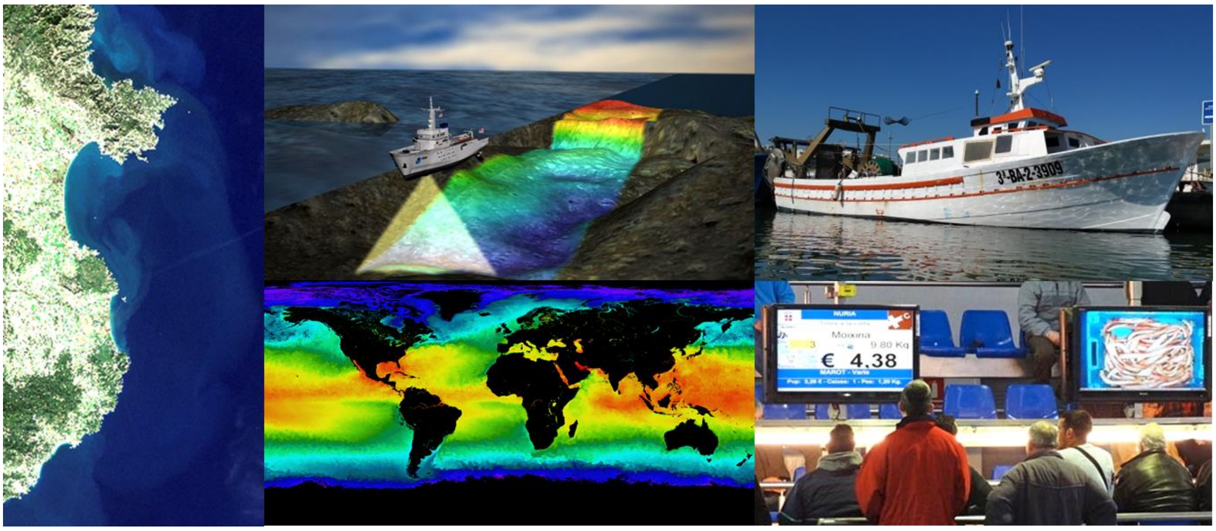
Development of a Geographic Information System for fisheries management



(Blanesaldia, 2012; ESA, 2020; EU Fleet Register, 2021; NASA, 2018; NOAA, 2021)

Jordi Ribera Altimir

Institute of Marine Sciences (ICM-CSIC)

Departments: Physical and Technological Oceanography | Renewable Marine Resources

Master in Oceanography and Marine Environmental Management

University of Barcelona (UB) | BarcelonaTech (UPC)

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DAVID AMBLAS NOVELLAS - DNI 33959073X

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Nombre de reconocimiento (DN): c=ES, sn=AMBLAS NOVELLAS, givenName=DAVID, serialNumber=IDCES-33959073X, cn=DAVID AMBLAS NOVELLAS - DNI 33959073X
Fecha: 2021.09.14 17:07:25 +02'00'

Jordi Isern Fontanet
Master thesis director
Physical and Technological Oceanography (ICM)

David Amblàs Novellas
University tutor
Earth and Ocean Dynamics (UB)

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Abstract

Managing fisheries from a scientific data-driven point of view is challenging because many biological and environmental variables, that change over time and space, must be taken into account in the assessment. Species analysis in combination with associated environmental factors are used to describe species behaviour, predicting their distribution, impacts on future climate conditions and managing fishing effort. In this context, there is a general lack of dynamic tools for addressing the common obstacles in elaborating these applications. Therefore, the present study introduces the development of a tool to combine environmental and fisheries variables and assist researchers and fisheries managers in the data analysis process. The tool was divided in scalable modules for automating the main aspects of this process; data download, format unification, spatial subsetting, interpolation, combination and results visualization. As a proof of concept, monthly spatial distribution of fishing effort and species biomass and revenue were incorporated in the tool, extracted from vessel positioning (VMS) and daily landings generated by bottom trawling and purse seine fishing fleet. Ongoing fisheries samplings were also included to obtain more resolution on catch composition and biological analysis. Monthly sea surface temperature (SST) and Chlorophyll-a concentration (Chl-a) distribution, extracted from MODIS, and bathymetry were the included environmental variables, as the critical parameters to the marine fishery ecosystem. The starting point for converting static fisheries management to dynamic is having an automated process for obtaining the historical and recent data, as well as predictions on future scenarios. Therefore, this eco-informatics tool is a step towards the transition to a dynamic management for facing fisheries sustainability.

1 Introduction

Ecological informatics (eco-informatics) is an emerging interdisciplinary framework that aims at creating new knowledge through innovative digital approaches on the generation, sampling, processing, analysis, visualization, management, and dissemination of relevant ecological, environmental and socioeconomic data (Michener & Jones, 2012). Eco-informatics tools for the marine environment are still on their early stages. An application of eco-informatics tools is dynamic ocean management, the management of marine resources that change rapidly in space and time in response to the shifting nature of the ocean and its users. Dynamic ocean management is a new paradigm that holds promise for fisheries sustainability, design of Marine Protected Areas (MPA) and management of marine species populations (Maxwell et al., 2015; Scales et al., 2017).

Mediterranean fisheries show the highest percentage of stocks fished at unsustainable levels (FAO, 2018, 2020). Despite professional fishing in Catalonia is a major economic activity, for almost two decades landings and revenues produced by Catalan fisheries show a decreasing trend, as well as their fleet size does, from 1087 vessels in 2002 to 591 in 2020 (Figure 1). However, the landings average price, € by kilo, has been increasing during this period (M. Coll et al., 2021; ICATMAR, 2021-01; Martín et al., 2014). The result of the scarce sea resources and its low economic performance, is threatening fisheries viability (Gómez & Maynou, 2020). Managing these fisheries, mostly multispecific, is challenging because many biological and environmental variables must be taken into account in the assessment (Colloca et al., 2015; Sion et al., 2019).

In that context, the Catalan Institute for Ocean Governance Research (ICATMAR) was created, which is a cooperation organism between the Ministry of Climate Action, Food and Rural Agenda of the Government of Catalonia and the Institute of Marine Sciences (ICM) of the Spanish National Research Council (CSIC). ICATMAR channels scientific monitoring and research to provide data-driven assessments, which enable sustainable management of marine and maritime activities (Generalitat de Catalunya, 2018).

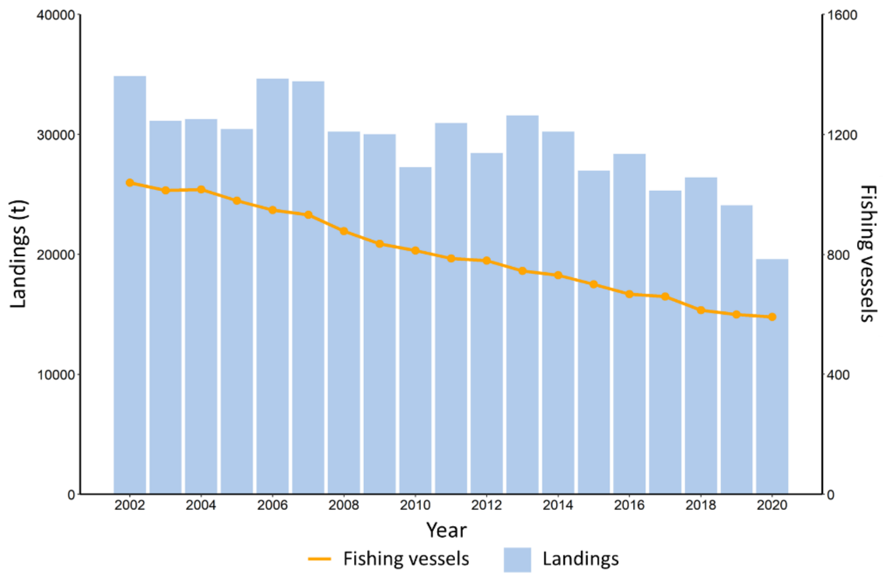

Figure 1. Trend of annual landings in tones (t) produced by Catalan professional fishing vessels and the amount of vessels from 2002 to 2020 (ICATMAR, 2021-01).

Vessel Monitoring System (VMS), a satellite surveillance system primarily used to monitor the location and movement of commercial fishing vessels, has many potential applications in fisheries science. Descriptions of the spatial and temporal distribution of the fishing effort are used as indicators of fishing pressure, to assess regulations compliance and area closures, to describe fishing behaviour and vessels interaction (Gerritsen & Lordan, 2011; Lee et al., 2010).

The explanatory power of VMS data can be increased by combining them with data from certain species, such as fishing landings or animal tracking. These combinations are used in several ways, like tracking the distribution of target species, assessing MPA's effectivity and analysing the interactions between commercial fishing vessels and certain species (Cianchetti-Benedetti et al., 2018; Sala-Coromina et al., 2021).

Environmental variables play a vital role for understanding the marine ecosystem. Sea surface temperature (SST) spatial patterns reveal the structure of the underlying ocean dynamics, such as, ocean fronts, eddies, coastal upwelling and exchanges between the coastal shelf and open ocean (Maurer, 2002; Minnett, 2014). It is also a major influencer for biological indicators (Fernández-Corredor et al., 2021). Phytoplankton is a key element in the biological carbon pump and contributes to the primary production, being the first step of the ecological pyramid as well as the food web. Phytoplankton distribution is influenced by biogeochemical variables such as light and nutrient availability, competence and predatory interactions, temperature and pH, that are all connected with ocean dynamics (Navarro & Ruiz, 2006; Salyuk et al., 2016; Sammartino et al., 2015). Therefore, combining environmental and species data expand the research capabilities to build new applications. Some of these are helpful for further explaining the behaviour of target species, predicting their distribution, assessing the impacts of climate change on the marine communities and allocating fishing effort for optimizing the harvest of target fish, while minimizing bycatch of protected species (M. Coll et al., 2019; Company et al., 2008; Hazen et al., 2018; Pennino et al., 2020; Ramírez et al., 2021). Therefore, understanding the patterns of spatial and temporal distribution of wild populations is a critical consideration in the development of effective management and conservation strategies (Albo-Puigserver et al., 2021; Colloca et al., 2015).

