibles que pour un petit nombre d'occurrences. En outre, elles ne sont disponibles que dans certaines régions. Les campagnes scientifiques nécessaires à la collecte des données quantitatives sont coûteuses, ce qui pose des difficultés pour de nombreux pays en développement. Dans les eaux tropicales, la diversité des espèces est élevée, mais le nombre d'enquêtes scientifiques est très faible. Ainsi, la quantité de données disponibles est très faible (Cheung et al., 2005).

Le concept de niche est multidimensionnel (Helaouët et Beaugrand, 2009), il évolue au fil du temps et est sujet à plusieurs interprétations (Chase et Leibold, 2003). Hutchinson (1987), dans une référence classique (Franklin, 2009), a défini la niche comme « ... l'hyper-volume défini par les dimensions environnementales dans lesquelles une espèce peut survivre et se reproduire ». Hutchinson distingue la niche fondamentale (physiologique ou potentielle), définie comme la réponse des espèces à l'environnement (ressources) en l'absence d'interactions biotiques (compétition, prédation, facilitation), de la niche réalisée (réelle, écologique) - les dimensions environnementales dans lesquelles les espèces peuvent survivre et se reproduire, en tenant compte des interactions biotiques. La niche fondamentale d'une espèce représente sa gamme de tolérance physiologique en l'absence d'interactions avec d'autres espèces (compétition, prédation). La niche réalisée est l'espace environnemental où une espèce est présente, ce qui tient compte à la fois de la disponibilité de conditions environnementales appropriées et de toutes les interactions biotiques.

La niche fondamentale représente la réponse de tous les processus physiologiques d'une espèce aux effets synergiques des facteurs environnementaux (Helaouët et Beaugrand, 2009). La niche réalisée est souvent décrite comme un sous-ensemble de la niche fondamentale. Hutchinson a défini le

« biotope » comme l'environnement réalisé dans le sens utilisé ci-dessus, et la niche réalisée comme l'intersection des biotopes et de la niche fondamentale (Franklin, 2009).

Pulliam (2000) a évalué les différences entre niche fondamentale et réalisée et, comme indiqué par Hutchinson (1957), son étude note que la niche réalisée est plus réduite lorsque des facteurs réduisant la survie, comme la concurrence, prédominent. Cependant, il fournit également des preuves que la niche réalisée peut être de dimension supérieure à la niche fondamentale lorsque la dispersion est élevée.

Pulliam (2000) souligne également l'importance de la mesure de la valeur sélective, en particulier le taux de croissance de la population, afin d'identifier la niche d'une espèce (où le taux de croissance est positif). Il propose que le concept de niche de Hutchinson, la théorie des métapopulations, et la théorie source-puits (Pulliam, 1988) puisse, ensemble, aider à expliquer la relation entre la répartition des espèces et un habitat convenable.

4.4.5.1 Niche thermique et température létale

La température est l'un des principaux aspects de la niche écologique, et aussi un bon indicateur pour son rôle crucial dans presque tous les aspects biochimiques, physiologiques et comportementaux d'un poisson (Helaouët et Beaugrand, 2009; Fry, 1947). Le paramètre est bien corrélé avec d'autres facteurs tels que la concentration en oxygène, en éléments nutritifs, ou la chlorophylle (Helaouët et Beaugrand, 2009). En outre, la température est le seul paramètre océanique pour lequel on dispose de longues séries d'observation par satellite. Il est également l'une des données les plus accessibles.

La grande majorité des espèces de poissons ne possédant pas la capacité de réguler leur température corporelle, leur capacité à éviter ou à sélectionner la température de l'environnement est donc l'un des composants les plus critiques de leur répertoire comportemental (Fry, 1947).

Un certain nombre de facteurs, à la fois biotiques et abiotiques, jouent également un rôle important sur la distribution thermique. Ceux-ci comprennent la saison, l'heure du jour, la disponibilité des aliments, la salinité, les exigences de l'habitat, l'état nutritionnel, la compétition et / ou la prédation, l'âge, et l'état pathologique (Olla et al., 1985).

Des études utilisant des adultes et des juvéniles de *P. saltatrix* ont suggéré que cette espèce est capable de thermorégulation comportementale. Cette capacité a été suggérée car les juvéniles et les adultes présentaient des augmentations de l'activité lorsqu'ils étaient exposés à des changements de température dans des conditions homéo-thermiques (Olla et Studholme, 1971).

Les poissons estuariens des eaux tempérées et sub-tempérées sont généralement considérés comme eurythermes par rapport aux poissons de mer et des eaux subtropicales ou tropicales. Cependant, dans certains cas, des conditions environnementales extrêmes peuvent produire une mortalité importante chez les poissons estuariens tempérés (sud, 1958).

Gilmore et al. (1978), dans leur étude menée dans les estuaires de la Floride du centre-sud pendant l'hiver 1977, ont montré que les poissons tropicaux et subtropicaux sténothermes avaient connu la plus forte mortalité. Ces poissons appartenaient presque exclusivement à des espèces estuariennes typiques et occupantes des zones côtières peu profondes. En cette saison, beaucoup de ces espèces atteignent leurs limites nord de reproduction dans les eaux de Floride, et deviennent vulnérables à de basses températures. Une combinaison de conditions physiques extrêmes est à l'origine de la mortalité massive de poissons observée dans les zones d'étude : 1) le passage du front froid a été soudain, 2) les minima de température de l'eau ont été très faibles (descendant jusqu'à 6 °C) et 3) la température de l'eau est restée faible (6 -12 °C) pendant cinq à six jours. Gilmore et al. (1978) ont également expliqué que les espèces les plus sensibles aux basses températures sont principalement des espèces tropicales. Les poissons à mobilité réduite ont également été largement affectés. Les poissons de l'ordre des *Plectognathes* se distinguent par leur affinité tropicale, leur faible mobilité et une grande présence dans les morts de poissons par hypothermie. Ils ne pouvaient pas échapper au refroidissement rapide des eaux peu profondes aussi facilement que d'autres espèces. On peut supposer que les espèces tropicales sont sensibles à la température à la plupart des stades de développement. Il est également supposé que les juvéniles peuvent résister à une température de l'eau plus faible que les adultes de la même espèce. Au final, un total de 132 espèces de poissons (y compris *P. saltatrix*) a souffert d'une mortalité due au froid dans cette région.

Graham (1972) a observé la gamme des températures létales chez divers poissons tropicaux dans les eaux panaméennes, dans des expériences de laboratoire contrôlées. Il a trouvé que les plus basses températures létales pour les poissons sont entre 8-13 °C. Ces observations démontrent aussi que certains poissons tropicaux sont plus eurythermes que d'autres.

4.4.5.2 Espèces pélagiques vs demersales

Les données satellitaires de mesures de la surface de la mer ne sont pas représentatives pour les espèces démersales, à l'exception de la température de surface de la mer de nuit. Selon la GHRSST Science Team (2010), la SST mesurée durant la nuit montre peu de différence avec la température de fondation de surface de la mer (voir Figure 5), par rapport à la différence avec la SST mesurée pendant la journée. Ainsi, l'utilisation des données de la SST de nuit est recommandée.

Les données bathymétriques sont plus utiles pour les espèces démersales que pour les espèces pélagiques. Malgré cela, pour les eaux peu profondes, les données dérivées à partir des données bathymétriques pourraient également influer sur la colonne d'eau qu'occupent les espèces pélagiques. L'utilisation de la SST comme prédicateurs pour les modèles de distribution des espèces d'eau profonde a soulevé de nombreuses questions sur leur corrélation. Whitehead et al. (2010) ont déclaré que la diversité, du point de vue écologique, est une fonction de chevauchement des niches. Ils ont supposé que la profondeur de l'eau et la SST sont des facteurs importants qui distinguent les habitats d'espèces différentes. La physiologie de la régulation énergétique et thermique des espèces, et leur anatomie en lien avec la plongée sont dépendantes de ces deux paramètres environnementaux. La diversité des espèces d'eau profonde et la SST peuvent présenter des structures similaires à celles des modèles de diversité des espèces de proies, y compris le zooplancton.

La température de surface de la mer (généralement abrégée en SST) est la température de l'eau de mer près de la surface (y compris la partie sous la glace de mer, le cas échéant), et non la température de l'interface, dont le nom standard est « température de surface ». Il existe plusieurs types de SST (GHRSST Science Team, 2010):

- La SSTskin est la température mesurée par un radiomètre infrarouge opérant typiquement à des longueurs d'onde de la gamme 3.7-12 micromètres. Elle représente la température à l'intérieur de la sous-couche conductrice à une profondeur d'environ 10 à 20 micromètres en dessous de l'interface air-mer. Cette définition est choisie pour sa compatibilité avec la majorité des mesures satellitaires infrarouge et par radiomètre embarqué.
- La SSTdepth ou SSTz est la terminologie adoptée par le GHRSST pour désigner des mesures *in situ* à proximité de la surface de l'océan, qui ont traditionnellement été rapportées simplement comme SST ou SST « en vrac ». Par exemple, SST6m se réfère à une mesure de la SST faite à une profondeur de 6 mètres. La terminologie a été introduite pour encourager le signalement de la profondeur (z) à laquelle la température a été mesurée.

- La SSTfnd, ou température de fondation de surface de la mer, désigne la température de l'eau qui n'est pas influencée par une couche thermiquement stratifiée de variabilité diurne de la température (par le réchauffement diurne ou refroidissement nocturne).

En général, la SSTfnd est similaire à une valeur minimale de température de nuit ou avant l'aube à des profondeurs comprises entre 1 et 5 mètres. En l'absence de signal diurne, la SSTfnd est considérée comme équivalente à la quantité dont le nom standard est sea_surface_subskin_temperature, ou la température à proximité de la surface mesurée par satellite. La SSTfnd est mesurée à la base de la thermocline diurne ou aussi près de la surface de l'eau que possible en l'absence de stratification thermique. Seule la mesure *in situ* en thermométrie est capable de mesurer la SSTfnd (voir GHRSST Science Team, 2010).

