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OCLE: An updated of the European high-resolution database for assessing marine ecological systems under present conditions and climate change scenarios

Camino F. de la Hoz *, Elvira Ramos, Adrián Acevedo, Melisa Menéndez, Alejandra G. Cabanillas, Araceli Puente, José A. Juanes

IHCantabria - Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Spain

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ABSTRACT

Understanding the impacts of climate change on coastal marine species requires high- resolution environmental datasets that integrate physical, chemical, and biological variables. However, existing databases often lack key environmental parameters necessary for accurately assessing species distribution. The OCLE database (https://ocle.ihcantabria.com/), originally introduced in 2018, has now been significantly updated and expanded to address these limitations and meet current research needs in European littoral ecosystems. This new version of OCLE includes a wide range of 16 environmental variables: wave height, wind speed, currents, bottom current speed, sea level, tidal range, bottom shear stress, sea and air temperature and salinity, alongside physicochemical parameters like light, nutrients, pH, turbidity, and extreme event metrics such as marine heatwaves and cold spells. These data are provided at fine-scale spatial resolution (0.05°, approximately 5 km from the coastline up to 20 km offshore; and 0.1°, approximately 10 km beyond this distance to 70 Km) and temporal resolution (yearly from 2000 to 2023), ensuring an accurate representation of local and regional oceanographic processes. In addition, the database incorporates biological records of 22 macroalgae taxa, enhancing its applicability in species distribution models. To support climate impact assessments, OCLE integrates projections from the latest IPCC AR6 scenarios (SSP2-4.5 and SSP5-8.5) for the horizon years 2050 and 2100, allowing researchers to explore potential future shifts in marine ecosystems. By offering freely accessible, spatially homogeneous, and high-resolution environmental data, OCLE represents a major advancement for ecological research, conservation planning, and climate change adaptation strategies. Its integration into ecological forecasting tools provides a valuable resource for assessing the effects of changing environmental conditions on European coastal biodiversity.

1. Introduction

Advancing the assessment of marine communities under changing climate scenarios is essential for improving ecological understanding and informing management decisions. This requires integrating both biological and environmental data to capture the complex interactions between species and their surroundings. While existing open-access databases, such as E.U. Copernicus Marine Service Information, the World Ocean Atlas (Reagan et al., 2023), or more species distribution models (SDMs) oriented such as Bio-Oracle (Assis et al., 2024), MARSPEC (Sbrocco and Barber, 2013), GMED (Basher et al., 2018), EMODNET (Míguez et al., 2019) and OCLE (de la Hoz et al., 2018), that have significantly contributed to environmental data availability, they often lack critical variables and biological insights necessary for evaluating community dynamics in response to climate change.

A critical limitation of current datasets is their lack of integration of key variables and parametrisations relevant to marine species, such as hydrodynamic variables (e.g., wave height, bottom shear stress) and metrics characterising extreme conditions (e.g., marine heatwaves), which are factors that significantly influence the distribution, settlement, and survival of benthic species (de la Hoz et al., 2019; Pace et al., 2017; Ramos et al., 2016).

Hydrodynamic variables, such as wave height and bottom shear stress, are key drivers of the distribution and abundance of marine

* Corresponding author at: Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Avda. Isabel Torres, 15, Parque Científico y Tecnológico de Cantabria, 39011, Santander, Spain.

E-mail address: camino.fernandez@unican.es (C.F. de la Hoz).

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organisms, particularly sessile species such as seagrasses and macroalgae (Callaghan et al., 2015). Shear stress, for instance, can determine the survival of benthic species by affecting their ability to thrive in high-energy environments (Jackson-Bué et al., 2022; Jones et al., 2015). Despite the ecological significance of these variables, few global databases include them, although it would enable researchers to explore the interplay between physical forces and biological processes in European marine ecosystems.

Recent studies have shown that extreme temperature events, rather than average conditions, are often the main drivers of species shifts in response to climate change (Lima and Wethey, 2012; Seabra et al., 2015; Smith et al., 2024). They can have devastating effects on marine ecosystems, leading to mass mortality events and the loss of biodiversity. By incorporating data on the frequency and intensity of marine heatwaves in the modelling process, researchers could better predict how future extreme climate might affect species distributions in European seas.

Furthermore, the environmental variables available are frequently inconsistent in spatial and temporal resolution, hindering their ability to accurately capture regional processes. Striking a balance between spatial coverage and fine-scale resolution remains a persistent challenge, as efforts to improve resolution often compromise spatial extent.

Species distribution models are valuable tools for predicting the geographic distribution of species based on environmental conditions and occurrence records (Guisan and Zimmermann, 2000; Peterson et al., 2011). These models are instrumental in understanding species-environment relationships and forecasting potential shifts in distributions. However, the reliability and accuracy of SDMs hinge on the quality and resolution of the data used, including both species occurrence data and environmental predictors. High-quality, comprehensive datasets are critical for capturing the multifaceted interactions between species and their habitats, particularly in the face of rapid environmental change. One of the challenges in ecological modelling is balancing spatial coverage with resolution. While it is important to cover large areas to understand regional and global patterns, the accuracy of SDMs often depends on high-resolution data to capture local environmental conditions. Existing databases tend to rely on interpolation methods to fill data gaps, which can introduce inaccuracies, particularly in dynamic and highly variable coastal environments.