In order to obtain these kind of applications, there are multiple data sources available and ways of acquiring, storing, merging, curating, analysing and visualizing them. Therefore, most of the stakeholders will address common challenges and will face similar obstacles, such as finding the right datasets, downloading and storing them, lack of common formats, resolutions, projections and data quality, and difficulties on data treatment and visualization. Moreover, a recent survey done by SHAREMED project (Sharing and enhancing capabilities to address environmental threats in the Mediterranean Sea) highlights that difficulties on data accessibility, lack of data homogeneity and insufficient technical skills are the main obstacles in exploiting existing marine data (SHAREMED, 2021).

In this context, it is essential developing informatics infrastructure for providing structured high-quality data and products. The purpose of this study is building a tool for achieving the first steps towards a dynamic ocean management approach. This tool pretends assisting scientific research and marine environment management, combining environmental and fisheries variables in order to facilitate data reuse, accessibility and analysis, automate data gathering process, structure datasets and unify formats. As fisheries variables, monthly spatial distribution of fishing effort, species biomass and revenue were included in the tool. All data from the ongoing ICATMAR fisheries samplings are integrated in the tool for obtaining more resolution on catch composition and biological analysis. Three environmental variables were also included as potential influencers on the distribution of marine species, therefore as conditioning factors of the fishing activity. These variables include two oceanographic ones: Sea Surface Temperature (SST) and chlorophyll-a concentration (Chl-a), and a topographic one: bathymetry. Although this tool is designed for being capable to shelter other variables in the future, the selected ones for this study play a major role influencing pelagic and demersal marine populations and are routinely available through satellite observations (Druon et al., 2015; Fernández-Corredor et al., 2021; Lloret-Lloret et al., 2021).

2 Materials and methods

2.1 Study area

The study area is located within the Catalan Sea in the NW Mediterranean, covering the entire area where the Catalan fisheries are allowed to fish (Figure 2). Most of the physical and biological processes that characterize the global ocean, occur analogously in the Mediterranean Sea. In particular, fresh water input, upwelling and currents contributes in the area's high productivity (M. Coll et al., 2021; Sammartino et al., 2015).

This study comprises the bottom trawling and purse seine fleets from the 19 landing ports in Catalonia. Demersal resources are mainly exploited by the bottom trawling fleet, targeting European hake (*Merluccius merluccius*), red mullet (*Mullus surmuletus*), horned octopus (*Eledone cirrhosa*) and a variety of crustaceans; Norway lobster (*Nephrops norvegicus*), blue and red shrimp (*Aristeus antennatus*), spottail mantis shrimp (*Squilla mantis*) and triple-grooved shrimp (*Penaeus kerathurus*). Bottom trawling fishery produces the greatest revenue due to the high price of some of the target species in this sector. Small pelagic fish are mainly exploited by purse seine fleet, targeting European sardine (*Sardina pilchardus*), European anchovy (*Engraulis encrasicolus*) and round sardinella (*Sardinella aurita*). Purse seine fishery produces the greatest volume of landings (ICATMAR, 2021). Small-scale fisheries are not covered in this study for the lack of vessel positioning data from these fleets.

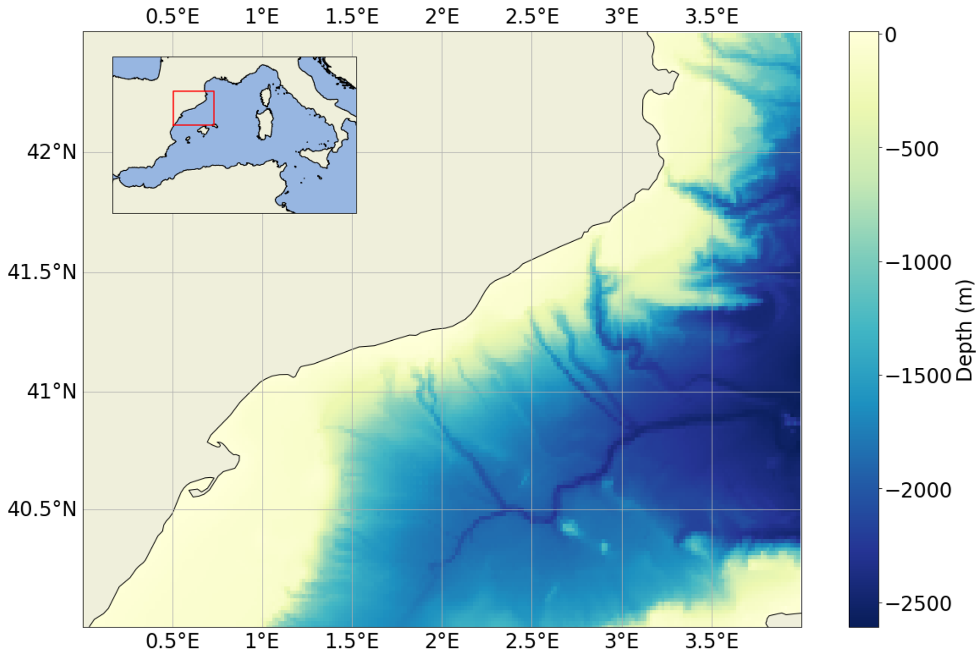

Figure 2. Study area in the NW Mediterranean Sea.

2.2 Fisheries data

2.2.1 Daily fishing landings

Professional fishing fleet in Catalonia is obliged to land its daily catches on the Catalan landing ports. Sales that take place at the auctions upon vessels arrival are registered and transmitted daily to the Catalan Government and on demand, to ICATMAR for integrating it into its database. The almost 24 million registers from 2000 to 2020 were imported, containing information about the landing date, fishing vessel, port, species, weight and income. No data from discards is available on this dataset.

2.2.2 Vessel positioning

In 1997, the European Commission (EC) introduced legislation to monitor European fishing vessels for control and enforcement purposes. Vessel Monitoring System (VMS) is a mandatory tool for European fishing vessels of more than 24 m length since 2000, over 15 m since 2005 and over 12 m since 2012. Initially, vessels were required to transmit their position and since 2006, also vessel speed and course information (European Commission, 1997, 2003, 2009, 2011; Gerritsen & Lordan, 2011; Shepperson et al., 2018). The required reporting interval is 2 h, but some records proved to be more frequent. More than 8 million of daily VMS records were provided by the General Fisheries Secretariat of the Spanish Ministry of Agriculture, Food and Environment from 2004 to 2020 for bottom trawling and purse seine fisheries and were integrated in the ICATMAR database.

To identify the different vessel activities, spatial, temporal and speed filters were applied to unprocessed VMS data. The considered fishing effort of bottom trawling fleet is related with the fishing time. Therefore, it was considered that a vessel is fishing when the speed was between 1 and 4.5 knots and between 3 nautical miles of coast or 50 m depth and 1000 m depth, as it is prohibited to fish out of this area for the Spanish Mediterranean trawling fleet (European Commission, 2006; Gerritsen & Lordan, 2011; Lee et al., 2010). For purse seine, fishing strategy differs compared to bottom trawling, therefore fishing effort was defined as the sum of all operations involved, considering speeds between 0 and 15 knots at depths more than 25 m and during night-time. Landings were assigned to positions where vessels have a direct interaction with the exploited resource, not only fishing it, considering speeds between 0 and 6.5 knots (ICATMAR, 2019-01, 2020-02; Martín et al., 2014).

2.2.3 Fishing fleet

The EU Fleet Register (http://ec.europa.eu/fisheries/fleet/) is a database where all the fishing vessels flying the flag of an EU country have to be registered. Any changes in the status of a fishing vessel need to be registered by the member country in the Fleet Register (European Commission, 2013). The almost 150000 registers for all the historical changes of the Spanish fishing fleet from 2000 to 2020 were integrated in ICATMAR database. Each register contains information about vessel identifications, technical characteristics and historical events, such as vessel identification code (CFR), base port, fishing gear, gross tonnage (GT), overall length (LOA), power, etc.

2.2.4 Integrating fishing fleet, daily landings and VMS data

The EU fleet register was merged with the VMS data and daily landings through the vessel identification code (Community Fleet Registration number). Changes in fleet history have been taken into account when linking datasets.

For each day and vessel, the corresponding fishing time was calculated with the time interval between successive VMS fishing positions and distributed homogeneously among them. In order to obtain a spatial distribution of landings, these were aggregated by day and vessel. Then, the daily aggregations were distributed homogeneously among VMS fishing positions of the same date and vessel, through the vessel identification code. As a proof of concept, only total weight and revenue for some target species were considered, as well as the total landing for the fishing day and vessel. Then, points were allocated on a 1 km^2 grid and the variables within each cell were summed up. Data were aggregated in monthly resolution to make sure that data accumulation reduce the bias on VMS data reporting frequency. All this process was automated through a Python script accessing ICATMAR database and generating CSVs as vector outputs for the monthly combination of landings, VMS and fishing fleet data. These outputs were provided by ICATMAR as an input for this study, where they were rasterized and transformed to NetCDF to unify data formats (Gerritsen & Lordan, 2011; ICATMAR, 2019-01, 2020-02; Lee et al., 2010; Shepperson et al., 2018).

2.2.5 Fisheries sampling

From October 2018 to September 2021, more than 800 fisheries samplings have been carried out by ICATMAR. The ongoing samplings are taking place in 10 ports along the Catalan coast, divided into north, centre and south areas. Once every season and port, the demersal resources are sampled on board of a fishing bottom trawling vessel on three different fishing grounds. All commercial catch is measured on board and part of the target species sample, discards and debris are carried to ICM for collecting extra data. Similarly, small-scale fisheries sampling of sand eel and common octopus are carried out twice a month. Pelagic resources are sampled by buying a part of the catch and analysing it (ICATMAR, 2019-01). ICATMAR has developed a Website to introduce all sampling data in the database and automatically perform the needed calculations for its analysis (Figure 3).