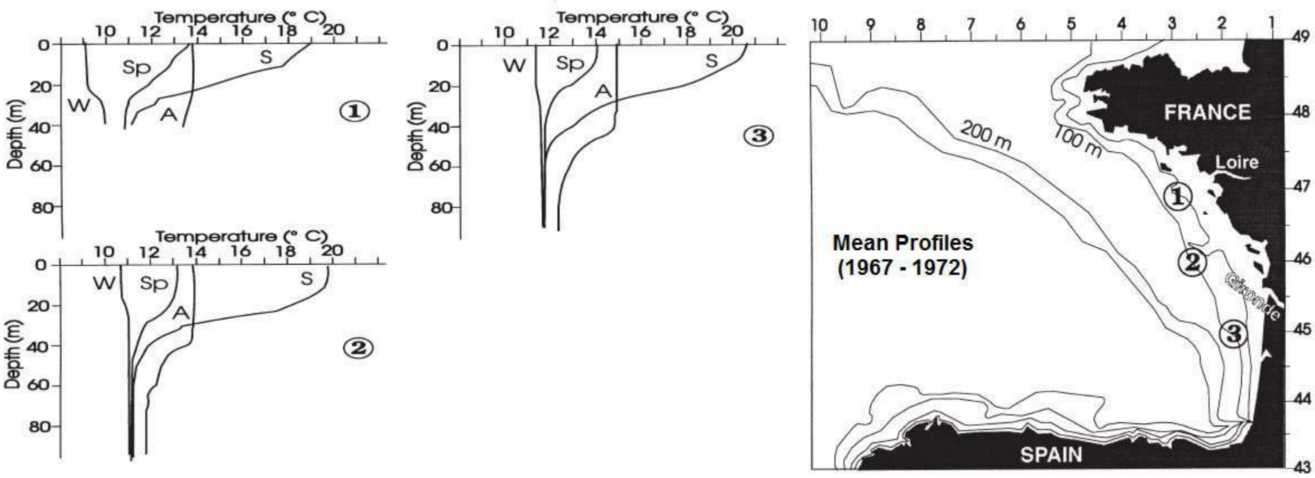


Figure 5 : Profils verticaux de températures moyennes selon Koutsikopoulos et Le Cann (1996) dans le golfe de Gascogne en trois points indiqués par les numéros 1, 2 et 3. W = hiver, Sp = printemps, S = été, A = automne.

La Figure 5 montre que la stratification de la température de l'eau varie selon la saison. Durant la période hivernale, les différences de température entre la surface et la colonne d'eau étaient réduites. Ces différences ont augmenté au fil des saisons et ont atteint leur maximum en été. La Figure 6 montre un autre exemple de température de surface de la mer et du fond marin en mer Méditerranée.

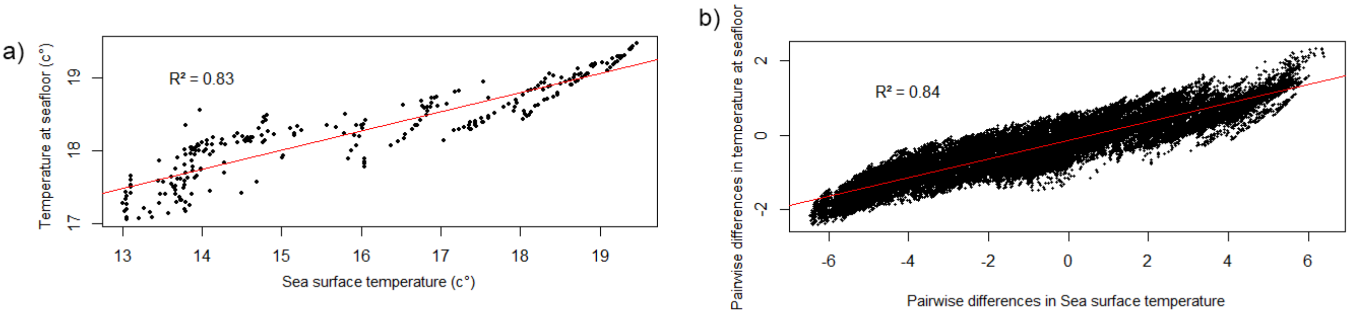


Figure 6: Distribution spatiale et variation temporelle entre la température de surface de la mer et de la température du fond marin dans les eaux méditerranéennes (Lasram et al, 2015).

4.4.5.3 Biais dans les données d'occurrence

Les biais dans les données d'occurrence des espèces ont été discutés (Beck et al., 2014). Plusieurs facteurs, tels que l'emplacement de l'enquête, l’échelle spatiale, des erreurs d’identification, la saisie de données et leur mobilisation peuvent être à l'origine de tels biais. Cela pourrait conduire à une potentielle forte distorsion de notre vision des tendances de la biodiversité à grande échelle (Yang et al., 2013).

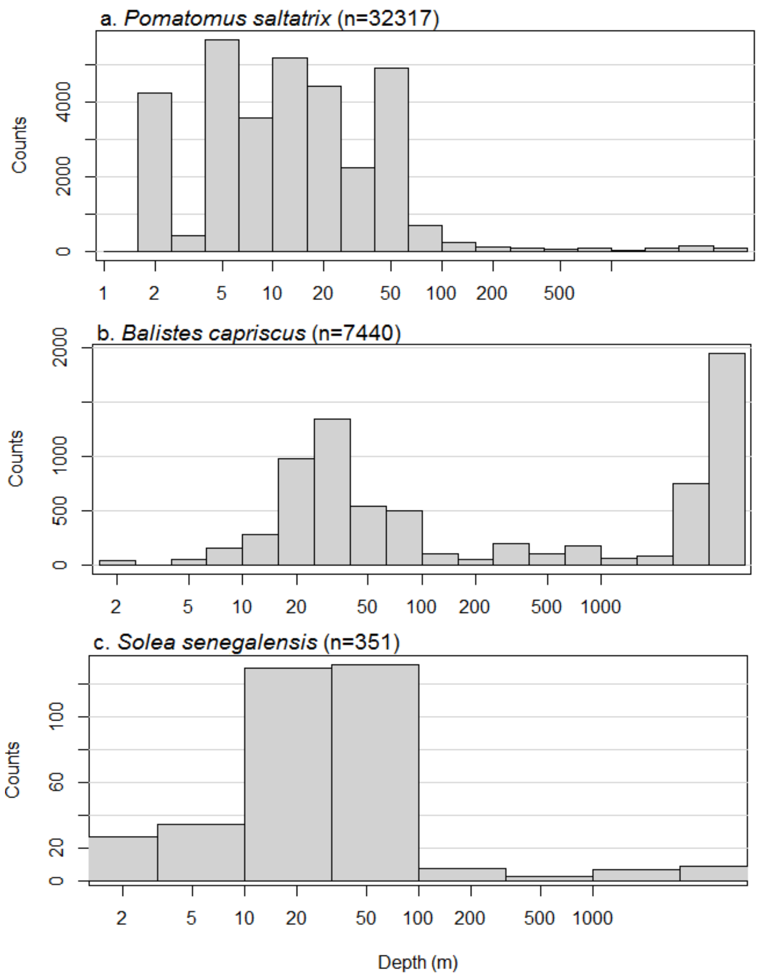


Figure 7 : Répartition des zones de profondeur pour (a) *P. saltatrix*; (b) *B. capriscus*; (c) *S. senegalensis*.

Certaines sources de données utilisées dans cette étude ont des problèmes de qualité, et le manque de transparence sur la qualité des données a été noté par de nombreux auteurs et publiquement critiqué (Graham et al., 2007; Soberon et al., 2002; Yesson et al., 2007). Pour résoudre ce problème, nous avons augmenté le nombre d'occurrences en assemblant et recoupant des données issues d'au moins cinq sources. Le nombre total d’occurrences de *P. saltatrix* recueillies et utilisées pour générer sa niche réelle dans cette étude était de 34517 points. Pour générer les niches thermiques, nous avons utilisé 13784 points d'occurrence pour les données AVHRR et 3037 points pour les données MODIS. Le nombre d'occurrences utilisées dans la génération de niches bathymétriques est beaucoup plus élevé, environ 32317 points, car ces paramètres sont considérés comme stables. Ce nombre est beaucoup plus élevé que le nombre utilisé pour créer des enveloppes dans AquaMaps, qui est de 577. Néanmoins, une étude approfondie sur la façon dont ces données sont distribuées doit être menée. Par exemple, des occurrences de *P. saltatrix* ont été trouvées dans des zones de moins de 300 m de profondeur (Figure 7). La fréquence des occurrences trouvées dans les zones de plus de 500 m de fond était très faible. De même pour *S. senegalensis*, cette espèce a été principalement trouvée dans des zones de moins de 100 m de profondeur. Les occurrences de ces espèces observées dans les zones plus profondes que 1000 m sont discutables et nécessitent une étude plus approfondie, même si elles ne sont pas négligeables, comme le montre le cas de *B. capriscus*.

Yañez-Arenas et al. (2014) ont déclaré que, pour assurer une représentation adéquate d'une niche d'espèces, la taille de l'échantillon doit être assez grande. Certaines études tentent de prédire la répartition des espèces en utilisant un petit nombre d'occurrences; Pearson et al. (2006) ont cependant montré que le taux de réussite de ces modèles était faible. Ils suggèrent que les modèles ont été fortement influencés par la taille de l'échantillon. Par conséquent, nos résultats pourraient améliorer la capacité de prédiction du modèle, et fournir des informations utiles pour la modélisation de la distribution des espèces à grande échelle.

Une autre problématique que soulève la petite taille des échantillons est celle du regroupement de données. Beaucoup de données d'occurrence des espèces disponibles proviennent des pays développés, où la recherche est bien financée, mais la densité réelle des occurrences peut être plus élevée ailleurs (Beck et al., 2014). Pour cette raison, lors de l'étape de la génération de niches, nous avons recueilli les occurrences observées à l'échelle globale afin de maintenir la qualité de prédiction.

L'approche que nous avons présentée ici illustre les capacités de la technique du SIG pour générer les niches écologiques des espèces en utilisant uniquement les points d'occurrences, massivement disponibles en ligne, ainsi que les données satellitaires et d'autres données environnementales. La méthode montre des résultats efficaces, robustes et fiables, car ils étaient en accord avec les résultats obtenus à partir des études observationnelles ou expérimentales. Par conséquent, ces résultats peuvent fournir des informations précieuses pour une utilisation dans la modélisation de la distribution des espèces.

Avec la création par modélisation de niches écologiques, notre étude ouvre une voie pour prédire la répartition des espèces. La disponibilité d'images haute résolution à l'échelle globale est une source importante de données pour élucider les relations entre les organismes marins exploités et leur habitat (Chassot et al., 2011). Les résultats peuvent maintenant être utilisés pour améliorer la modélisation ainsi que les projections permettant d'orienter les modèles ou les enquêtes futures.