Given the increasing global concern over climate change, it is essential to integrate the latest climate scenarios in ecological researches. The Intergovernmental Panel on Climate Change AR6 (IPCC, 2023) provides updated Representative Concentration Pathways and Shared Socioeconomic Pathways (SSPs) that outline possible future emission trajectories and their impacts on global climate patterns. According to the AR6, a set of five new illustrative emission scenarios have been developed to study the climate's response to potential future conditions, differing from those evaluated in AR5. This set of scenarios supports climate model projections on changes in climate. The report categorises future years within the 21st century into three categories relative to the 1850–1900 period: short-term (2021–2040), medium-term (2041–2060) and long-term (2081–2100). In addition to the historical data, an analysis of future scenarios for the medium and long-term was conducted, with 2050 and 2100 as horizon years. The inclusion of projections based on these scenarios, would allow researchers to explore how different levels of global warming might affect marine ecosystems. By integrating both historical and projected data, researchers will be able to conduct retrospective analyses and future projections, providing insights into how marine species in European waters might respond to ongoing climate change (Collins et al., 2013; Perez et al., 2017).

To ensure that ecological models capture the complexity of species-environment interactions, it is important to consider not only abiotic factors but also relevant biological data. Great efforts have been done to compile the information available in the existing databases, such as GBIF (GBIF, 2013), OBIS (OBIS, 2015) or EMODnet Biology (Beja et al., 2024). However, records are often lacking in coastal areas such as intertidal zones (Thyrring et al., 2024).

OCLE seeks to address gaps in variables, including hydrodynamic and stress related variables, and providing homogeneous and high-resolution data across space and time in Europe and contribute to the advancement of ecological assessment systems. By integrating historical and climate change data, it provides insights into species-environment interactions, enabling robust assessments of climate change effects on European littoral ecosystems.

OCLE main contributions.

The database OCLE has been designed to address the challenges detected and its main contributions are summarized below:

- The OCLE dataset provides a comprehensive set of environmental variables essential for understanding marine species ecology and their responses to changing conditions. It integrates both baseline metocean, oceanographic and physicochemical parameters, as well as specialized metrics of hydrodynamic forces and extreme events, ensuring a robust representation of the environmental factors influencing species distribution, survival, and ecosystem dynamics. The dataset includes the variables wave height, wind speed, currents, bottom current speed, sea level, tidal range, sea and air temperature and salinity, alongside physicochemical parameters like light, nutrients, pH, and turbidity. Importantly, it also incorporates critical hydrodynamic factors, such as bottom shear stress, key for understanding physical impacts like the uprooting of marine flora (Pace et al., 2017), and metrics of extreme events, including the frequency and intensity of marine heatwaves (MHWs) and marine cold spells (MCSs). By bringing together this wide range of variables, OCLE offers a unified dataset that captures the complex environmental conditions shaping marine ecosystems, from baseline processes to stress-inducing extremes.
- To address the challenge of balancing large-scale spatial coverage with the detailed resolution required to capture fine-scale processes, such as nutrient discharges from rivers that primarily occur near the coast, OCLE has been designed with a tiered spatial resolution covering all European coast with the detailed resolution to capture regional processes, and incorporates datasets accounting for effects near the coast.
- OCLE offers spatially and temporally homogeneous environmental variables with detailed resolution, ensuring comprehensive coverage of European seas. This combination enables the study of both large-scale patterns and fine-scale processes, critical for understanding ecological dynamics. Besides, it prioritises the use of the data wherever possible, rather than interpolations. This approach will enhance the reliability of ecological models, especially when studying fine-scale processes that affect species distributions.
- Finally, the integration of the latest climate change scenarios from the IPCC AR6 provides a forward-looking perspective, enabling robust projections of species responses to future environmental changes.

2. Materials and methods

2.1. Study area

The study area spans the European coasts, covering an area bounded by 21.6° N, 71.8° N, 32° W and 43.5° E with a total of 56,119 points (Fig. 1). The grid has been optimised to provide higher resolution (0.05°, approximately 5 km) from the coastline up to 20 km offshore, ensuring the representation of processes critical to marine flora. Beyond this distance, the resolution transitions to 0.1° (approximately 10 km) until 70 km from coast, reducing computational demands while maintaining sufficient detail for broader marine ecosystem studies. This approach ensures that both regional-scale patterns and localised processes are captured effectively.