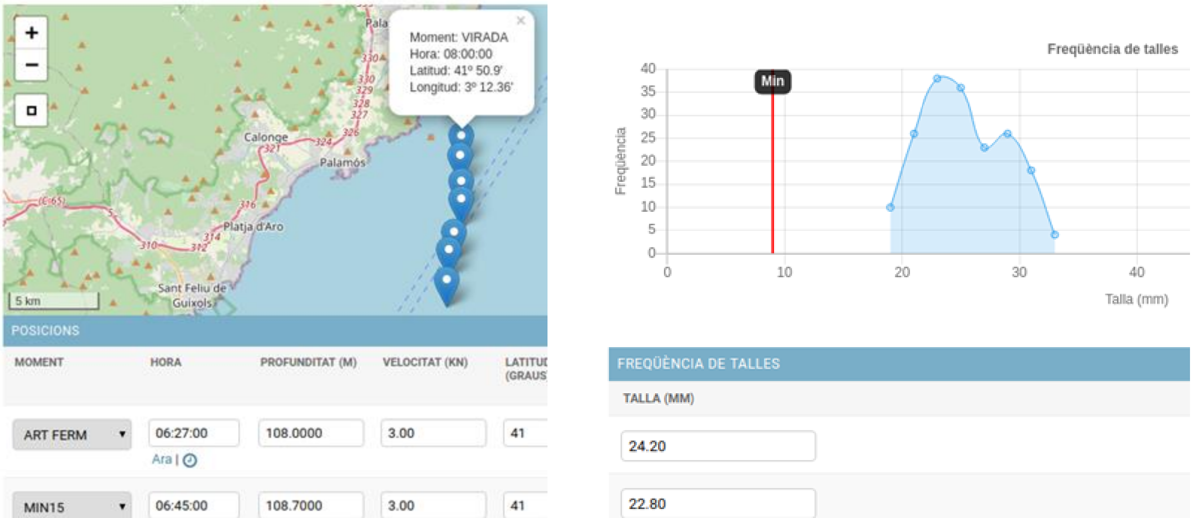

Figure 3. ICATMAR data introduction Website. The left part is the position section, where the positions from the sampling are introduced and visualized for their validation. The right part is the samples section, where the main measurements from each species are introduced and a size-frequency chart is visualized for their validation.

2.3 Environmental data

Three environmental variables were selected for this study; two oceanographic ones: Sea Surface Temperature (SST) in °C and chlorophyll-a concentration (Chl-a) in mg/m3, and a topographic one: bathymetry in metres.

2.3.1 Sea surface temperature (SST)

Methods for determining SST from satellite remote sensing include thermal infrared and passive microwave radiometry. Thermal infrared allows measuring SST near 10 µm below the surface, it has a long heritage (~40 years) and provide good resolution (~1 km at nadir) and accuracy (~0.1 K). Measurements can differ between daytime and night-time due to the relatively strong reflection of solar irradiation and the existence of a daily thermocline, which is typically 1-2 m depth and 0.1-1 K in amplitude (Chin et al., 2010). Moreover, the used bands are sensitive to the presence of clouds and scattering by aerosols and atmospheric water vapour. However, weekly or monthly SST composites are used for getting cloud-free pixels over a region.

On the other side, passive microwave measurements allow measuring SST to 1mm depth, but due to lower signal strength of the Earth's Planck radiation curve in the microwave region and the influence of other contributions such as wind and sea state, accuracy is poorer for SST derived from passive microwave compared to thermal infrared measurements, and resolutions are of the order of 25 km. However, the advantage gained with passive microwave is that radiation at these longer wavelengths is largely unaffected by clouds and generally easier to correct for atmospheric effects (Maurer, 2002; Minnett, 2014).

2.3.2 Chlorophyll-a Concentration (Chl-a)

The global distribution of Chlorophyll-a (Chl-a), the direct proxy for phytoplankton biomass, can be remotely sensed from a satellite by measuring the visible solar radiation that has interacted with the ocean, the ocean colour. The need for accurate retrievals of Chl-a concentrations from ocean colour data has driven most of the research in algorithm development over the past thirty years (Blondeau-Patissier et al., 2014).

The typical Chl-a seasonal cycle of the temperate regions occurs in the Mediterranean Sea, with its maximum in spring, when the main bloom occurs, and its minimum in summer, when the water column is highly stratified and nutrient concentrations are low at surface (Arin et al., 2005; Nurdin et al., 2013).

2.3.3 SST and Chl-a data source

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites. Terra and Aqua MODIS view the entire Earth's surface every 2 days, acquiring data in 36 spectral bands. The set of data records covers the entire period from 2002-07-04 to present (NASA, 2018).

Regarding the current restriction of having monthly aggregation for the fishing effort variables and the temporal coverage of both VMS and landings from 2004, the selected configuration for this study has been Level 3 binned data products of SST and Chl-a variables from Aqua MODIS on a monthly aggregation and 4 km of spatial resolution (Figure 4). The data were downloaded from the NASA's Ocean Color server (http://oceancolor.gsfc.nasa.gov/). For SST products, the selected observations are night-time due to the relatively strong reflection of solar irradiation, which contaminates the retrieved radiation.

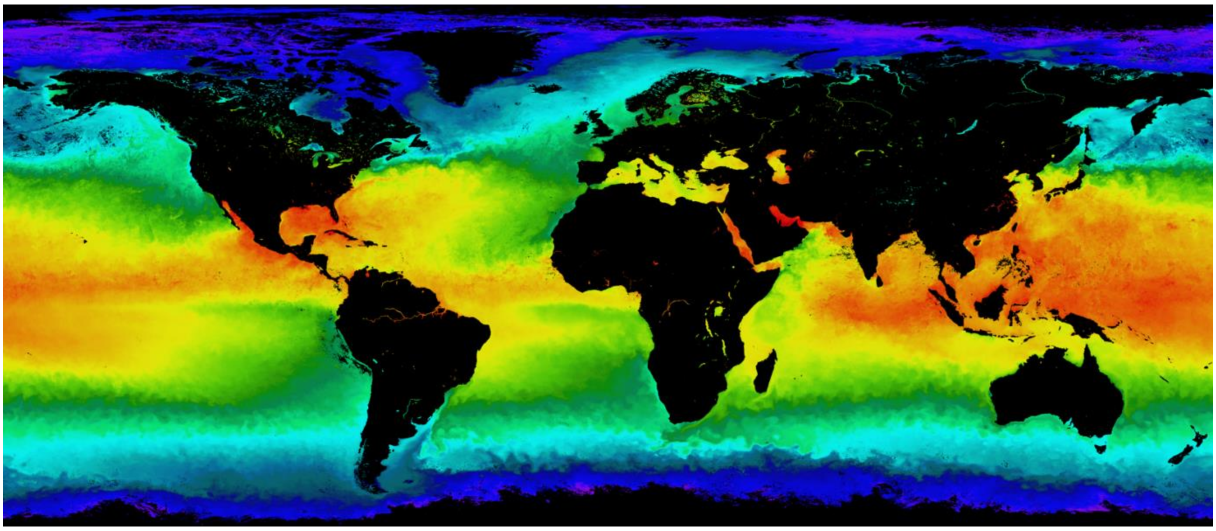

Figure 4. Level 3 binned data product of SST from Aqua MODIS on a monthly aggregation and 4 km of spatial resolution for July 2018.

2.3.4 Bathymetry

Bathymetry data was acquired from ETOPO1, a 1 arc-minute global relief model of Earth's surface that integrates land topography and ocean bathymetry developed by the National Oceanic and Atmospheric Administration (NOAA). In particular, the Mediterranean bathymetry was provided by Mediterranean Science Commission (CIESM) derived from multibeam swath sonar surveys (NOAA, 2009).

2.4 Technologies

2.4.1 Python

Python is an open-source interpreted high-level programming language. It’s syntax as well as its object-oriented approach, facilitate writing clear code for rapid application development in many platforms. As 2021, it is the third most popular programming language by TIOBE Programming Community Index.

The tool was entirely programmed in Python 3.8.5 (Python Software Foundation, 2021) using Anaconda 2020.11 (Anaconda, 2020), a Python distribution for scientific computing (data science, machine learning applications, large-scale data processing, predictive analytics, etc.), that aims to simplify package management and deployment. The packages used were NumPy for scientific computing (Harris et al., 2020), Scipy for interpolating (Virtanen et al., 2020), Matplotlib for visualising plots and maps (Hunter, 2007), Pandas for data manipulation and analysis (McKinney, 2010) and NetCDF4 for NetCDF file treatment (Rew et al., 2006).

2.4.2 PostgreSQL database

PostgreSQL, an open-source relational database management System (RDBMS), is the technology used for storing the fisheries related data in its version PostgreSQL 10.18 (https://www.postgresql.org/). It is being used in combination with PostGIS 2.5, a database extender for facilitating spatial data treatment.

2.4.3 NetCDF

NetCDF (Network Common Data Form) is a set of software libraries and machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data (Rew et al., 2006; Rew & Davis, 1990). As an example, it is a file format for storing multidimensional variables, such as SST, Chl-a, fishing landings biomass or revenue, which can be displayed through a dimension such as time, latitude or longitude (Figure 5). Each position [*x*, *y*] of the SST array, contains the SST value on the location defined by the position *x* of the latitude array and the position *y* of the longitude array, and likewise the other variables.

NetCDF is widely used in earth, ocean, and atmospheric sciences by educational, research, and government sites because of its simple data model, ease of use, portability, scalability and strong user support infrastructure. A wide range of Software support NetCDF file format, such as QGIS, ArcGIS or Panoply. Moreover, SeaDataNet, a distributed Marine Data Infrastructure for the management of large and diverse sets of data deriving from in situ of the seas and oceans, has adopted the NetCDF format (Lowry et al., 2019; Pecci et al., 2020). For these reasons, in this study, NetCDF has been chosen as de common format for storing and sharing data (Unidata, 2021).

Metadata provides descriptive information about datasets and products to make them easier to discover, use and understand. NetCDF CF (Climate and Forecast) conventions aim that the conforming datasets contain sufficient metadata to be self-describing, in the sense that each variable in the file has an associated description of what it represents and that each value can be located in space and time. An important benefit of a convention is that it enables software tools to display data and perform operations on specified subsets of the data with minimal user intervention (Eaton et al., 2011; Gregory, 2003). In this study, all generated NetCDF files are compliant with CF Metadata convention version CF-1.8, using Standard Names Table version 77 (https://cfconventions.org/).