L'utilisation de grandes bases de données montre des résultats prometteurs, mais, comme indiqué par Soberon et al. (2002), sans un contrôle adéquat de la qualité de ces bases de données, on risque de conserver des erreurs potentielles. Cependant, l'existence de ces grandes quantités de données de bonne qualité devrait encourager une multiplicité d'utilisateurs. Le développement d'outils ou de procédures pour repérer et corriger les problèmes de type de données est une priorité pour le futur proche. En outre, un défi majeur dans l'avenir consistera à négocier l'accès aux différentes bases de données de biodiversité importantes qui ne sont pas encore librement accessibles à la communauté scientifique, comme l'ont souligné Yesson et al. (2007), et comme c'est le cas dans les eaux portugaises et marocaines. Des recherches supplémentaires sont également requises pour étudier l'impact des erreurs de localisation et l'effet de la résolution spatiale.

4.5.10 Discussion : Modèles de distribution des espèces

Cette étude présente la distribution potentielle et optimale d'un certain nombre d'espèces de poissons marins, à l'aide de cartes ou graphiques et de tableaux, élaborée à partir d'une approche méthodologique basée sur le SIG, comme expliqué dans le chapitre méthodologique précédent.

Les modèles saisonniers de distribution potentielle des espèces présentent la zone la plus adéquate pour l'espèce pour les périodes d'hiver, printemps, été et automne. Ils montrent les zones où les espèces sont très susceptibles d'être présentes, c'est-à-dire les aires dans lesquels les exigences de l'espèce sont remplies en termes de température et de contraintes bathymétriques.

La zone de couleur rouge représente la classe-1, classe de préférence maximale de l'espèce. La zone orange représente la classe préférée ou la classe-2. Bien qu'il y ait moins de chances de rencontrer l'espèce dans cette zone que dans la zone de classe 1, c'est encore une zone où l'espèce est susceptible d'être présente car 30 % des occurrences de l'espèce ont été observées dans cette zone. La zone jaune, ou classe de préférence limitée, ou classe-3, est une zone où les espèces pourraient être présentes, mais les probabilités sont plus faibles que dans les deux zones précédentes. La zone bleue est la zone tolérée, où les espèces ne sont guère susceptibles d'être présentes, mais qui présente les valeurs environnementales extrêmes où l'espèce a été observée. La zone de couleur blanche est la zone qui ne répond pas aux exigences de l'espèce. Les superficies et les localisations de chaque zone varient selon les saisons.

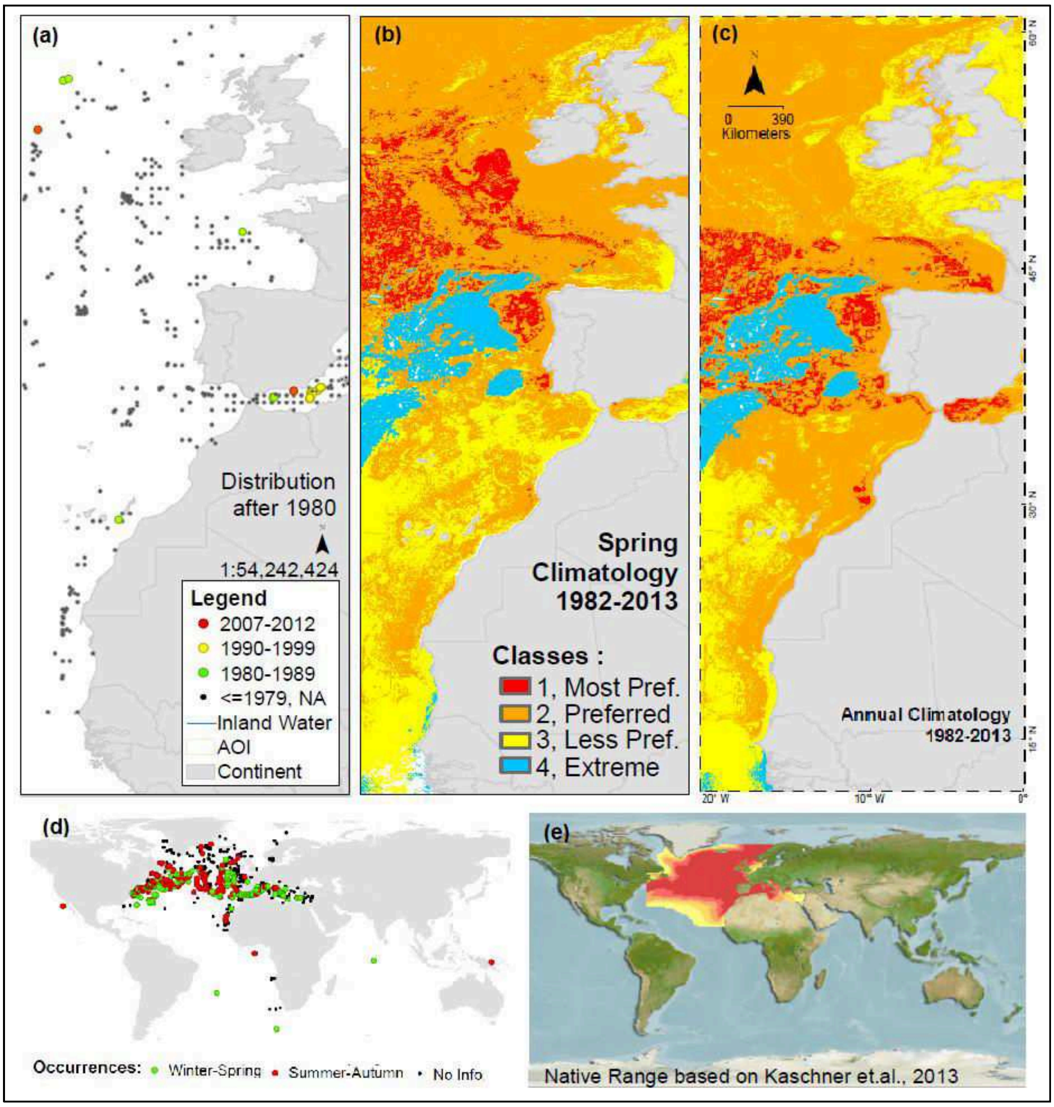


Figure 8 : (a) Occurrences de *M. punctatum* dans la zone d'étude. (B) Modèle climatologique de la répartition de l'espèce au printemps et (C) modèle climatologique annuel. (D) Occurrences des espèces à l'échelle mondiale. (E) Modèle de distribution produit par AquaMaps pour disposer d'informations supplémentaires.

Nous présentons le cas de *M. punctatum* pour démontrer les capacités de la technique du SIG dans la modélisation de la distribution des espèces, en particulier dans les zones pauvres en données (Figure 8). Les points colorés dans la Figure 8a et Figure 8d représentent des occurrences accompagnées de données sur la date de l'observation, qui ont été potentiellement utilisées pour déterminer la niche thermique de l'espèce, tandis que les points noirs représentent les observations sans date d'observation, qui ont été utilisées pour former les niches bathymétrique. Malgré le petit nombre de points de couleur dans la zone d'étude (Figure 8a), en utilisant les données d'observation à l'échelle mondiale (Figure 8d), le modèle a été capable de représenter la distribution potentielle de l'espèce dans la zone d'étude suivant les variations saisonnières (Figure 8b).

Les poissons démersaux sont un groupe clé des organismes marins qui influencent la biodiversité marine (Moore et al., 2011). Ils sont fortement associés au fond marin. Nos modèles dynamiques saisonniers offrent une prévision alternative de la distribution des espèces qui peut servir d'informations de base pour comprendre les mouvements des espèces en lien avec les changements environnementaux saisonniers. Ces informations sont rares et l'observation directe par les campagnes scientifiques peut être coûteuse et limitée aux eaux relativement peu profondes (Moore et al., 2011).

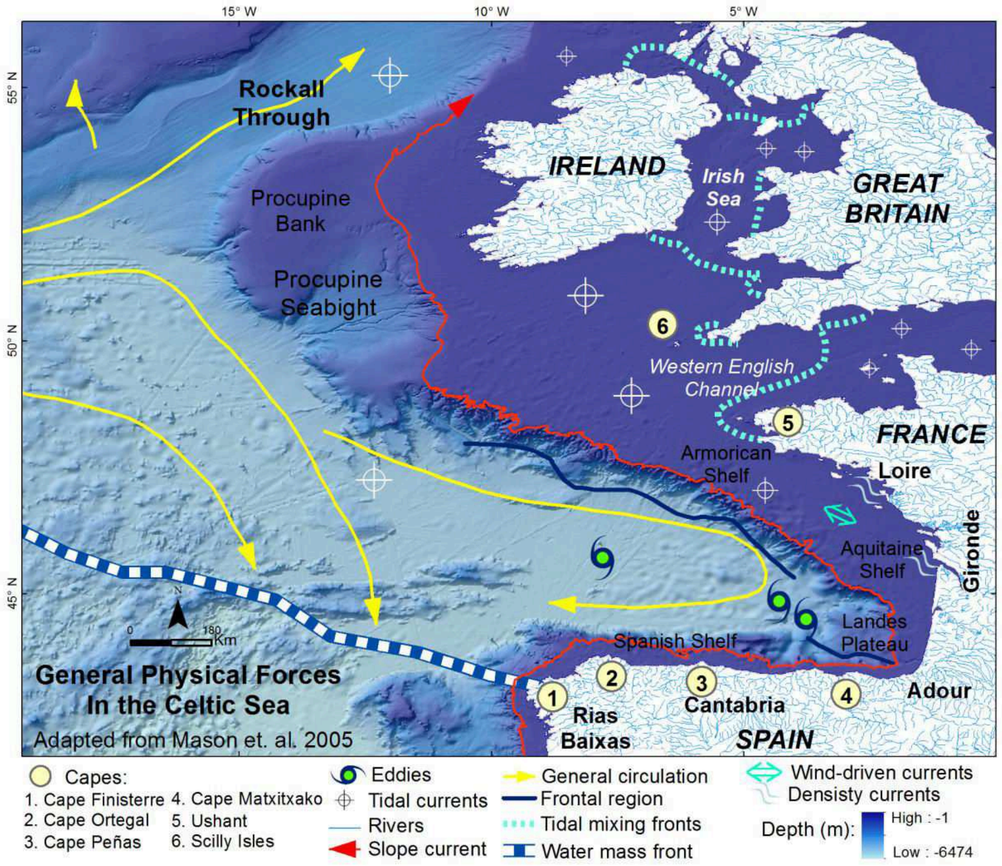


Figure 9 : Caractéristiques physiques majeures des mers celtiques et du golfe de Gascogne.

Comme l'ont prévu de nombreux auteurs, l'une des réponses des espèces au réchauffement climatique est un déplacement latitudinal de leur distribution pour chercher des endroits plus froids (Pinsky et al. 2013). Les conditions environnementales dans les régions du nord de la zone d'étude sont plus fortement influencées par une variabilité saisonnière que les régions du sud (Mason et al., 2005).