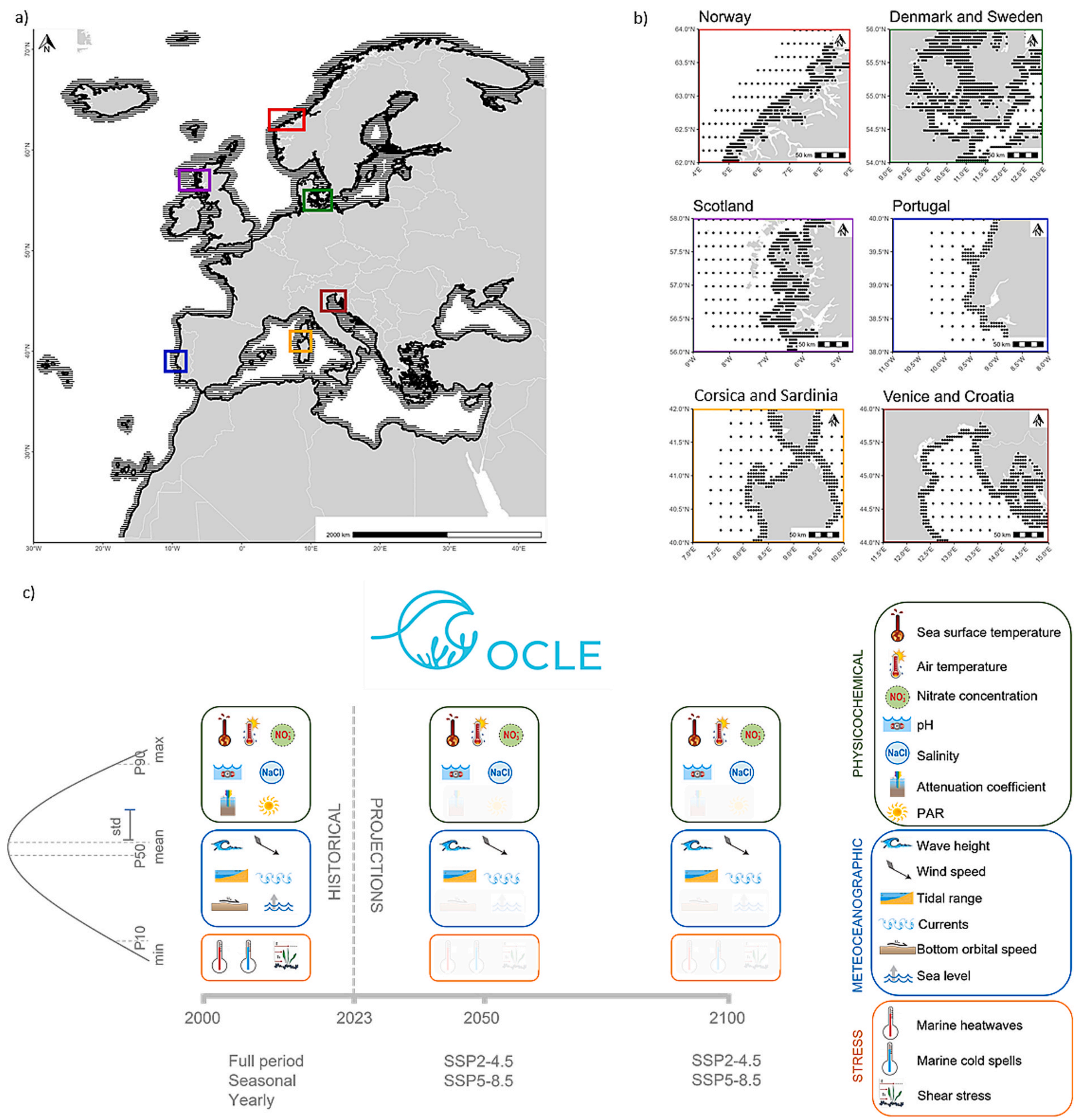

Fig. 1. a) Grid points in the ocle database. b) Zoomed-in details of selected areas: Norway, Denmark and Sweden, Scotland, Portugal, Corsica and Sardinia, Venice and Croatia. c) Overview of the variables available for historical and climate change scenarios, including calculated parameters and temporal resolution. symbols courtesy of the integration and application network(ian.umces.edu/symbols/).

2.2. Environmental data

2.2.1. Historical period

Each variable is compiled and postprocessed from the available sources with the highest resolution, daily (except for the pH for which only monthly was available) and a minimum spatial resolution of 0.05° to avoid interpolations in the grid points. To reflect stressful conditions that could limit marine species distribution two variables are developed. First mechanical stress is calculated as the exposure of subtidal species to uprooting conditions. It is characterized by the bottom shear stress (Pace et al., 2017) based on Soulsby (1997) formulation and daily information of waves height, peak period and currents. Additionally, information about substrate roughness is derived from a compilation of geomorphological sources obtained in the first version of OCLE (de la Hoz et al., 2018), improved with EMODnet Geology Seabed substrate product (Version: September 2023) where more detailed data is available. Information is homogenised into five categories (mud, sand, coarse sediment, mixed sediments and rock) and a value of roughness assigned to each one according to Soulsby (1983).