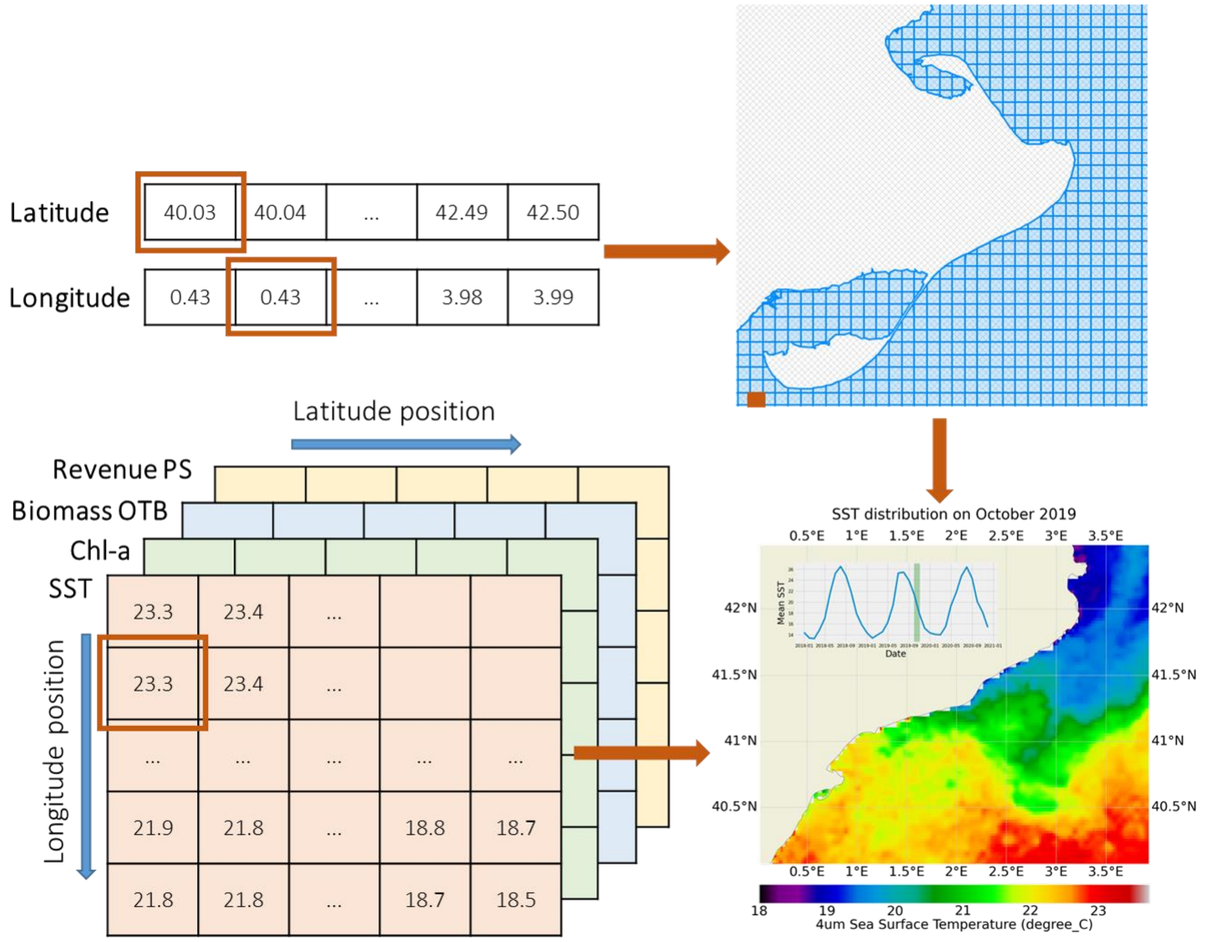

Figure 5. Example of NetCDF internal structure. Each combination of latitude and longitude corresponds to a position on the map, which combined with data from a variable stored in a two-dimensional array, such as SST, results into the spatial representation of the variable.

2.5 Methods

In order to be able to compare the different variables, they were all aggregated into a monthly resolution, spatially subsetted regarding the same study area and interpolated into the same 1x1 km^2 grid.

2.5.1 Spatial subsetting and projection

All spatial data were subsetted by retrieving the selected study area (40º N - 0º E / 42.5º N - 4º E) from the original data. All positions were transformed to WGS84 Coordinate Reference System.

2.5.2 Averaging

For each month and environmental variable, its arithmetic mean is calculated to generate the monthly evolution of the variable (Figure 6).

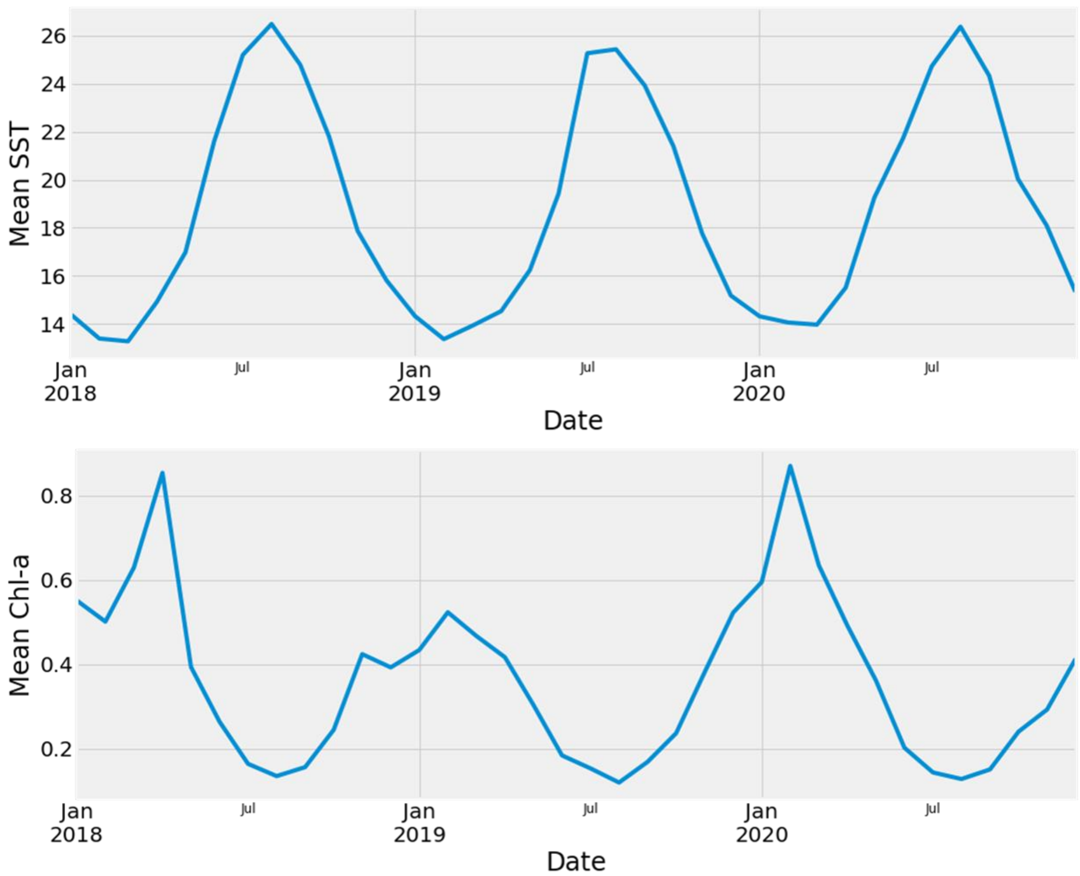

Figure 6. Temporal series chart with the SST and Chl-a monthly mean from 2018 to 2020.

2.5.3 Spatial interpolation

Spatial interpolation, the process of predicting unknown points from known values, is used to increase the spatial resolution of the satellite images (from $4km^2$ to $1km^2$) and merging all spatial products into the same grid (Figure 7). The interpolation method selected for this study is cubic spline interpolation, as results are smoother and has smaller error than other interpolating polynomials (Habermann & Kindermann, 2007).

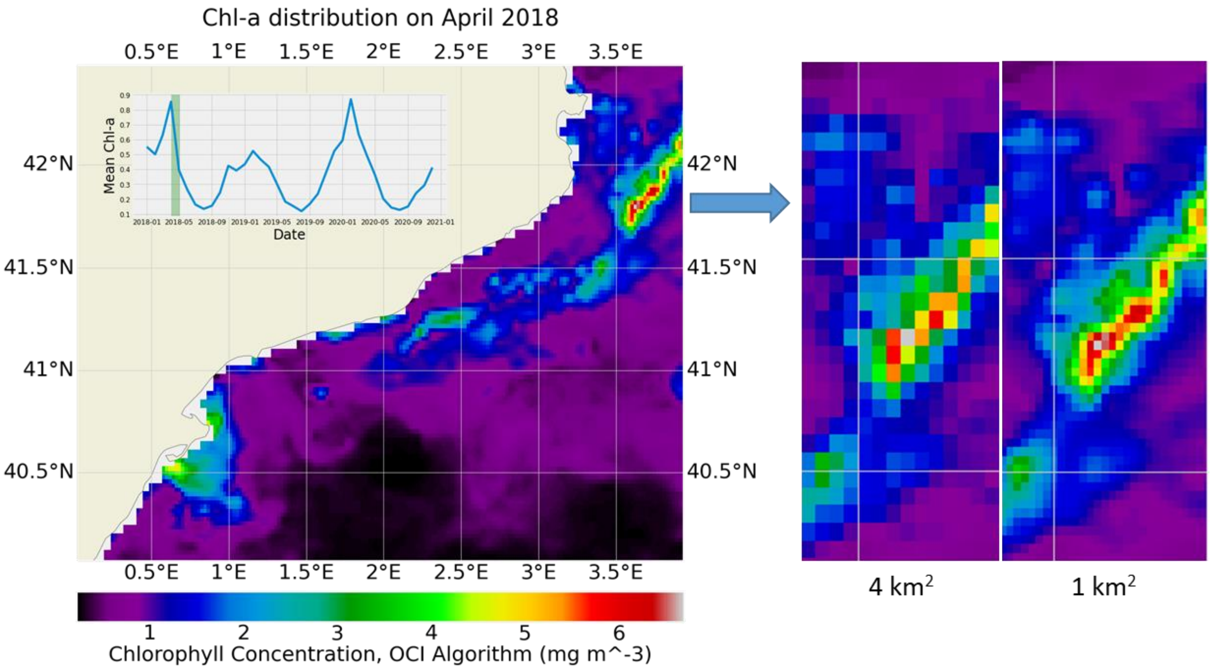

Figure 7. Comparison between the original 4km² resolution and the interpolated one at 1km² for Chl-a distribution on April 2018. The chart contains the monthly Chl-a mean evolution for 3 years and the green vertical bar indicates the corresponding month.