La Figure 9 présente les conditions physiques et topographiques des mers celtiques et du golfe de Gascogne. La zone située entre 48-52 °N est un lieu de frai pour certaines espèces, telles que *Sardina pilchardus* (Mason et al., 2005). Le fond de la mer de cette région a une topographie très complexe. Leur localisation dans les latitudes moyennes font que les mers celtiques ainsi que la Manche subissent de forts réchauffements et refroidissements, et des vents énergétiques (en direction de l'ouest) qui prévalent pour une grande partie de l'année (Mason et al., 2005).

Les ondes de marée qui vont de l'océan profond vers le plateau varient en degré selon la topographie côtière et les fonds marins. Les marées les plus fortes se produisent sur la côte française, comme à Saint-Malo, où l'élévation de marée dépasse 8 m, en raison du resserrement des côtes dans la Manche et de l'action de la force de Coriolis (Mason et al., 2005). Les courants de marée (souvent supérieurs à 1 m/s) dans cette région sont rectilignes et deviennent progressivement plus forts vers le canal de Bristol (Mason et al., 2005). Le frottement avec le fond marin dans les zones de forte influence des marées atténue les courants résiduels. Un upwelling côtier transitoire au large de la côte sud-ouest de l'Irlande a été signalé par Edwards et al. (1996). Couplées à l'énergie mécanique du vent, les marées sont à l'origine d'une colonne d'eau homogène très mélangée tout au long de l'année dans la Manche occidentale et les mers celtiques, sauf pour certaines parties des mers celtiques qui connaissent une stratification estivale en raison du réchauffement de l'eau de surface par le soleil dans les zones les moins agitées (Pingree et Griffiths 1978).

Les fronts de marée soutiennent et améliorent la production biologique et la biomasse. Ces caractéristiques sont couramment observées dans les mers celtiques. Pingree et al. (1978) ont rapporté les fortes concentrations de chlorophylle dans le front de marée d'Ouessant, au large de la Bretagne nord-ouest, l'un des plus importants fronts de marée. Une augmentation des concentrations en éléments nutritifs et de la biomasse au voisinage des îles Scilly, au large du sud-ouest du R.U., a également été signalée par Simpson et Tett (1986).

4.5.10.1 Technique de SIG

Dans ce rapport, nous avons décrit l'application des techniques du SIG dans la création de modèles de distribution des espèces, en utilisant des donnés satellitaires en tant que couches environnementales. Nous avons appliqué cette approche pour modéliser la distribution des espèces rares trouvées dans la zone centrale de l'AOI. Certaines de ces espèces ont été bien étudiées en raison de leur importante valeur commerciale. En présentant des cartes temporelles et spatiales de haute résolution des habitats préférentiels, cette étude a tenté de fournir des informations en réponse aux questions sur ces habitats des espèces, qui ne sont pas bien compris jusqu'à ces jours-ci, comme indiqué par Summerson et al. (2007).

La modélisation de la distribution des espèces est largement utilisée dans les études terrestres, en raison de l'énorme quantité des données environnementales terrestres disponibles. Les limites de la zone modélisée sont déjà fixées par les littoraux. Ainsi, on peut facilement effectuer la modélisation en utilisant des logiciels disponibles gratuitement, comme *MaxEnt*.

Contrairement à des zones terrestres, les limites des écosystèmes marins ne sont pas claires. En outre, ces limites changent au fil du temps, suivant l'évolution de nombreux facteurs environnementaux tels que le changement de saison. Avant de procéder à la modélisation de la répartition des espèces dans un écosystème marin, il faut d'abord fixer les limites de la zone d'étude pour toutes les données environnementales car certains logiciels ne fonctionnent pas si ces limites ne sont pas identiques.

Un modèle SIG ne nécessite pas de limites fixes et permet une grande flexibilité dans la préparation et la réalisation d'analyses spatiales et temporelles de séries chronologiques de données environnementales.

La plupart des modèles sont basés sur la relation entre les espèces et les conditions environnementales dans les zones où l'espèce est présente. Les modèles existants aujourd'hui sont très dépendants de l'ensemble des occurrences des espèces modélisées dans la zone d'étude. Il existe de longues discussions sur cette méthode dans divers articles. Il serait nécessaire d'avoir un nombre représentatif de données d'occurrence dans la zone d'étude afin d'avoir un bon modèle. GIGO (*gold in, gold out or garbage in, garbage out*), un concept commun en informatique, s'applique ici. Par conséquent, afin de pouvoir modéliser la distribution d'une espèce donnée dans une région, il faut d'abord avoir un bon nombre d'observations avec une distribution appropriée sur ces sites, donc il est difficile d'effectuer la modélisation dans une zone avec peu d'observations.

Nous avons utilisé des occurrences à l'échelle mondiale pour trouver les valeurs environnementales maximum et minimum d'une espèce pour chaque paramètre environnemental pris en compte. Le résultat de ce processus est la niche réelle de l'espèce. Cette niche est ensuite utilisée comme entrée pour projeter l'enveloppe environnementale de l'espèce sur une série de données environnementales dans la zone d'étude. Cette technique fournira une bonne approche, simple pour la modélisation, en particulier pour les zones avec peu de données d'observations.

L'hypothèse du modèle, comme l'ont déclaré Hijmans et Elith (2013) et Kesner-Reyes et al. (2012), est que la prédiction peut être réalisée entièrement ou potentiellement dans une région en mettant en lien des sites d'occurrence connus et peut-être de non-occurrence connus avec les variables d'environnement connues pour ces sites locaux et pour tous les autres sites.

Boitani et Fuller (2000) ont expliqué que, de toute évidence, un paramètre (par exemple, la température) ne suffit pas à prédire la présence d'une espèce dans tous les lieux pour lesquels les valeurs de ce paramètre sont appropriées. Il existe beaucoup d'autres paramètres écologiques qui contribuent à la détermination de la répartition de l'espèce, comme celui que nous avons utilisé dans cette étude, la contrainte bathymétrique. La probabilité de trouver les espèces augmente si la couverture des données environnementales est représentative, sans quoi le modèle ne saurait afficher une forte précision. En utilisant des techniques de SIG et en y incorporant des données environnementales satellitaires, les cartes de distributions potentielles d'espèces peuvent être produites rapidement et efficacement.

Les données d'occurrences sans aucune information sur la date d'observation n'ont pas été utilisées dans la définition de niche écologique de l'espèce, mais elles pourraient être utilisées pour mesurer l'efficacité de l'approche ; voir Figure 8. Le modèle est ensuite utilisé comme description de la distribution de l'espèce (Franklin, 2009).

Les capacités des SIG à gérer de grandes quantités de données spatiales permettent de modéliser les distributions à des résolutions spatiale et temporelle plus grandes, et de suivre leurs mouvements.

Cette étude fournit une méthode rapide et efficace pour présenter des cartes temporelles et spatiales haute résolution de l'habitat préférentiel des espèces marines. Toute information qui participe à l'évaluation d'une espèce permettra d'apporter une réponse rapide et augmentera la probabilité d'une gestion réussie. L'extension du travail à toutes les espèces permettrait de déterminer quelles sont les espèces les plus touchées par les effets du changement climatique.

4.5.10.2 Effet du changement climatique sur le déplacement de la distribution des poissons

Le réchauffement de l'océan affecte la répartition des espèces marines en déplaçant leur zone de confort au fil du temps, comme le démontre l'évolution du point le plus septentrional des limites supérieure et inférieure des zones de distributions potentielles des espèces.

La tendance au déplacement vers le nord des zones potentielles des espèces est plus évidente au niveau de la limite inférieure de la plupart des zones préférentielles (Tableau 3) qu'au niveau de leurs limites supérieures (Table 4).

La tendance de la distribution de l’espèce à remonter vers le nord est plus évidente au niveau de la limite inférieure de la zone adéquate pour l'espèce. Cette tendance concerne toutes les espèces ayant une affinité subtropicale et tropicale, indiquant la forte incidence du réchauffement climatique. Les valeurs de pente sont significatives à chaque saison pour toutes les espèces sélectionnées, qu'elles soient bathypélagique, pélagiques, benthopélagiques ou démersales.

Les espèces pélagiques sont connues pour leurs niches étroites, ce qui explique leurs mouvements nord-sud vers leur zone la plus appropriée. Ces mouvements varient selon la saison avec une forte variabilité qui affecte en outre la valeur significative de leurs régressions linéaires.

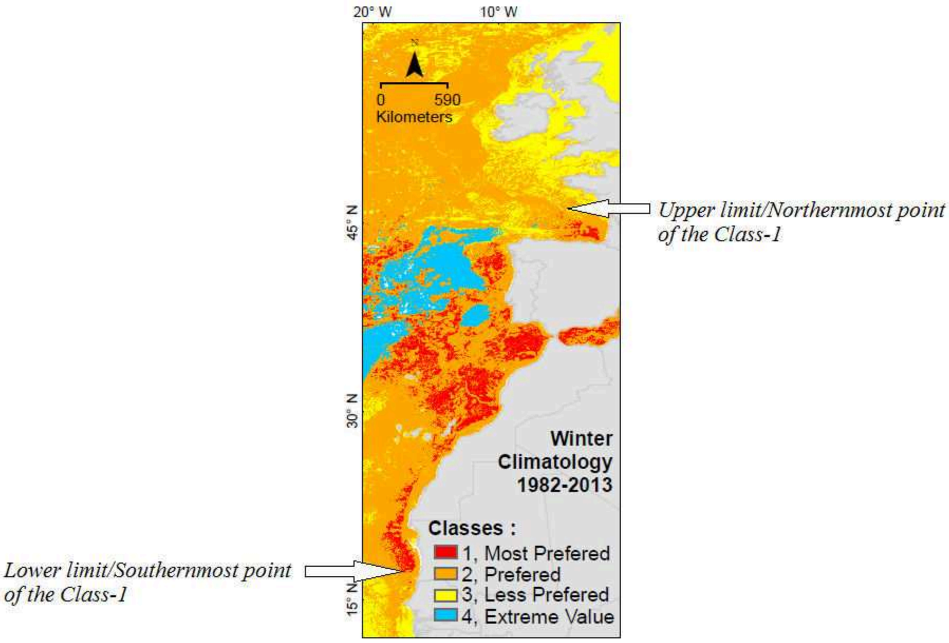


Figure 9: Limites supérieure et inférieure d'une zone (Classe 1).

Tableau 3 : Pente et sa significativité pour la limite inférieure de chaque zone / classe.