The stress from sea surface temperature is characterized through the number of MHWs and MCSs. MHWs are detected according to the definition by Hobday et al. (2016), which establishes a period of five or more days above the 90th percentile threshold of the SST data, with at least two days of separation between events (Oliver et al., 2019). MCSs are calculated following Schlegel et al. (2021), which determines that the anomaly should persist for at least five days below the 10th percentile SST threshold. The importance of colder temperatures is gaining attention, specially concerning invasive species (Hernández et al., 2024). To account for the rising temperature trend that can be seen in the data used as the baseline (1985–2023) it is necessary to detrend data. This ensures that the variable under study, the number of times the temperature exceeds the 90th percentile for MHWs or under 10th percentile for MCSs for the period of 2000–2023, is not influenced by a shifting baseline. The methodology and reasoning for this choice are from Xu et al. (2022). To remove the overall trend from the data the approach uses singular spectrum analysis (SSA), a non-parametric method used for time series decomposition (Golyandina and Korobeynikov, 2014). In essence, SSA breaks down a time series into a set of additive components. These components are then grouped and interpreted to reveal underlying structures such as trends, periodicities, and noise within the data. It is this trend that is then removed from the base data.

Table 1
Variables selected with indication of its units, periods, temporal resolution, sources and their references.

VARIABLE	UNITS	INITIAL DATE	END DATE	TEMPORAL RESOLUTION	SOURCE	REFERENCE
Sea surface temperature (SST)	°C	2000–01-01	2023–12-31	Yearly, seasonally	Copernicus Marine Service Information	(Good et al., 2020)
Photosynthetic active radiation (PAR)	Einsteins/ m^2/day	2003–01-01	2022–12-31	Yearly, seasonally	Ocean Color (NASA)	(Frouin et al., 2002)
Light attenuation (KD490)	1/m	2000–01-01	2022–12-31	Yearly, seasonally	Copernicus Marine Service Information.	https://doi.org/10.48670/moi-00281
Nitrate concentration	mmol/m^3	2000–01-01	2020–12-31	Yearly, seasonally	Copernicus Marine Service Information	(Aznar et al., 2016; Ciavatta et al., 2018; Grégoire, 2020; Teruzzi, 2021) https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3 https://doi.org/10.48670/moi-00028 https://doi.org/10.48670/moi-00058 https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_BGC_007_005_BAMHBI https://doi.org/10.48670/moi-00012 https://doi.org/10.48670/moi-00019
pH	–	2000–01-01	2020–12-31	Yearly, seasonally	Copernicus Marine Service Information	(Aznar et al., 2016; Ciavatta et al., 2018; Grégoire, 2020; Teruzzi, 2021) https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3 https://doi.org/10.48670/moi-00028 https://doi.org/10.48670/moi-00058 https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_BGC_007_005_BAMHBI https://doi.org/10.48670/moi-00012 https://doi.org/10.48670/moi-00019
Salinity	psu	2000–01-01	2020–12-31	Yearly, seasonally	Copernicus Marine Service Information	(Escudier et al., 2021; Escudier, 2020; Lima, 2020; Nigam, 2021) https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1 https://doi.org/10.48670/moi-00029 https://doi.org/10.48670/moi-00059 https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004 https://doi.org/10.48670/moi-00013 https://doi.org/10.48670/moi-00021
Air Temperature (AT)	°C	2000–01-01	2022–11-30	Yearly, seasonally	Copernicus Climate Change Service Climate Data Store	(Hersbach et al., 2020)
Wind speed (W)	m/s	2000–01-01	2023–08-31	Yearly, seasonally	Copernicus Climate Change Service Climate Data Store	(Hersbach et al., 2020)
Wave height (Hs)	m	2000–01-01	2022–12-31	Yearly, seasonally	GOW3 (Global Ocean Waves)	(Perez et al., 2017)
Currents	m/s	2000–01-01	2020–12-31	Yearly, seasonally	Copernicus Marine Service Information	(Escudier et al., 2021; Escudier, 2020; Lima, 2020; Nigam, 2021) https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1 https://doi.org/10.48670/moi-00029 https://doi.org/10.48670/moi-00059 https://doi.org/10.25423/CMCC/BLKSEA_MULTIYEAR_PHY_007_004 https://doi.org/10.48670/moi-00013 https://doi.org/10.48670/moi-00021
Root mean square orbital velocity of the bottom (urm)	m/s	2000–01-01	2022–12-31	Yearly, seasonally	GOW3 (Global Ocean Waves)	(Perez et al., 2017)
Tidal Range (TR)	m	NA	NA	NA	GOT (Global Ocean Tides) and TPXO9	(Egbert and Erofeeva, 2002)
Marine heatwaves (MHW)	count	2000–02-15	2023–12-31	Yearly and seasonal	Calculated from SST data	Hobday et al. (2016)
Marine cold spells (MCS)	count	2000–02-15	2023–12-31	Yearly and seasonal	Calculated from SST data	Schlegel et al. (2021)
Shear Stress	N/m^2	2000–02-15	2020–12-31	Yearly and seasonal	Calculated from wave and current data	Soulsby (1997)
Sea level rise	m	2041	2100	NA	CMIP6	(IPCC, 2019)

For more spatially sensitive variables, such as salinity, seabed current, pH and nitrates concentration, sources covering the whole area were not detailed enough to capture local variations. Thus, a regional database for each area is selected. Therefore, data are compiled and homogenised from different sources (Table 1), so that the more detailed sources available are considered (details in Supplementary Material 1).

Details for all variables included in OCLE can be checked in Table 1.