3 Results

3.1 Spatial data analysis workflow

Typically, the workflow for scientific spatial data analysis has the following steps:

1. Define the hypothesis.
2. Data gathering: Finding data sources needed for meeting the objective and obtaining them.
3. Data cleaning: Converting and unifying data in a structured format with the same resolution and projection, through subsetting and interpolation. It includes data refinement and corrections for achieving the needed data quality.
4. Data consolidation: Merging data from different sources.
5. Data visualization and analysis.

This process is iterative as the information obtained during the process can trigger changes on the previous steps.

3.2 Tool implementation

Based on the automation of the workflow for spatial data analysis, the tool for obtaining environmental variables and combining them with the fisheries variables was designed on five modules developed in Python. Each module is totally independent from the others, can be used standalone and be extended to improve its functionalities and reach a broader scope. Moreover, they are focused on assisting the stakeholders in addressing the common challenges and overcome the obstacles mentioned previously. Figure 8 is a simplified visual representation of the end to end workflows of the tool. In other words, it shows the processes to obtain the final products from the data sources, the technologies involved and how the modules interact.

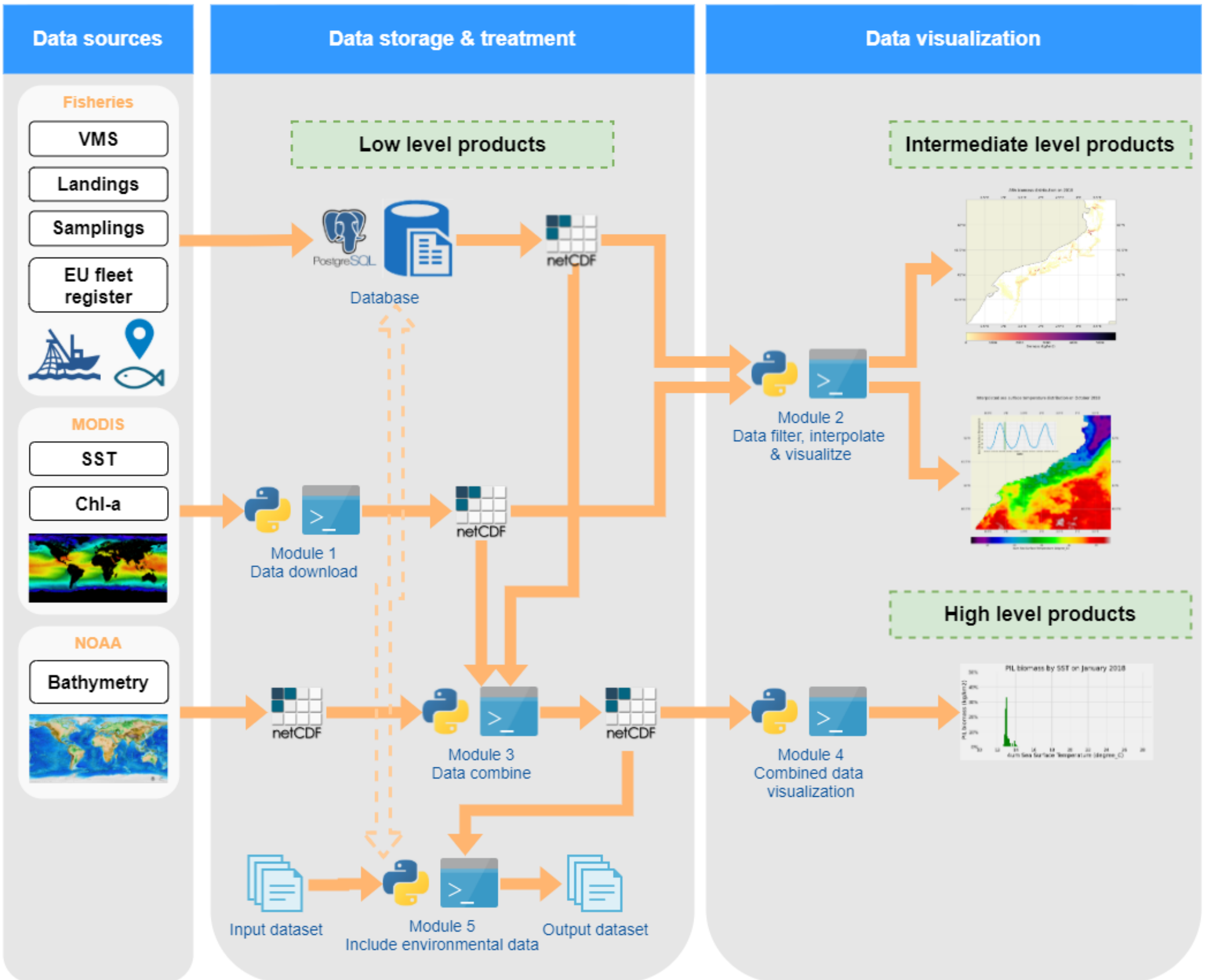

Figure 8. Simplified design of the end to end workflows of the tool, including data sources, technologies involved, modules interaction and generated products.

- Module 1. Data download: This module main purpose is the massive download of environmental variables from different data sources. Currently, this module downloaded automatically from MODIS monthly L3 SST 4km night-time and Chl-a NetCDF files from 2000 to the current date. Other temporal or spatial resolutions as well as other variables can be added for downloading on the module.

- Module 2. Data filter, interpolate and visualize: This module main purpose is extracting data of the NetCDF files, spatial subsetting for obtaining the desired region, interpolating to higher resolution (1 km^2) and visualizing the target variable on its own. The visualization is a spatial distribution of the target variable and, for the environmental variables, a temporal series chart with the monthly mean of the environmental variable is generated in the map to get the variation through the year.
- Module 3. Data combine: This module main purpose is merging different data products into the same grid for performing data comparisons. Once data are merged, a NetCDF file with different variables is generated. As an example, for each month, this module imports its corresponding monthly products of SST, CHL, total weight and revenue for *Merluccius merluccius* (HKE) and *Aristeus antennatus* (ARA) caught by bottom trawling fleet, total weight and revenue for *Sardina Pilchardus* (PIL) and *Engraulis encrasicolus* (ANE) caught by purse seine fleet, and the area bathymetry. Then, all data are merged on the same 1 km2 grid and a NetCDF file in created, containing all the variables and the same latitudes and longitudes arrays.
- Module 4. Combined data visualization: This module main purpose is extracting the data of the NetCDF downloaded files and performing some visualizations of the merged data in order to facilitate its analysis. Currently, histograms combining two variables are generated. As an example, for January 2018, this module generates histograms combining *Sardina Pilchardus* (PIL) biomass (kg/km2) with SST, Chl-a and depth.
- Module 5. Include environmental data: Given a dataset containing dates and locations, this module includes the corresponding monthly environmental data for each date and location. The input dataset can be extracted from the database or from a CSV file, as well as the output can be a CSV file or be inserted back in the database. This module facilitates the process of adding remotely sensed data to any dataset, taking into account that as other variables are included in the system, they will also be automatically included by the module.

3.3 Product generation

Each module generates different products itself from a lower to a higher level of complexity. At a low level, the aim of the tool is being used for research or academic purposes, as data are in NetCDF or CSV formats. Therefore, these products are less processed and require visualization and analysis for their interpretation. The higher product level is, the broader audience can reach, meaning that in a high level product, data are simpler to interpret as they are merged, simplified and visualized. The results that can be obtained with the developed tool are much broader, so some examples generated with the tool are presented to better understand its scope.

3.3.1 Low level products

The lowest level products, meaning that they are less processed, are the generated NetCDF or CSV files. The data download module eases the process of downloading historical sensor-based satellite data, as well as adding the new generated data automatically. Currently, only MODIS products are supported but the module can be extended to other satellites, data sources, variables and spatial and temporal resolutions (Figure 8).

Another low level group of products are the NetCDF files generated by the data combine module, which merges fisheries and environmental variables onto the same spatial and temporal resolution. Currently, a monthly NetCDF file is generated containing a set of arrays and all the Metadata for being compliant with CF Metadata convention. Each NetCDF contain the same one-dimensional arrays of latitudes and longitudes and a set of two-dimensional arrays with the monthly variables for these positions (Figure 5). The environmental variables included are SST, Chl-a and bathymetry. The fisheries ones are, for bottom trawling: fishing time, total biomass and revenue, biomass and revenue for *Merluccius merluccius* (HKE) and *Aristeus antennatus* (ARA), and the same ones for purse seine, except that the species are *Sardina Pilchardus* (PIL) and *Engraulis encrasicolus* (ANE).

Using include environmental data module, environmental data can be added to any dataset containing dates and locations. A CSV database extraction with the 216 bottom trawling and 143 purse seine samplings from 2018 to 2020 was used as input for module 5. The result is the same dataset including two extra columns, one for SST and another for Chl-a. As an example, this output can be used for analysing the relationship between SST and Chl-a with the reproductive cycle of European sardine or anchovy along the year.

3.3.2 Intermediate level products

The intermediate level products are generated by the data filter, interpolate and visualize module (Figure 8). The aim of these products is having a visualization of a target variable on its own, after applying spatial subsetting and interpolating data to 1 km^2 resolution.

3.3.2.1 Vessel positioning products

Once VMS data are processed, as explained in materials and methods, products like the fishing effort (h/km^2) or vessel density distribution can be represented for a certain period and fishing fleet. An example of these products is the fishing effort distribution produced by bottom trawling fleet during 2018 (Figure 9).