Species	**Affinity**	**Habitat**	**Depth pref. (m)**	**Class**	**Slope (p-value) by season***				
					1	**2**	**3**	**4**	**All**
M. punctatum	Temperate	Bathy-pelagic	909-3726	1	▲+	▲+	▲+	▲	▲+
P. saltatrix	Sub/Tropical	Pelagic	5-27	1	▲+	▲	▲+	▲	▲
A. tobianus	Temperate	Bentho-pelagic	20.6-61	1	▲+	▲+	▲	▲+	▲+
				2	▲	▲+	▲	▲	▲
L. whiffiagonis	Temperate	Demersal	122-173	1	▲	▲+	▲+	▲+	▲+
				2	▲	▲+	▲	▲+	▲+

*1 = Winter; 2 = Spring; 3 = Summer; 4; Autumn;

▲ = regression line has a positive slope (tendency of going north);

▼ = regression line has a negative slope (tendency to go south); + = *p-value* < 0.05 (significant)

Tableau 4 : Pente et sa significativité pour la limite supérieure de chaque zone / classe.

Species	**Affinity**	**Habitat**	**Depth pref. (m)**	**Class**	**Slope (p-value) by season***				
					1	**2**	**3**	**4**	**All**
M. punctatum	Temperate	Bathypelagic	909-3726	1	▲	▼	▲+	▲	▲
P. saltatrix	Sub/Tropical	Pelagic	5-27	1	▲	▲	▲	▲	▲

*See Table 4-28 for legend

Le Tableau 9 présente la pente et les valeurs significatives de la régression linéaire réalisée sur l'évolution du point le plus septentrional de la zone de préférence maximale de l'espèce, pour chaque saison et pour toutes les saisons calculées ensemble. En général, le déplacement latitudinal de ce point n'est pas significatif sauf pour *M. punctatum* (benthopélagique). Les valeurs de pente significatives ont été observées en période estivale (Saison 3 sur le Tableau 9) pour cette espèce uniquement.

La tendance de la distribution des espèces à se déplacer vers le nord a également été observée pour l'ensemble des espèces au cours de chaque saison, sauf pour *M. punctatum*, qui a montré une tendance vers le sud au printemps (Saison 2). Ces valeurs de tendances étaient très faibles en raison de la variabilité plus élevée durant les premières années (1982 à 1994), elles sont donc négligeables.

Aucune valeur de pente significative n'a été observée pour les espèces pélagiques représentées par *P. saltatrix* (Tableau 9).

Une forte variation des valeurs de limite supérieure et / ou de limite inférieure des zones appropriées de l'espèce a été observée dans la gamme latitudinale de 22 °N à 42 °N, de la côte mauritanienne à la côte sud du Portugal. Comme mentionné précédemment dans le sous-chapitre sur la zone d'étude, cette région est particulièrement connue pour représenter une zone de transition environnementale entre les eaux subtropicales ou tropicales et les eaux tempérées. Par conséquent, de nombreuses espèces ont leur limite de répartition dans ces domaines. Les forts mouvements dus à la variabilité saisonnière dans ces zones affectent les valeurs significatives des régressions linéaires.

L'un des effets du changement climatique qui affecte le plus la plupart des organismes marins est l'augmentation de la température des océans. Summerson et al. (2007) ont indiqué que la température de l'eau de mer contrôle la reproduction et la croissance des espèces, ainsi que la disponibilité de leur nourriture. Ainsi, l'augmentation des températures permet aux espèces tropicales d'étendre leur aire de répartition dans les latitudes plus élevées lorsque les températures de ces zones deviennent plus chaudes en été et vice versa.

En hiver, par exemple, les zones appropriées pour les espèces subtropicales / tropicales, telles que *P. saltatrix*, se trouvent dans les latitudes les plus basses. En été, quelques-unes des zones de plus hautes latitudes, qui étaient auparavant inhospitalières pour ces espèces en hiver, peuvent leurs devenirs favorables. Cela pourrait être l'une des principales raisons de la migration de ces espèces, comme le soulignent Oliver et al. (1989). Ballenger (2014) a mentionné que *P. saltatrix* est une espèce pélagique migratrice d'eau chaude sur la côte atlantique, qui se déplace généralement vers le nord au printemps et en été, et vers le sud en automne et en hiver.

Teixeira et al. (2014) ont confirmé dans leur rapport que les données de débarquements officielles pour les espèces commerciales ayant une affinité subtropicale / tropicale dans la région centrale de la côte portugaise ont montré une tendance à la hausse dans les années chaudes, tandis que les données de débarquement pour les espèces tempérées ont présenté une tendance inverse, et vice-versa pour les années froides. En outre, le *Secretariat of the Convention on Biological Diversi*ty (2009) a déclaré que certains des plus grands impacts des espèces invasives peuvent aussi résulter de l'intensité des événements climatiques extrêmes, car certaines espèces, de par leur large gamme de tolérance aux conditions climatiques et leur capacité à se déplacer rapidement, vont subir une mortalité plus faible lors de ces évènements que les espèces locales. .

La tendance vers le nord est évidente pour la limite inférieure des zones les plus appropriées pour toutes les espèces étudiées. Cela indique le fort effet du réchauffement climatique. Le Secrétariat de NOBANIS (2012) a mentionné que l'augmentation du réchauffement des océans peut faciliter l'invasion des espèces exotiques marines en augmentant leur croissance et leur recrutement par rapport aux espèces indigènes, et, pour les espèces marines pélagiques, la dispersion des œufs et / ou des larves a la possibilité de se propager sans l'aide de l'activité humaine.

De nombreux modèles actuels ne prennent pas en compte l'effet de la variabilité saisonnière qui affecte clairement la répartition des espèces. La plupart de ces modèles utilisent la température moyenne annuelle comme prédicteur des occurrences distribuées dans une zone donnée sans tenir compte de leur date d'observation. Ainsi, les résultats obtenus pourraient ne pas montrer la variation saisonnière qui existe dans la distribution des espèces.

4.5.10.3 Effet d'autres paramètres océanographiques

La Chlorophylle-a n'a pas été incorporée dans cette étude en raison de la présence de zones sans données dans de nombreux secteurs de la zone d'étude. Ce fait pourrait réduire la précision du modèle, car le modèle SIG utilisé exclut les zones sans données dans un des paramètres environnementaux incorporés. Cependant, des études analysant la distribution du zooplancton (Rutherford et al., 1999), la productivité primaire (Behrenfeld et Falkowski, 1997) et la diversité des poissons (Worm et Lotze 2009) ont montré que la chlorophylle n'est pas un bon prédicteur, tandis que la SST est mieux corrélée avec la distribution de la richesse spécifique. La productivité primaire affecte clairement l'abondance mais n'est pas déterminante pour la diversité (Whitehead et al., 2010).

Une étude expérimentale sur le microcosme suggère que des changements de productivité influencent la diversité (Whitehead et al., 2010). Cependant, des études d'observation de la diversité des animaux à grande échelle ont souvent échoué à produire des modèles cohérents (Mittelbach et al., 2001), bien que les divergences actuelles entre les études peuvent être expliquées par des différences d'échelle (Chase et Leibold 2002).

La salinité pourrait avoir un effet important sur la limitation de la distribution des espèces. De nombreux modèles existants ont utilisé les données de salinités issues des atlas de l'océan mondial de la NOAA. Malheureusement, l'intégration de ces données dans le modèle était problématique : les données ont été produites à partir d'échantillonnages physiques, avec une résolution spatiale faible par rapport aux données portant sur d'autres paramètres que nous avons utilisés dans le modèle.

Le projet de SMOS (*Soil Moisture and Ocean Salinity*) lancé en 2009 est capable de mesurer la salinité à distance. Néanmoins, les séries temporelles disponibles ne couvrent qu'une courte période et ne peuvent pas être utilisées dans cette étude. Incorporer ces données dans le modèle se traduirait par une déviation de la distribution potentielle réelle de l'espèce. En outre, de nombreuses espèces marines invasives ont une grande tolérance à la salinité, comme mentionné par Summerson et al. (2007), qui expliquent que la plupart des espèces potentiellement invasives sont d'origines estuariennes, des milieux où la variabilité de la salinité est très importante.

Le type de substrat, les modèles de circulation océanique résultant des interactions complexes entre les courants de surface, les courants poussés par le vent et les courants de marée, ainsi que la perturbation du milieu marin causée par l'activité humaine pourraient également avoir une influence majeure sur la répartition des espèces démersales. Les données de type de substrat sont disponibles pour certaines régions de la zone d'étude, mais des données couvrant une zone à grand échelle avec une résolution spatiale suffisante sont difficiles à trouver. Par ailleurs, l'intégration de ces données dans le modèle occulterait l'effet du changement climatique. D'ailleurs, comme rappelé par Summerson et al. (2007), de nombreuses espèces marines invasives ont des gammes de tolérance très larges en ce qui concerne l'habitat, ce qui leur permet de s'adapter aux nouveaux environnements.

4.6.3 Discussion : modèle de la richesse "spécifique"

L'idée de faire un modèle de richesse "spécifique" nous est venu lorsque nous avons travaillé avec des modèles individuels pour chaque espèce. En superposant tous les modèles individuels de distribution des espèces à un moment donné, nous avons été en mesure de calculer le nombre potentiel d'espèces dans une région. Ce modèle de richesse est alors susceptible d'être utilisé pour évaluer l'efficacité de l'emplacement d'une AMP par rapport aux zones de forte richesse en espèces (voir le sous-chapitre suivant).

4.6.3.1 Richesse réelle vs richesse du modèle

La richesse spécifique réelle et la richesse spécifique du modèle présentent un motif différent. La richesse spécifique réelle a été fortement influencée par la disponibilité des données d'occurrences. Ces données étaient généralement plus abondantes dans les eaux d'Europe du Nord (données obtenues à partir des pays développés) que de la côte du Portugal au sud des eaux marocaines. Dans la partie sud de la zone d'étude (les pays en développement), la disponibilité de ces données était très faible. Ce pourrait être dû au faible nombre d'enquêtes menées dans cette zone sud, à l'accès limité aux bases de données disponibles dans la région, aux mouvements d'espèces mobiles à grande échelle et à la variabilité temporelle des conditions océanographiques.

En général, les données d'occurrence d'espèces marine sont rares, car il est difficile de faire l'enquête sur toute la gamme des variations environnementales dans la région (Araujo 2002). Les enquêtes de terrain sur la mer et l'inventaire des espèces sont coûteuses et limité par le temps. Quantifier les pattern de la biodiversité exige des efforts coûteux et difficiles, en particulier dans les océans où les espèces ne peuvent pas facilement être vues et dont beaucoup sont très mobiles, avec de grandes aires de distribution qui vont jusqu'au large (Tittensor et al., 2010). L'utilisation d'espèces « indicatrices », qui dans cette étude sont des espèces considérées comme potentiellement invasives, pour estimer la richesse des espèces, est alors commune (Fleishman et al., 2005).