Typically, only mean values of variables are available, which can limit the ecological relevance of analyses. Proper ecological parametrisation of variables is vital for a reliable and accurate evaluation of marine communities, ensuring that both variability and extremes are adequately represented in assessments. In OCLE for each variable, a comprehensive set of parameters is selected to holistically reflect the state of the environment as a proxy for ecological processes. For historical data, the maximum, minimum, mean, percentiles 10, 50, and 90 and the standard deviation are calculated at each grid point yearly and for the full period (2000–2023). In the case of MHWs and MCSs, the number of events per year and seasonally is available. Additionally, information on the duration of events, their intensity, and category (moderate, strong, severe, and extreme) according to Hobday et al. (2019) classification is provided, as the key relevance that mean and cumulative intensity and duration of MHWs have to macrophytes (Smith et al., 2024). Due to the large volume of data, it has not been possible to include this information in OCLE website, but it is available upon request.

Due to the relevance of seasonality for the ecology of marine species, each parameter has been calculated seasonally for the full period. To that, winter is considered to include the months of January, February, and March; spring included April, May, and June; summer included July, August, and September; and autumn included October, November, and December.

2.2.2. Climate change projections

In order to consider the most updated information, OCLE incorporates data of the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) of the WRCP (World Climate Research Programme), based on the AR6 (IPCC, 2023) for the air temperature, nitrates concentration, pH, sea salinity, wind speed and significant wave height. A total of 12 climate models from the CMIP6 project under the WRCP were selected, ensuring that all of them contained information on the SSP scenarios and the selected time periods. For each variable, a minimum of 3 models that provided relevant information are used. The selection of models is conducted in such a way that the different variables share the greatest number of models possible. Detailed information on the models applied to each variable can be found in the Supplementary Material 2.

For future scenarios, two out of the five SSPs are selected to represent a range that captures the associated uncertainty: a scenario with intermediate greenhouse gas (GHG) emissions (SSP2-4.5), where CO_2 emissions remain around current levels until mid-century; and a scenario with very high GHG emissions (SSP5-8.5), where CO_2 emissions nearly double compared to current levels by 2050 and 2100.

Once the data for each grid point is downloaded, the annual mean of each variable is calculated for each climate scenario, period, and model used, based on the original resolution of each climate model. After obtaining the mean, the changes for each period (2040–2060 and 2080–2100) are calculated relative to the historical period (1995–2015) for each of the two climate scenarios (SSP2-4.5 and SSP5-8.5). This calculation is performed both in terms of magnitude and percentage, with the optimal method chosen for each variable to best observe changes in the medium and long term across the entire area covered by the grid points. For nitrates concentration, wave height, sea surface temperature and air temperature the changes are applied; meanwhile for salinity, pH and wind speed the percentage of change is considered.

After calculating the monthly and annual means and changes at the original spatial resolutions for the different models and variables, these are interpolated to the target grid points using nearest neighbour interpolation for land-sea interfaces and linear interpolation for the rest.

The ensemble average change in magnitude ($\Delta\overline{x}$) for the selected periods and scenarios is calculated with the average change for each model, the following formula has been used:

$$\Delta\overline{x} = \frac{\sum_{i=1}^{n_{models}} \overline{x}_{i,future} - \overline{x}_{i,historical}}{n_{models}}$$

where $\overline{x}_{i,future}$ is the average value of the model i and variable for the future period and scenario, $\overline{x}_{i,historical}$ is the average value of the model i and for the historical period and n_{models} is the number of considered climate models.

To calculate the ensemble average percentage change ($\Delta\overline{x}_{percentage}$) for a period and future scenario, the following formula was used:

$$\Delta\overline{x}_{percentage} = \frac{100\sum_{i=1}^{n_{models}} \frac{\overline{x}_{i,future} - \overline{x}_{i,historical}}{\overline{x}_{i,historical}}}{n_{models}}$$

where $\overline{x}_{i,future}$ is the average value of the model i and variable for the future period and scenario, and $\overline{x}_{i,historical}$ is the average value of the model i and for the historical period.

The final analysis involves detecting climate change signals across the different models for each variable. Once all historical and future projection data are obtained, the mean for each variable across all scenarios and periods is calculated with the proposed formulas. Subsequently, the significance level of the data obtained is determined to indicate the extent to which the data agrees across models, or if some models predict significantly different outcomes, thus assessing the reliability of the results. To achieve this, matrices indicating the sign of each numerical value (positive or negative) are generated from the model data. Based on these, it is observed which models agree on the change. All values that agree in sign are summed, resulting in a total ranging from 1 to n (where n is the number of models), where the sum equals n or n-1, indicating a significant point where all models, or all but one, agree on the sign of the change. Results can be verified in the Supplementary Material 2.

In the case of sea level rise, the information is not compiled from different models; rather, the values obtained directly for each point in metres for the mid and long-term for the SSP2-4.5 and SSP5-8.5 scenarios, based on the period 1995–2014.