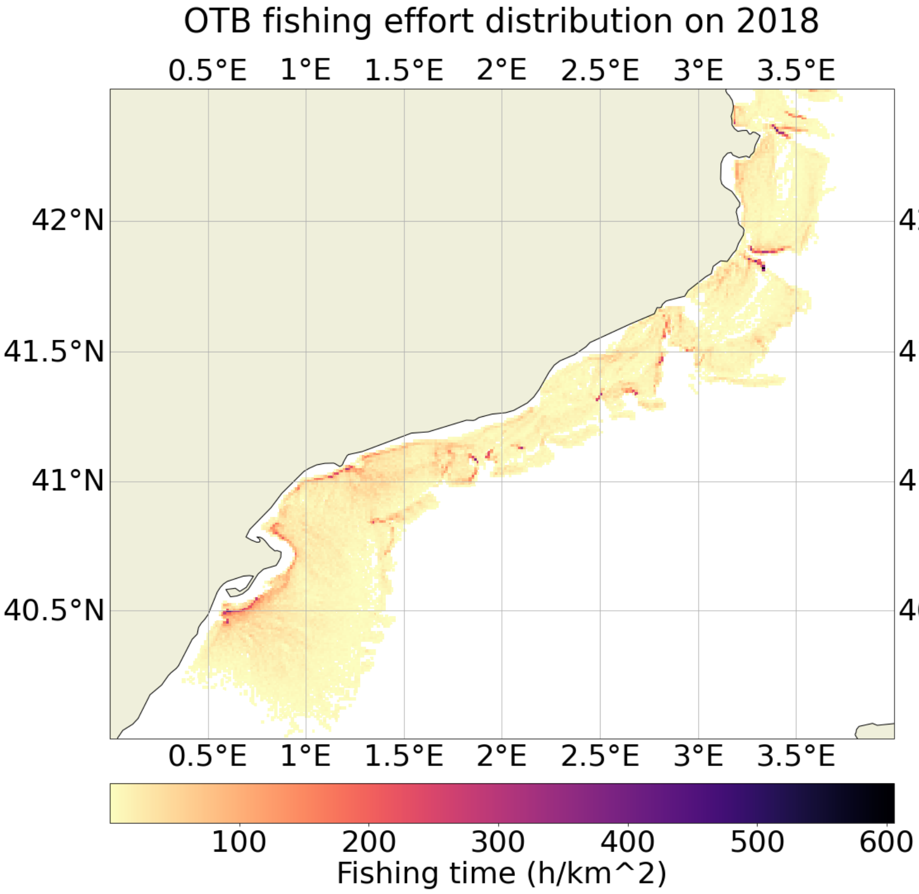

Figure 9. Fishing effort distribution by bottom trawling fishing fleet on 2018.

3.3.2.2 *Vessel positioning and daily landings combined products*

Once VMS data are merged with daily landings as explained in materials and methods, products like the biomass (kg/km^2) or revenue ($€/km^2$) distribution can be represented for a certain species, period and fishing fleet. An example of these products is the biomass distribution of blue and red shrimp (*Aristeus antennatus*) caught by bottom trawling fleet during 2018 (Figure 10).

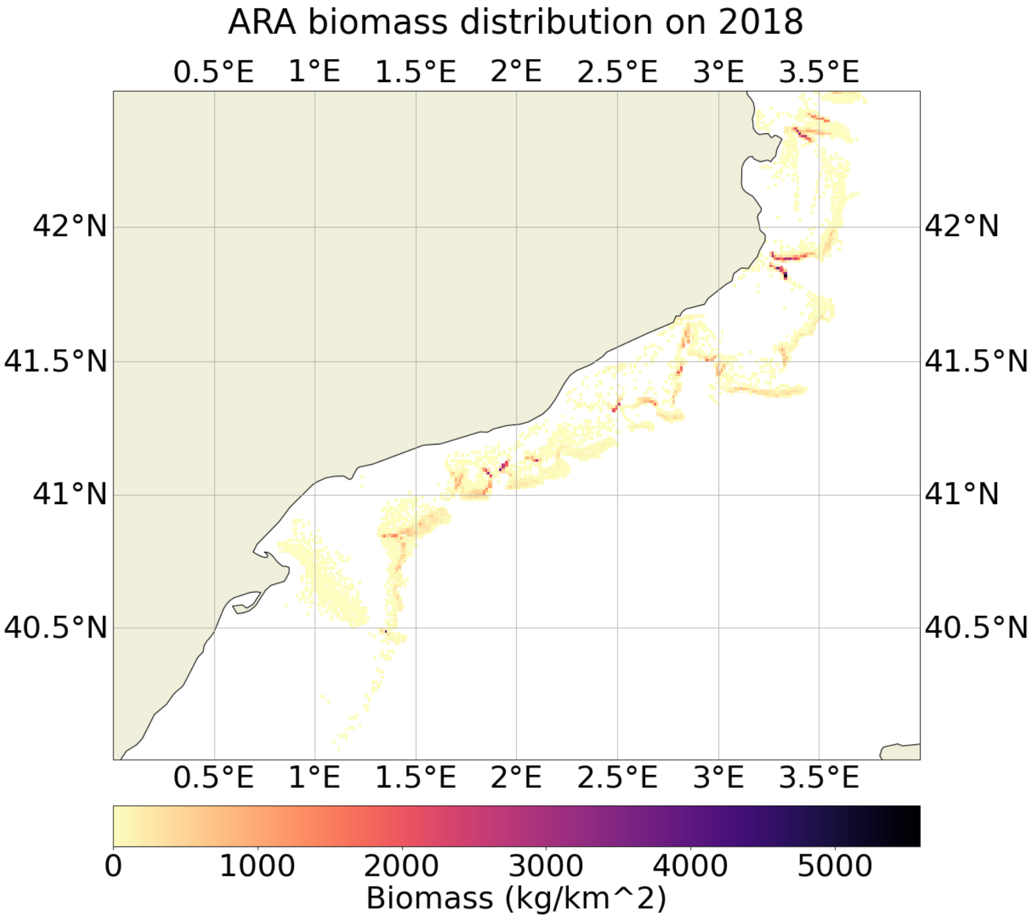

Figure 10. Aristeus antennatus (ARA) biomass (kg/km²) distribution on 2018 caught by bottom trawling fleet.

On a higher temporal resolution, examples of these products are the biomass distribution of European sardine (*Sardina pilchardus*) caught by purse seine fleet on different months of 2018 (Figure 11).

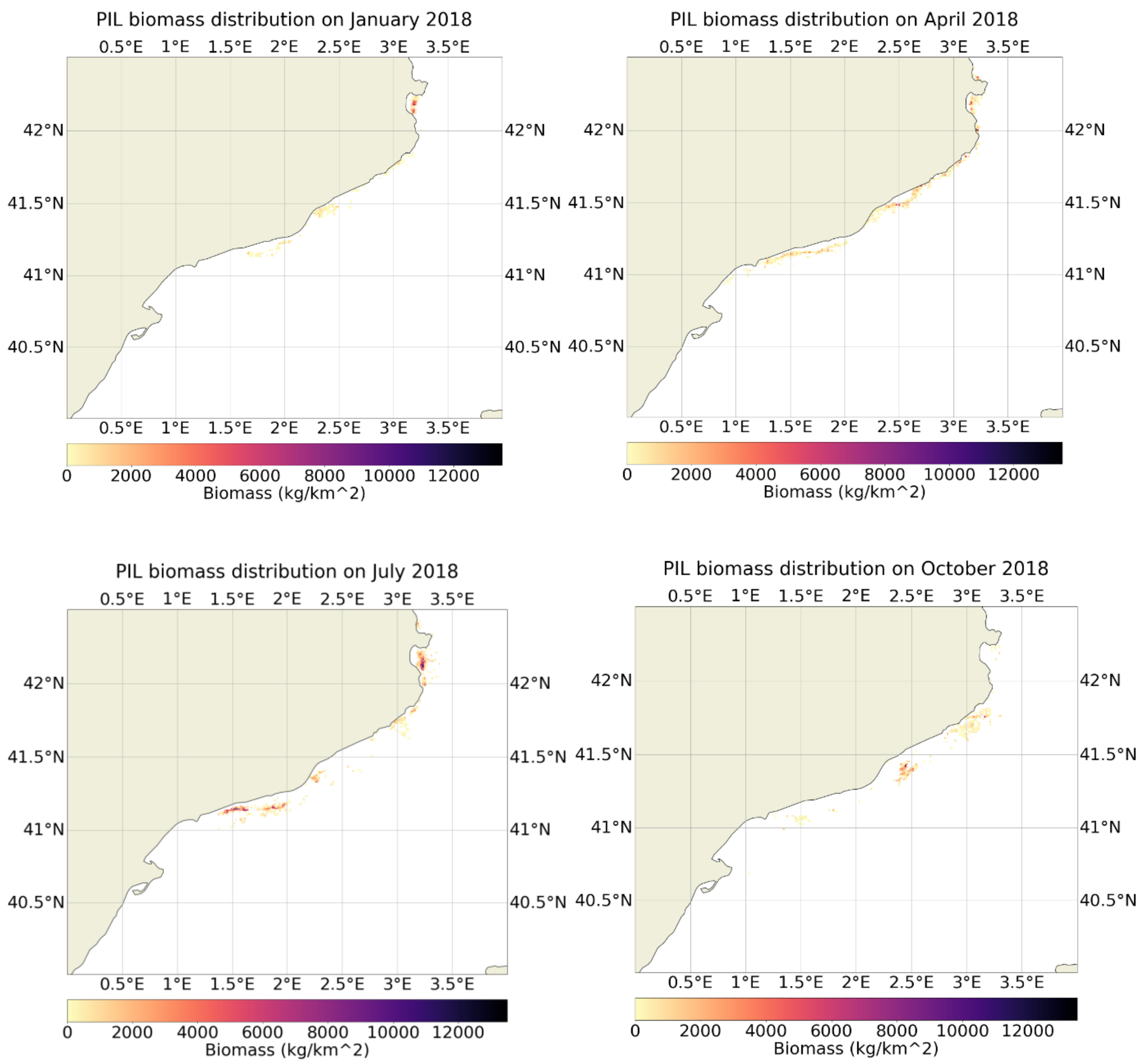

Figure 11. Sardina Pilchardus biomass (kg/km^2) distribution on different months of 2018 by purse seine fleet.

3.3.2.3 Sea Surface Temperature products

Downloaded SST products are subsetted by the selected region, interpolated for getting higher resolution and visualized. Bear in mind SST range differs for each month in order to observe the SST structures more precisely. However, a temporal series chart with the SST monthly mean is generated in the map to get the variation through the year (Figure 12).