Les mesures disponibles de la biodiversité sont principalement analysées à l'aide de dire d'expert ou par des observations régionales, qui ne peuvent pas être utilisées directement pour enquêter sur l'éventuel changement de leurs distributions sous différentes conditions environnementales. La plupart des tentatives empiriques pour mesurer la biodiversité existante ont été basées sur les données d'occurrences. Le manque de données dans de nombreux endroits et le fait que les analyses ont été limitées dans la couverture taxonomique et spatiale réduit la qualité des prédictions (Whitehead et al., 2010).

En outre, la division des données d'observation réelles en quatre saisons réduit le nombre d'occurrences de l'espèce. Cela empire encore la situation des espèces pour lesquelles on dispose de peu de données. Ainsi, le modèle de la richesse "spécifique" est essentiel pour la compréhension de l'évolution saisonnière de la richesse des espèces.

4.6.3.2 Variabilité interannuelle

La température de la mer dans les eaux européennes atteint son maximum en été. À cette période, la plupart de la partie nord de la zone d'étude devient adéquate pour de nombreuses espèces (plus de 41 espèces), en particulier dans le golfe de Gascogne et au large de la côte portugaise.

La Figure 10 présente l'évolution de la richesse spécifique en période estivale, de 2010 à 2013. Dans le golfe de Gascogne et la Manche, les zones les plus occupées par des espèces étudiées (rouge et rouge foncé) se déplacent au fil du temps. Des tendances similaires ont été observées au large de la côte marocaine, alors que sur la côte portugaise, les emplacements des zones les plus appropriées pour la plupart des espèces étaient relativement stables chaque année.

Nos modèles devraient correspondre aux résultats décrits dans plusieurs articles tels que Teixeira et al. (2014). Ils ont déterminé que la richesse spécifique dans la région centrale de la zone d'étude (côte portugaise) est généralement élevée, car de nombreuses espèces y ont leur limite de distribution méridionale ou septentrionale. Cette région est en effet une zone de transition entre les eaux tempérées chaudes de l'Atlantique nord-est et les eaux tempérées froides. Les données de débarquement officielles pour les espèces commerciales avec une affinité subtropicale/tropicale dans cette région centrale ont montré une tendance à la hausse dans les années froides, alors que dans les années chaudes, ce sont les espèces ayant une affinité tempérée qui ont montré une tendance à la hausse.

Les limites de la zone à hotspots changent suivant les saisons. Myers et al. (2000) ont déclaré qu'un hotspot devait contenir des espèces endémiques ou menacées. Dans notre étude, nous nous sommes concentrés principalement sur les espèces potentiellement invasives, y compris les espèces menacées. La détermination des hotspots pourrait aider à identifier les zones prioritaires pour la conservation.

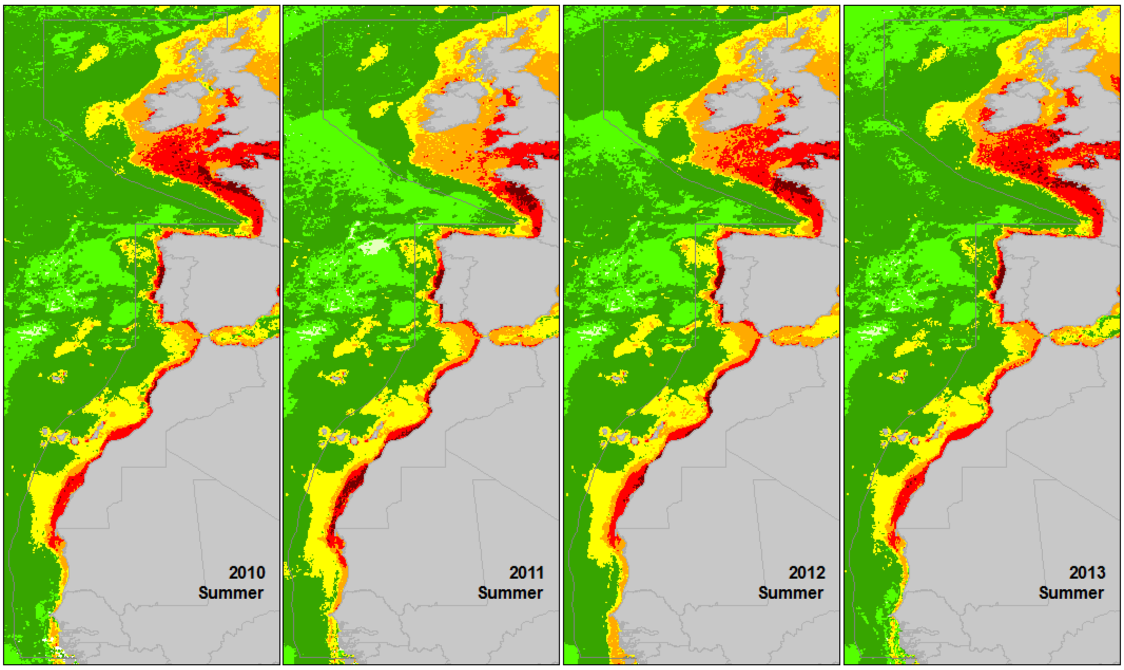


Figure 10 : Évolution des modèles de la richesse spécifique en période estivale, de 2010 à 2013. Les modèles saisonniers complets sont disponibles dans les documents supplémentaires.

Notre analyse présente des prévisions de richesse spécifique à différentes échelles temporelles. Notre approche tient compte du manque de données dans de nombreuses parties de la zone d'étude, en particulier lorsque l'on considère des périodes saisonnières. La méthode calcule simplement le nombre de zones appropriées des espèces qui se superposent. Ces zones appropriées proviennent des modèles SIG présentés dans le chapitre précédent. Les données environnementales clés utilisées étaient la température de surface de la mer, conformément aux recommandations de Whitehead et al. (2010).

4.6.3.3 Variation saisonnière

Les zones les plus riches en espèces invasives varient de manière saisonnière. Les espèces réagissent au réchauffement climatique en modifiant leur distribution latitudinale, en cherchant des eaux froides qui leur conviennent (Cheung et al. 2009). Cela affecte la réorganisation de la communauté locale et pourrait provoquer des extinctions locales.

En prenant le modèle de la richesse spécifique en 2013 à titre d'exemple (Figure 10), la figure montre que pendant l'hiver, les pics de richesse ont eu lieu dans les zones situées entre 15 °N et 30 °N. Au printemps, le pic a été observé dans les zones situées entre 18 °N et 38 °N. En été, ces zones se sont déplacées vers le nord, vers 40 °N au large de la côte portugaise et dans la zone de la côte sud de la Bretagne à 48°N. En automne, lorsque la température a commencé à diminuer, les zones où la richesse spécifique a atteint son apogée ont été trouvées entre 20 °N et 38 °N. Ces latitudes reflètent la température optimale pour les espèces étudiées.

La variabilité saisonnière est forte aux latitudes les plus élevées (Figure 11). Dans la région nord de la zone d'étude, les zones les plus riches se trouvaient généralement dans le golfe de Gascogne (Figure 11). La circulation générale dans cette région est fortement affectée par une topographie complexe, ce qui affecte la distribution environnementale et biologique (Koutsikopoulos et Le Cann 1996). Les vents du nord et de l'est de la zone centrale du golfe de Gascogne produisent les upwellings sur les côtes françaises et espagnoles, les plus importants se trouvant sur la côte française (Borja et al., 1996).

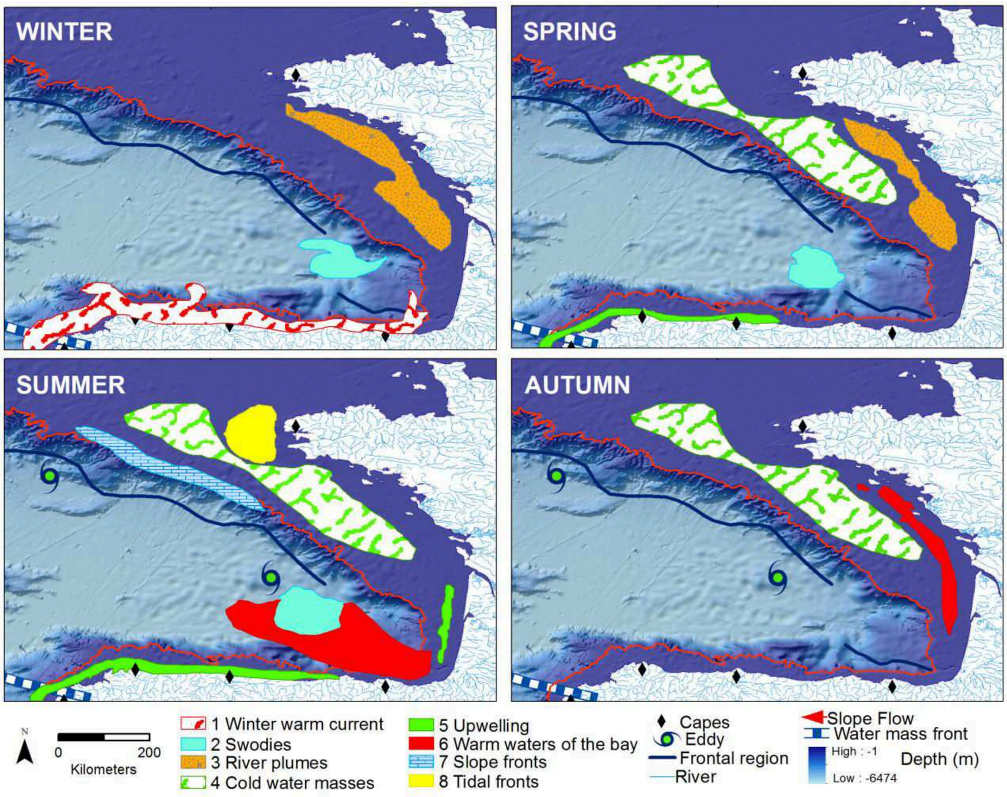


Figure 11 : Principales structures hydrologiques dans le golfe de Gascogne, adapté de Kotsikopoulos et Le Cann (1996).