Following this approach, future values (under two climate change scenarios) for each variable affecting marine species ecology, along with the associated uncertainty and data reliability, is obtained. Data is obtained for each of the future year horizons (2050 and 2100) meanly values but also maximum and minimum derived from monthly data. The analyses are conducted using R Studio software v4.4 (R Core Team, 2024), Matlab 2022b (The MathWorks Inc., 2022), Python 3.12.7 (Python Software Foundation, 2023) and ArcGis Pro 3.0.0 (ESRI, 2023).

2.3. Biological data

Concerning biological data, information of presences of 22 macroalgae species collected by IHCantabria along the NE Atlantic and the Mediterranean Sea (De Ugarte, 2012; Guinda et al., 2014, 2012; IEO, 2012; IHCantabria, 2018, 2008; Juanes et al., 2008, 1991; Juanes and Gutiérrez, 1992; Ramos et al., 2017, 2016; UC, 2005) are accessible at OCLE (Table 2). Records are available yearly and seasonally for each year, due to the relevance of seasonality in species presence. For species that can be found both in the intertidal and subtidal (e.g. *Gelidium corneum*), results can be obtained separately. By clicking on the presence point of each species, information related to the project and the data provider is displayed, enabling users interested in further details (e.g., coverage, depth) to directly contact the source.

3. Results and discussion

OCLE represents a significant advancement in the tools available for improving the assessment of marine communities under climate change scenarios.

Table 2
Macroalgae species included in OCLE.

Macroalgae species			
Bifurcaria bifurcata	*Cystoseira tamariscifolia*	*Gelidium corneum*	*Laminaria ochroleuca*
Chondrus crispus	*Ellisolandia elongata*	*Gelidium spinosum*	*Pelvetia canaliculata*
Corallina	*Fucus*	*Halopteris scoparia*	*Saccorhiza polyschides*
Corallina officinalis	*Fucus serratus*	*Himanthalia elongata*	*Sargassum muticum*
Cystoseira	*Fucus spiralis*	*Laminaria*	
Cystoseira baccata	*Fucus vesiculosus*	*Laminaria hyperborea*	

This updated version of the OCLE database represents a substantial enhancement over the initial 2018 release (de la Hoz et al., 2018), addressing both temporal and spatial limitations, as well as expanding the range and resolution of the variables included. First, the historical period covered now has been extended through 2023, providing over two decades of environmental data (2000–2023). Spatial resolution has also been significantly improved, with a refined grid of 0.05° (~5 km) resolution up to 20 km from the coast, and 0.1° (~10 km) resolution beyond that, up to 70 km offshore. Second, two new variables derived from sea surface temperature (marine heatwaves (MHWs) and marine cold spells (MCSs)) have been added, offering crucial metrics for assessing extreme conditions and their impacts on marine ecosystems. The environmental data sources have also been updated to reflect the most recent and accurate products available. In some cases, such as salinity, datasets from multiple origins were homogenized to ensure consistency across the spatial domain. In terms of temporal resolution, OCLE now provides annual data instead of five-year averages, allowing for the detection of interannual variability and trends. Furthermore, climate projections have been updated to integrate the latest IPCC AR6 scenarios using CMIP6 models, including both medium- and high-emission pathways (SSP2-4.5 and SSP5-8.5). Finally, the statistical parameters available for each variable have been streamlined. While the previous version included percentiles 25 and 75, the current version offers minimum, mean, maximum, standard deviation, and percentiles 10, 50, and 90 to reduce the dataset volume. However, the raw data remains stored on IHCantabria servers, and additional derived parameters can be provided upon request to researchers requiring them for specific applications.

OCLE provides high-resolution environmental data that enables the identification of localized processes in coastal areas. As an example, Fig. 2 illustrates the average nitrate concentration in the Severn Estuary and Bristol Channel (UK) for the period 2000–2020. This region, known for strong riverine nutrient inputs, clearly displays a concentration gradient reflecting estuarine plume dynamics (Jonas and Millward, 2010). This example demonstrates the improved spatial resolution of OCLE in coastal environments, highlighting its capacity to detect small-scale patterns that are ecologically relevant but often missed in lower-resolution datasets.

OCLE includes variables highly relevant to species ecology, such as hydrodynamic factors (e.g., wave height, currents) and metrics for extreme conditions (e.g., shear stress, marine heatwaves and cold spells), which are often overlooked in existing datasets. It provides a comprehensive depiction of environmental factors that critically influence marine ecology, particularly benthic species. The example of bottom shear stress along the northern Iberian Peninsula (Fig. 3) highlights OCLE's ability to capture seasonal variability, showing elevated stress levels during autumn and winter that pose significant risks to the stability and survival of benthic organisms (Vousdoukas et al., 2012).

The availability of annual data allows for the detection of temporal trends and anomalous years. For instance, in the case of MHWs in the Mediterranean (Fig. 4), the yearly resolution reveals a marked increase in frequency and spatial extent since 2010, in line with Martínez et al. (2023) findings, enabling the identification of years with intensified thermal stress. Results indicated that MHWs have intensified, with significant impacts on marine ecosystems, particularly in biodiversity hotspots such as the Western Mediterranean and Adriatic regions (Smith et al., 2023; Verdura et al., 2019). Such insights are crucial for understanding the evolving impacts on biodiversity-supporting species and their ecosystems, as documented by multiple studies (Garrabou et al., 2022; Martínez et al., 2023; Smith et al., 2024).