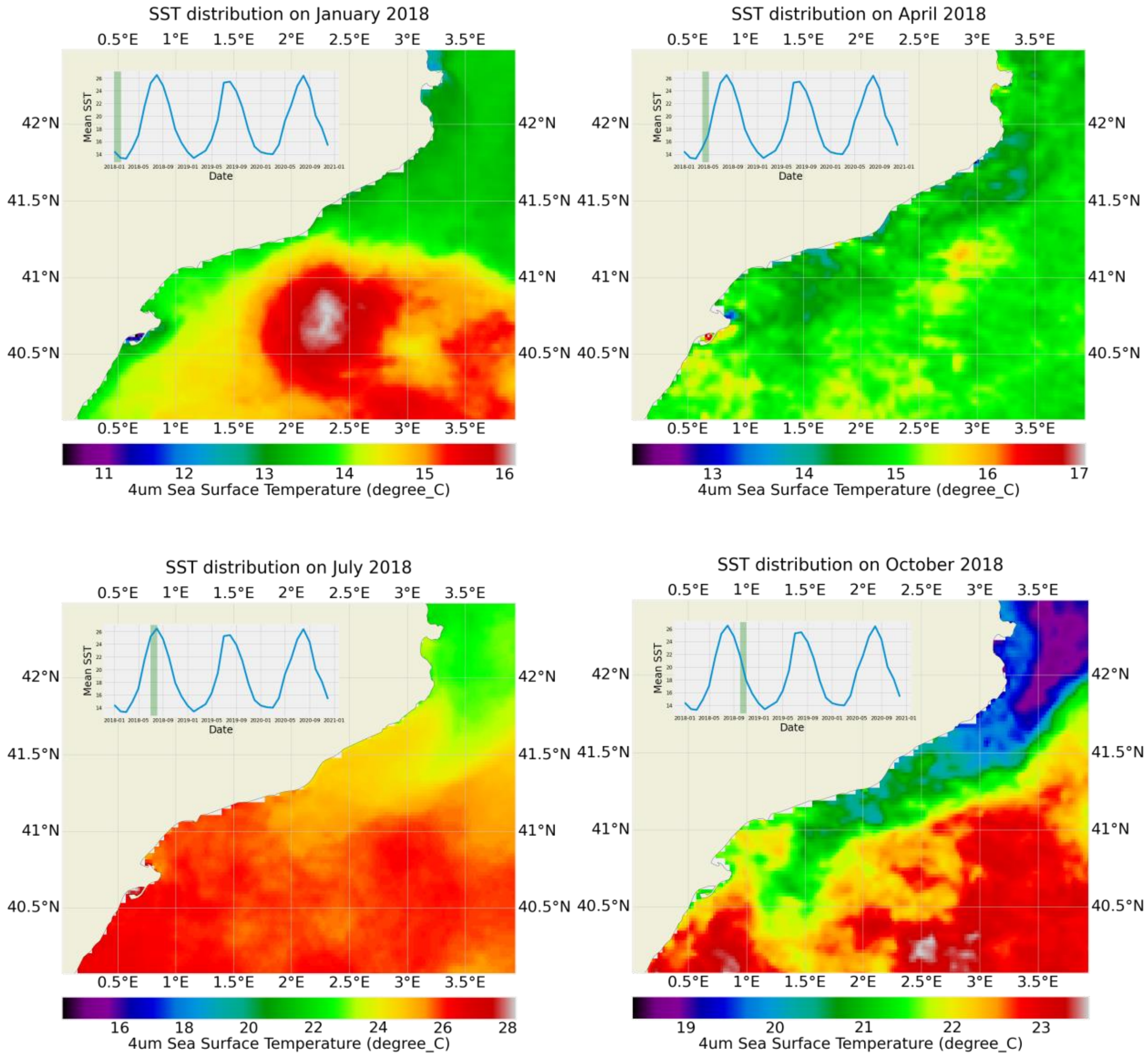

Figure 12. Monthly SST distribution on different months of 2018. The chart contains the monthly SST mean evolution for 3 years (2018-2020) and the green vertical bar indicates the corresponding month.

3.3.2.4 Chlorophyll-a Concentration products

Downloaded Chl-a products are subsetted by the selected region, interpolated for getting higher resolution and visualized. Bear in mind Chl-a range differs for each month in order to observe the Chl-a structures more precisely. However, a temporal series chart with the Chl-a monthly mean is generated in the map to get the variation through the year (Figure 13).

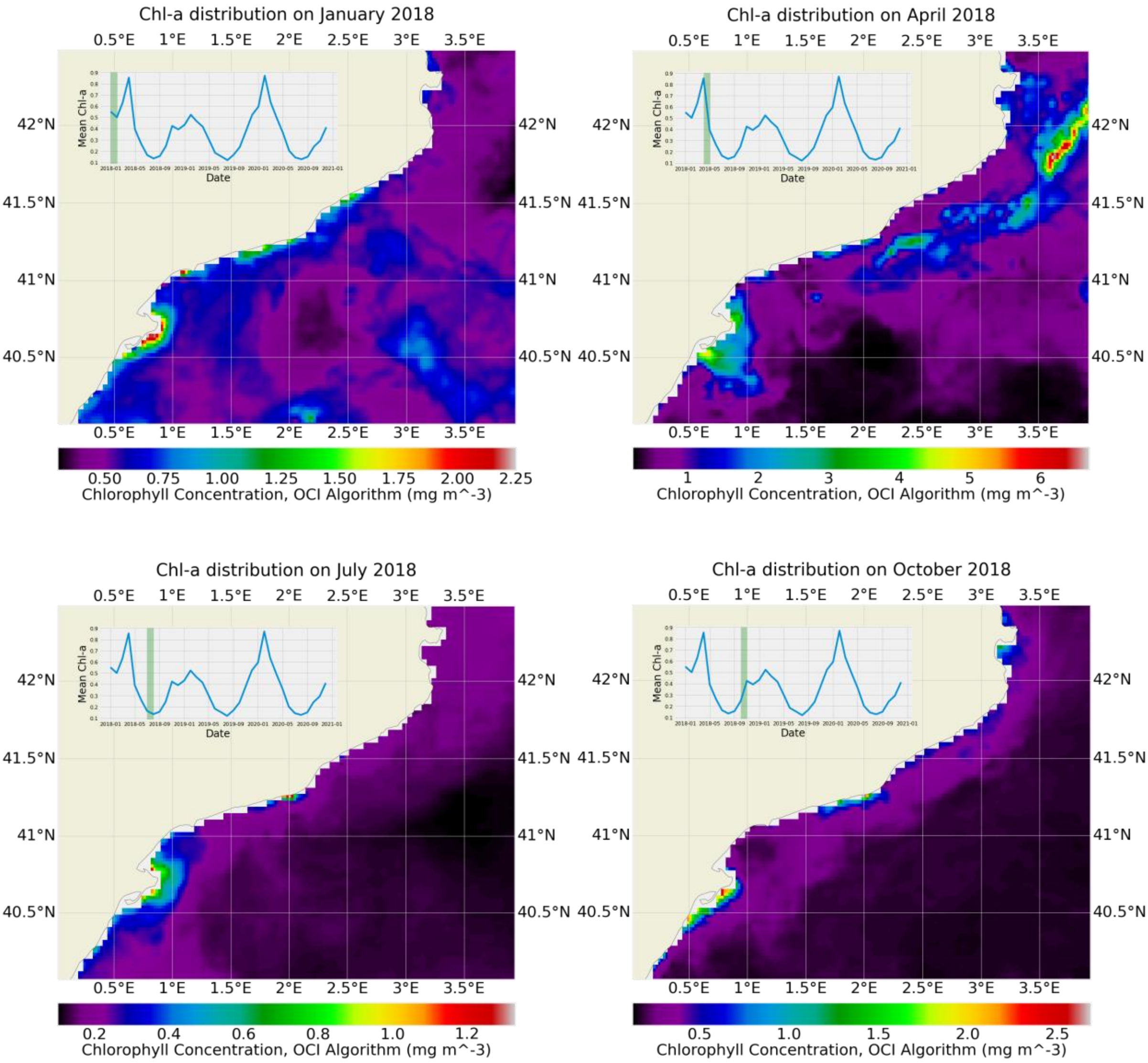

Figure 13. Monthly Chl-a distribution on different months of 2018. The chart contains the monthly Chl-a mean evolution for 3 years (2018-2020) and the green vertical bar indicates the corresponding month.

3.3.3 High level products

The aim of the high level products is having a visualization of the combination of environmental and fisheries variables. These combined products are generated by the outputs of the data compare module and visualized by the data visualization module (Figure 8). Products like the biomass distribution depending on an environmental variable can be represented for a certain species, period and fishing fleet. For instance, generated histograms determine Sea Surface Temperature, Chlorophyll-a concentration and bathymetric ranges were higher *Sardina Pilchardus* catches took place along 2018. (Figure 14; Figure 15; Figure 16). These results in combination with other variables, can be used as input for species distribution modelling.

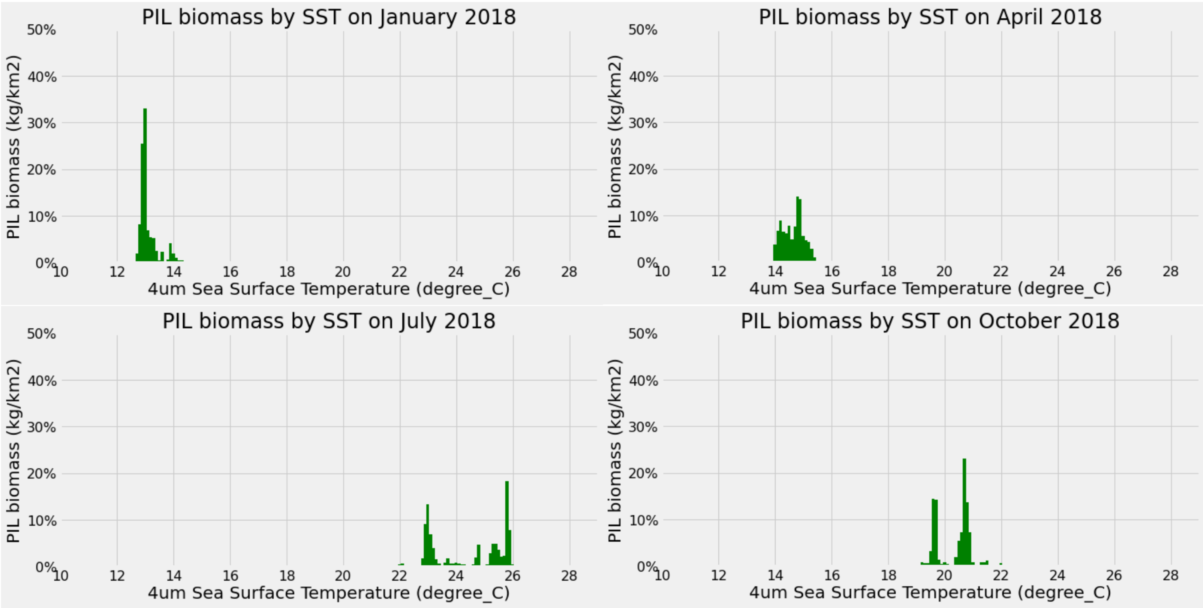

Figure 14. Histogram of the monthly percentage of Sardina Pilchardus biomass caught by purse seine along 2018 depending on Sea Surface Temperature.