Les vitesses moyennes de vent les plus élevées se produisent pendant l'hiver dans le golfe de Gascogne (Figure 11). Des eaux de surface plus froides s'étendent sur les régions du plateau français suite aux apports fluviaux qui atteignent leur maximum durant cette période (Koutsikopoulos et Le Cann 1996), et apportent de l'eau fluviale froide et de faible salinité. Au niveau des côtes espagnoles, dans la partie sud du golfe de Gascogne, les eaux relativement chaudes et salé du courant dirigé vers le pôle de la péninsule ibérique (IPC) s'écoulent le long du bord du plateau et de la pente supérieure au large du nord de la péninsule ibérique (Mason et al., 2005). Cette eau anormalement chaude est impliquée dans la formation de structures appelées SWODDIES (*Slope Water Oceanic Eddies*) qui persistent jusqu'à une année (Pingree et Le Cann 1992). Ces SWOODDIES, qui présentent de faibles taux de diffusion horizontale, ont tendance à retenir le matériel biologique (Fernández et al., 2004).

Au printemps, de faibles upwellings se produisent sur la côte espagnole du golfe de Gascogne (Figure 11). Le recrutement d'anchois a tendance à être plus élevé au cours de cette période (Borja et al., 1996). Le réchauffement saisonnier des eaux de surface commence durant cette saison. Au large des côtes françaises, sur les zones de plateau dans la partie sud du golfe de Gascogne, la propagation au large d'eaux de faible salinité venant des fleuves peuvent créer un environnement stable riche en nutriments (Mason et al., 2005).

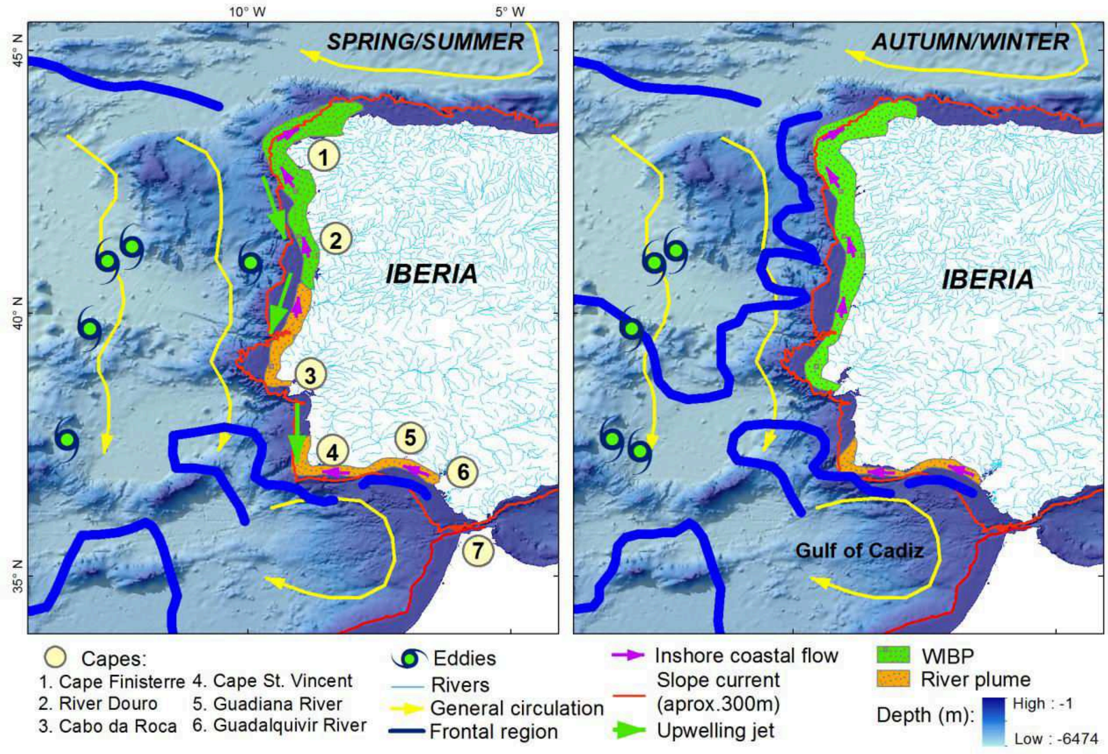


Figure 12: Caractéristiques océanographiques au large de la péninsule ibérique ; a) au printemps et en été, et b) en automne et hiver; adapté de Mason et al. (2005). Les images ont été prises initialement depuis Peliz et al. (2002) et Peliz et al. (2005). WIBP représente *the Western Iberia Buoyant Plume*.

En été, la température de la mer atteint sa valeur maximale dans la zone sud-est et conduit à la formation d'un bassin d'eau chaude important, une structure riche en chlorophylle (Gil et al., 2002). Cette zone de mélange pourrait avoir un impact biologique significatif. L'upwelling au le nord-ouest de la péninsule ibérique est particulièrement prononcé en été lorsque les vents du nord persistants actifs soufflent au large de (Mason et al., 2005). L'upwelling au large de la côte espagnole est plus faible qu'au large de l'ouest de la péninsule et au large des côtes françaises au cours de cette période

(Borja et al., 1996). L'interaction entre la bathymétrie et les courants de marée sur la partie nord du plateau français de Bretagne occidentale provoque des fronts de marées thermiques saisonniers (Koutsikopoulos et Le Cann 1996). Ce phénomène pourrait avoir des conséquences biologiques (Mason et al. 2005).

En automne, les eaux homogènes résultant de processus de mélange vertical apparaissent au nord du plateau français (Mason et al., 2005). L'apparition d'une « langue d'eau chaude » le long de la côte française est due au mélange entre les marées et les courants induits par le vent, et aux échanges océan-atmosphère (Cann, 1982).

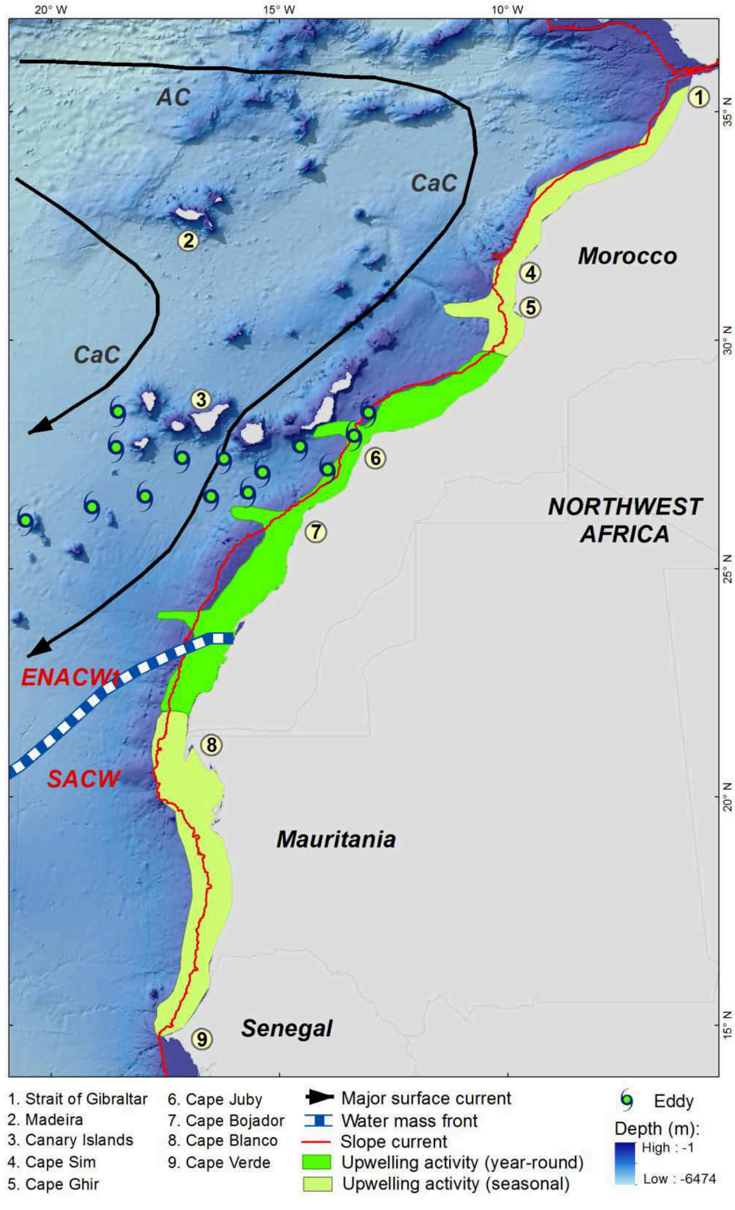


Figure 13 : Upwelling dans les eaux nord-ouest africaines. La couleur vert foncé représente les zones où les activités d'upwelling continuent toute l'année. La couleur vert clair représente les zones avec des activités d'upwelling saisonnières, adapté de Mason et al. (2005).

Cette étude a montré que la température joue un rôle important dans la répartition des espèces. La distribution de la richesse spécifique a changé et s'est déplacée considérablement au cours de l'année. Ainsi, les variations saisonnières doivent être prises en considération. Une étude plus approfondie de la SST, la productivité et la relation de la diversité à l'échelle supérieure sera nécessaire.

Au large de la péninsule ibérique occidentale, la principale saison d'upwelling (vents du nord) se produit pendant l'été, tandis qu'en hiver, les vents diminuent avec des périodes intermittentes où l'on observe à la fois upwelling et downwelling (Mason et al., 2005). Au printemps et en été, des upwellings persistants d'environ 100-300 m de profondeur se produisent le long de la zone côtière occidentale (Figure 12). Les upwellings sont généralement intenses dans les eaux du Cap Finisterre, Cape St. Vincent et Cabo de Roca. Ils s'étendent à plus de 100 km au large.

Dans les eaux nord-ouest africaines, les upwellings se produisent toute l'année dans la zone située entre 20 °N et 30 °N (Figure 13). L'upwelling saisonnier s'effectue en dessus et en dessous de cette zone. Des informations détaillées sur les conditions océanographiques dans ces domaines peuvent être trouvées dans Mason et al. (2005).

4.7.5 Discussion : Les AMPs et le changement climatique

Une aire protégée est un espace géographique clairement défini, reconnu, et géré par des moyens efficaces, juridiques ou autres, pour assurer la conservation à long terme de la ressource naturelle avec ses services écosystémiques et ses valeurs culturelles (Day et al. 2012).

Les zones de transition écologique sont les plus susceptibles de promouvoir des réponses adaptatives au changement climatique (Araujo, 2002). Ces zones de transition dépendent de la période de l'année. C'est le défi des extinctions à grande échelle (Myers et al., 2000).

L'approche des *hotspots* pour assurer la préservation des espèces à l'échelle locale est risquée (Smith et al., 2001), tandis qu'à l'échelle continentale et nationale elle est prioritaire. Néanmoins, les zones situées au cœur des gammes de préférences de nombreuses espèces ou les zones de non-transition pourraient jouer un rôle fondamental (Araujo 2002).