The incorporation of climate change projections based on the most recent climate change projections (CMIP6) and scenarios (SSP2-4.5 and SSP5-8.5) is a key feature of OCLE, providing the best available knowledge to guide management and adaptation measures. Considering these scenarios is essential for developing strategies that are robust against future climate uncertainties and tailored to the specific

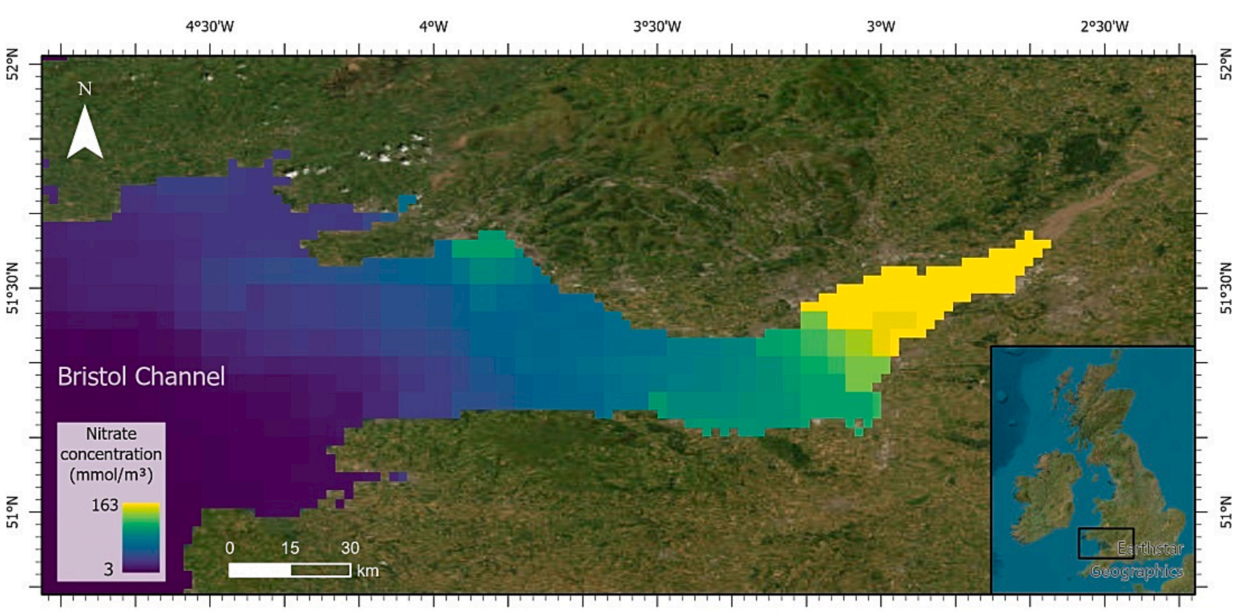

Fig. 2. Average nitrate concentration (mmol/m^3) along the Bristol channel in the period 2000–2020.