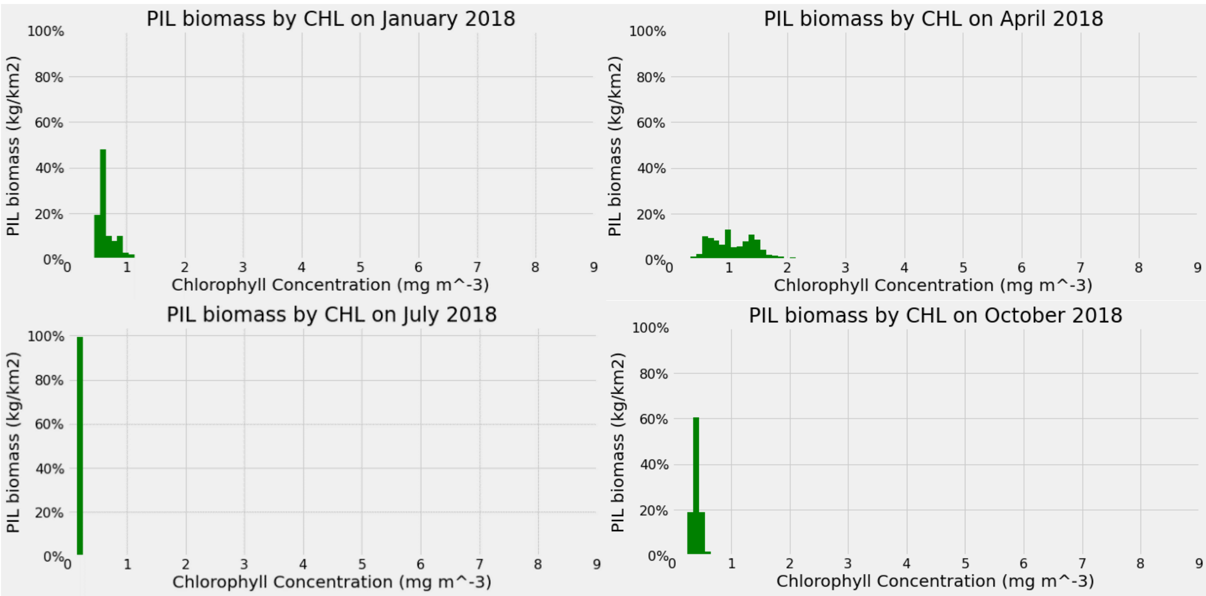

Figure 15. Histogram of the monthly percentage of Sardina Pilchardus biomass caught by purse seine along 2018 depending on Chlorophyll Concentration.

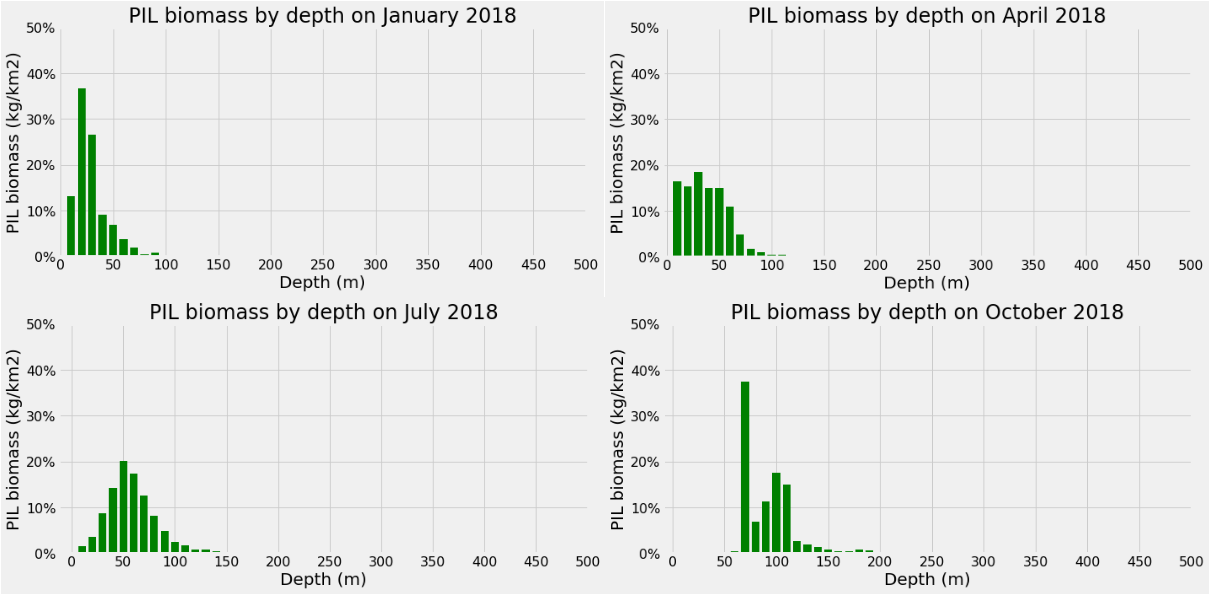

Figure 16. Histogram of the monthly percentage of Sardina Pilchardus biomass caught by purse seine along 2018 depending on bathymetry.

4 Discussion

Regarding the fisheries data used by the tool, VMS data have a good coverage on the Catalan fleet, 97% for bottom trawling and 98% for purse seine on 2017 (EU fleet register). Small-scale fisheries are not considered in this study due to the low VMS coverage for these fleets, as most of them are not obliged to have VMS system. Other ways to integrate VMS and daily landings can be considered, such as increasing VMS ping frequency via point interpolation methodologies to fill the gaps and produce a continuous track (Russo et al., 2011). Using AIS instead of VMS was not considered, as there is no obligation for using AIS, so gaps on AIS data might be too substantial (Shepperson et al., 2018). Despite VMS presents some limitations, such as low ping frequency and the underestimation of fishing effort due to lack of monitoring systems for certain type of vessels, it is still a good representation of the activity related to bottom trawling and purse seine, which has the highest impact on the pelagic and demersal community in our study area (ICATMAR, 2019, 2020; Lloret-Lloret et al., 2021). However, a future plan for implementing a new vessel positioning system in Catalonia, GeoBlau, might extend current coverage and increase ping frequency (Generalitat de Catalunya, 2021).

Regarding the selected environmental variables for this study, bathymetry was identified as a key variable to determine many demersal and pelagic species distributions, while SST and Chl-a are also significant (Druon et al., 2015; Fernández-Corredor et al., 2021; Lloret-Lloret et al., 2021). Although surface environmental variables have been used for studying the influence on demersal resources (Pennino et al., 2020; Vilas et al., 2020), depth environmental variables might be preferable. Some derivations can be performed for obtaining them from satellite-based sensors (i.e. Sea Bottom Temperature (SBT) or Sea Bottom Salinity (SBS)). Another key influencer for these species are ocean currents, which can be routinely derived from Sea Surface Height (SSH) measured by altimeters (Albo-Puigserver et al., 2021; Carreton et al., 2021; Isern-Fontanet et al., 2020). However, their observation and forecasting still have a relatively low spatial resolution and, considering the restriction of the monthly resolution on the fishing effort, only major structures would be identified (Isern-Fontanet et al., 2017). Therefore, once the fishing effort will be available on a daily resolution, SSH will also be included in the tool.

Most of the studies combining fisheries and environmental data in the study area, use fisheries-independent surveys data, which have precise data regarding catch composition and biological analysis, measure surface and depth environmental variables, but are limited on time and space, occurring mainly once or twice a year (M. Coll et al., 2019; Druon et al., 2015; Lloret-Lloret et al., 2021; Pennino et al., 2020; Sion et al., 2019). The fishing landings used in the developed tool are fisheries-dependent, having less precise data as only fishing time, commercial species biomass and revenue is obtained, but the sample size is much greater as data from all the fishing fleet is registered daily. Moreover, the data from the ongoing fisheries samplings can be used for complementing landings data, therefore obtaining more resolution on catch composition and biological analysis.

In the recent years, a few user applications have been developed spatially combining fisheries and environmental data. Some examples are EcoCast, a real-time data tool to help fishers and managers allocate fishing effort to optimize the harvest of target fish while minimizing bycatch of protected species (Hazen et al., 2018), Ecospace, a spatial and temporal dynamic Software designed for exploring impact and placement of protected areas (Coll et al., 2016; Walters et al., 2010) and CATSAT, a commercial tool to maximize professional fishing catch, by providing oceanographic data and marine weather information in near real-time (https://www.catsat.com/).

5 Conclusions

In summary, this study underpins the need to facilitate the process to analyse biological and environmental variables, that change over time and space, to manage fisheries from a scientific data-driven point of view. The developed tool, automatically obtains and processes environmental and fisheries data, producing combined products of different levels. Structured in scalable modules, this tool simplifies all the process to generate different outputs for enabling further research of complex data, automating the main tasks; data download, format unification, filtering, interpolation, combination and results visualization. The major advantages of the scalable modules are the possibility of extending the tool to incorporate further variables, interpolation methods and generate different outputs, such as other data combinations and visualizations. Automating these spatial data analysis workflows is the baseline for transitioning from static to dynamic fisheries management, because assessments can be performed as new data becomes available.

6 Tasks developed directly by the student

The following parts were developed directly by the student:

- Database creation.
- Daily fishing landings, VMS and EU fleet register database import and relate.
- Rasterization of fisheries data outputs.
- Python modules development: data download, filtering, interpolation application and product generation (NetCDF files and visualizations).

All data was obtained from the sources mentioned in materials and methods section.

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