Les hotspots d'aujourd'hui sont peu susceptibles d'être les hotspots de demain (Smith et al., 2001). Il est nécessaire de porter une attention aux variations adaptatives existant dans des environnements variés si l'on veut préserver la réponse évolutive aux changements environnementaux et climatiques (Smith et al., 2001).

L'analyse de surface de l'AMP montre que la distribution des hotspots est fortement influencée par les variations saisonnières. Prendre en compte des zones de transition écologique dans les efforts de conservation est donc nécessaire.

Il peut être facile d'observer les effets des changements climatiques dans les zones protégées, car elles sont normalement mieux protégées contre les impacts anthropiques que d'autres régions, et donc susceptibles d'être soumises à moins d'interférences provenant d'autres causes de changement. À cet égard, les AMP, comme dans les eaux portugaises, peuvent jouer un rôle important en tant que « sites sentinelles », où les effets du changement climatique peuvent être étudiés et les stratégies de gestion peuvent être développées pour s'adapter à, et autant que possible contrer, ces effets négatifs (Otero, Garrabou et Vargas 2013). Les AMP et les réseaux d'AMP dans les zones côtières des eaux de l'Atlantique Est ont un rôle important à jouer dans l'amélioration de notre compréhension et pour aider à élaborer des stratégies d'atténuation des effets des changements climatiques.

Otero, Garrabou, et Vargas (2013) ont mentionné que les changements globaux doivent être compris comme ceux qui affectent la planète entière, mais pas nécessairement de la même manière partout. Ils donnent l'exemple des changements de salinité : la modification du cycle hydrologique de la Terre et la fonte des glaciers et des calottes glaciaires affectent la salinité des océans à l'échelle mondiale, mais, alors que la salinité devrait diminuer aux latitudes élevées, elle va augmenter à des latitudes plus faibles en raison de la réduction des précipitations et de l'augmentation de l'évaporation.

Dans cette étude, les effets du changement climatique peuvent être surveillés dans les AMP de la zone. C'est un défi croissant dans la gestion des AMP.

Le changement climatique n'est souvent pas explicitement intégré dans la plupart des plans de gestion des AMP, et l'évaluation de la performance future d'une AMP devra prendre en compte ces effets (Otero, Garrabou et Vargas 2013). L'évaluation des effets des changements climatiques sur la biodiversité marine est également nécessaire pour soutenir la planification de l'adaptation dans les zones protégées.

Notre étude peut fournir des informations de base précieuses pour mesurer non seulement les effets des changements climatiques sur la biodiversité des espèces, mais aussi l'efficacité de la localisation des AMPs. Les risques d'impact dépendent des zones et de la période, et cette étude fournit des informations permettant d'allouer des efforts vers les zones à risques.

Cette étude démontre que la surveillance des AMP en relation avec le changement climatique ne nécessite pas de matériel coûteux ou des capacités techniques très développées. Cependant, elle pourrait aider les gestionnaires à comprendre les vulnérabilités et l'importance des différents sites. En outre, elle pourrait contribuer à la révision du zonage des AMP.

4.8.3 Discussion : Prédiction des distributions futures

Les modèles climatologiques tentent de simuler les changements de l'océan sur le long terme, plus de 50 à 100 ans. Nicol et al. (2014) mentionnent que les modèles climatiques prédictifs les plus avancées sont les modèles assimilant des données d'observation passées afin de saisir les conditions historiques lors de l'initialisation. Ils notent que cette inclusion a été achevée pour les modèles IPSL et GFDL.

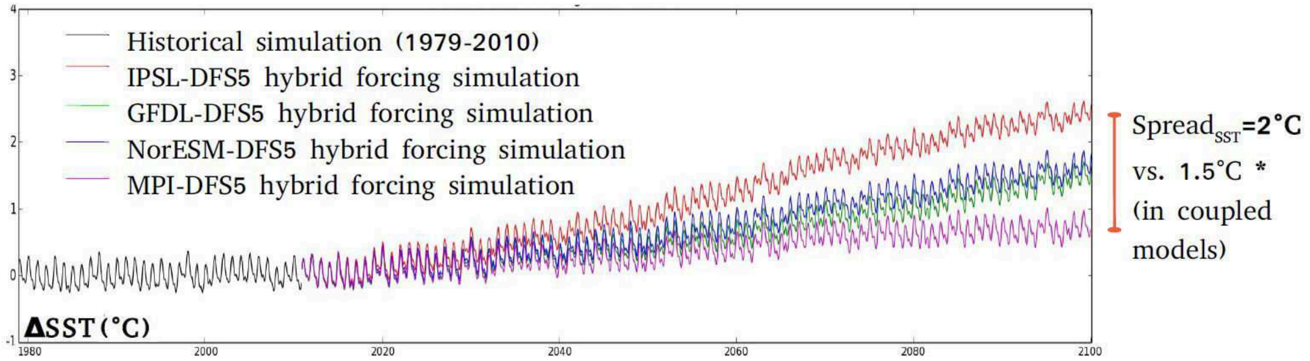


Figure 14 : Évolution de la SST dans les modèles couplés et la simulation forcée (Dessert et al 2015).

Une variabilité de prédiction, des écarts et des incertitudes existent entre les modèles. Elles influencent le modèle de répartition des espèces. Le modèle SST de l'IPSL prévoit une augmentation plus forte de la température (Figure 14). Malheureusement, ces questions ne seront pas abordées dans cette section car le sujet est au-delà de la portée de cette étude.

De nombreuses hypothèses et approximations ont été faites en matière de modélisation, pour les deux modèles climatiques et les modèles de distribution d'espèces, en particulier lors de la projection du décalage de la distribution au fil du temps. Les effets synergiques entre les espèces, ou les facteurs anthropiques tels que la pêche, sont difficiles à intégrer dans les processus de modélisation. L'effet de la chimie des océans n'est pas incorporé. Cependant, en dépit de ces incertitudes, nos modèles sont en accord avec les résultats d'autres études. Ce travail peut également être considéré comme l’information de base pour de futures études similaires.

Nos résultats montrent que l'augmentation de la température peut entraîner les espèces tropicales à migrer vers le nord. Ce phénomène pourrait changer la composition spécifique locale. Hiddink et Hofstede (2008) ont déterminé que l'augmentation de la richesse spécifique de poissons dans la mer du Nord ces dernières années est liée au changement climatique et à l’échelle biogéographique.

Les espèces marines peuvent avoir une capacité de dispersion plus importante que les organismes terrestres. Cela leur permet de trouver des habitats appropriés plus facilement. Cette étude montre comment la température détermine la répartition passée et l'avenir d'une espèce. Ce phénomène peut augmenter l'impact négatif des perturbations humaines sur les organismes marins. Les données dérivées de la bathymétrie présentent la façon dont ces distributions sont limitées par la disponibilité des habitats appropriés. D'autres informations provenant d'autres études montrent comment les conditions géographiques peuvent influer sur l'intensité des effets des changements climatiques sur la répartition des espèces.

Enfin, la disponibilité de toutes les données environnementales ou de pression de pêche à l'échelle de la zone d'étude est limitée, surtout lorsque l'on travaille avec des modèles saisonniers qui nécessitent des mesures cohérentes au fil du temps. Ces éléments sont considérés comme ayant des effets importants sur la répartition des espèces, et sont donc prometteurs pour les prochaines études.

Impact du Changement Climatique sur la Distribution des Populations de Poissons. Approche par SIG, Modèles et Scénarios d'Évolution du Climat

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Résumé

La compréhension des interactions liant la répartition des espèces, la biodiversité, les habitats marins et le changement climatique est nécessaire voire fondamentale pour la mise en œuvre d'une gestion efficace de la conservation. Dans cette étude, nous avons travaillé sur l'évolution de richess de 89 espèces de poissons notées «rares» ou «exotiques» (observées en dehors de leur aire de répartition connue) lié au changement climatique. Nous avons modélisé et predire leur distributions saisionnaire par le modèle SIG en fonction de leurs niches écologiques (determinée dans cette étude). En superposant tous les modèles en fonction du temps, cette approche permete d'identifier des zones d'occupation préférentielle de forte biodiversité (*hotspots*). La méthode offre une alternative pour mesurer la richesse d'espèces de façon saisonnière dans des zones peu connues, et de suivre leur movement au cours de temps, puis avoir information de base sur l'eficacité de positionnement des aires mairne protégés lié à ces zones *hotspots*.

La zone d'étude s'est située dans trois grands écosystèmes marins : le courant des Canaries, le plateau sud de l'Atlantique Européen et les mers celtiques. La région centrale est une zone de transition (entre les eaux tropicales et temperes) connue pour sa sensibilité aux effets du changement climatique.

De 1982 à 2012, la SST augmente constamment au fil du temps, avec des tendances et des magnitudes qui varient selon l'écosystème. Une augmentation du nombre d'espèces dans un écosystème dans une période a été généralement suivie par une tendance à la baisse ou à la hausse dans des écosystèmes adjacents.

Les niches écologiques des espèces étudiées ont été estimées par l'extraction des valeurs environnementales à l'echèlle mondiale au point d'occurrence au moment de l'observation. Les résultats de niches sont cohérents avec ceux obtenus à partir d'études observationnelles ou expérimentales.

La flexibilité du modèle SIG nous a permis de suivre l'évolution saisonnière de distribution des espèces au fil du temps. En général, les espèces montrent une tendance à élargir leur distribution vers le nord, montrant l'effet du réchauffement de l'océan sur la distribution des poissons marins. L'approche de modèle peut être utilisée pour modéliser la distribution des espèces moins connues, ou dans des zones où les données d'occurrences sont peu nombreuses, ainsi que pour predire le modèle de distribution future.

L'analyse spatiale de la superficie des AMPs (Aires Marines Protégées) par pays appartenant à la zone d'étude, montre que le Royaume-Uni puis la France possèdent le plus grand nombre d'AMP ainsi que les superficies totales protégées les plus importantes. La fréquence à laquelle les AMPs (Aires Marines Protégées) sont touchées par les zones de *hotspots* est fortement influencée par les variations de l'environnement, les zones favorables évoluant alors au fil des saisons. Ainsi, il est important de prendre en compte les variations saisonnières pour la création des AMPs afin de préserver les capacités adaptative des espèces soumises au changement global.

Mots-Clés : Changement Climatique, Poissons rares ou exotiques, Atlantique de l'Est, Niches, Model de la SIG, Hotspot ou Biodiversité, Aire Marine Protégées, Prediction de répartition future.

“I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today - and even professional scientists - seem to me like somebody who has seen thousands of trees but has never seen a forest. Knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is - in my opinion - the mark of distinction between a mere artisan or specialist and a real seeker after truth”

Albert Einstein
1879-1955