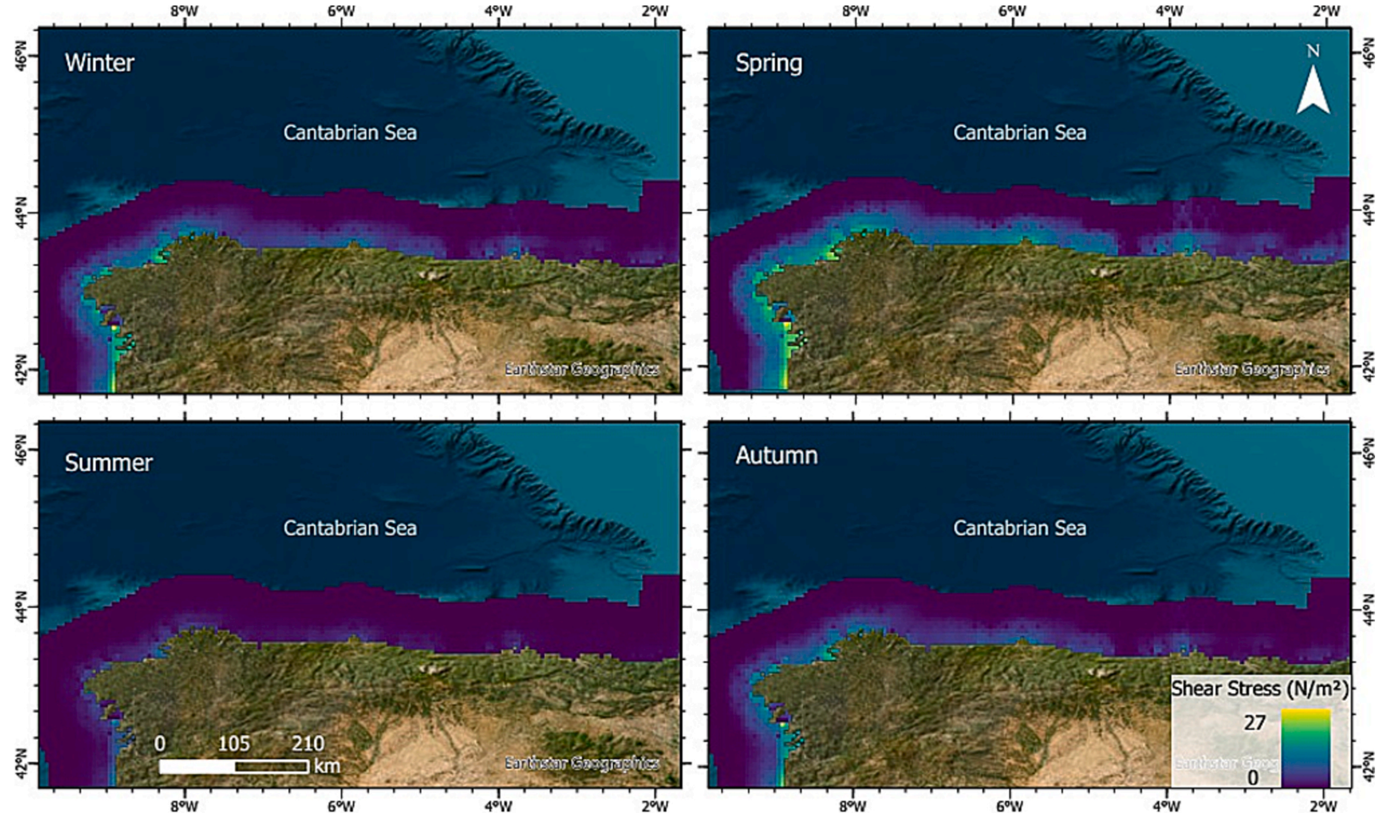

Fig. 3. Seasonal distribution of shear stress values along the north Iberian Peninsula.

challenges of marine ecosystems. One example of the insights provided by OCLE is the projected increase in sea surface temperature under a high-emissions scenario (SSP5-8.5), as shown in Fig. 5. By the late 21st century, significant rises in temperature are expected across European seas, with the Mediterranean region projected to experience some of the highest increases. These changes highlight the pressing need to address the vulnerabilities of marine ecosystems in this region, ensuring effective conservation and management strategies to mitigate the impacts on biodiversity and ecosystem services.

To complement the environmental dataset, OCLE includes the spatial distribution of 22 macroalgae species presence data. Fig. 6 provides an overview of the number of species recorded per location, illustrating the geographical spread of available biological data. While the density of records is highest along the northern coast of Spain, the dataset extends along the northeastern Atlantic and parts of the Mediterranean. The individual distribution maps for each species are accessible through the OCLE web platform, allowing users to explore detailed spatial patterns and download the corresponding data.

3.1. Case study

To illustrate the applicability of the OCLE dataset for ecological forecasting, we present a species distribution modelling case study using the red alga *Gelidium corneum*. This species has shown sensitivity to sea surface temperature (SST), photosynthetically active radiation (PAR), and wave height (Hs), as reported in previous studies (Borja et al., 2018; Sainz-Villegas et al., 2023; Sánchez-Astráin et al., 2024). Presence records were obtained from the OCLE database, and environmental variables for both the historical period (2000–2023) and future conditions under the SSP5-8.5 scenario for the year 2100 were retrieved using the web-based data extraction tool. Climate projections derived from IPCC AR6 were included for SST and Hs, while PAR was held constant due to the absence of projected data.

Species distribution models were built using Maxent v3.4.4 (Phillips and Dudík, 2008), with 20 % of the presence records reserved for testing. The models achieved high performance, with an area under the curve value of 0.99.

The results reveal a clear contraction in the potential distribution of *G. corneum* towards the western part of the northern Iberian Peninsula (Fig. 7). This finding aligns with recent observations (Arriaga et al., 2024; Ramos et al., 2020) and suggests that this range retraction is likely to continue under future climate conditions. This case study highlights the value of integrating OCLE's environmental and biological data for species distribution modelling and ecological impact assessments.

The diversity and quality of environmental variables of OCLE facilitate its integration into SDMs, enhancing model accuracy in ecological niche predictions through specific, relevant physical and biological data (de la Hoz et al., 2019; Elith and Leathwick, 2009; Guisan et al., 2017; Wilson et al., 2019). Beyond SDMs, OCLE can support conservation and coastal restoration studies. Hydrodynamic and climate variables, such as bottom shear stress and projected temperature extremes, help identify critical habitats and forecast habitat shifts under environmental stress, thus positioning OCLE as a useful tool for broader ecological and environmental management applications. Additionally, the ability to analyse both historical trends and future scenarios allows researchers to assess the resilience of ecosystems and test the potential efficacy of management strategies. This dual approach supports adaptive planning, enabling the prioritisation of actions to protect biodiversity hotspots and mitigate the impacts of climate change on vulnerable species and habitats.

4. OCLE website

OCLE results are available for free and with stepwise download at https://ocle.ihcantabria.com, to allow users' choice of the most appropriate data for their research needs, regarding the period (historical or projected), the time of the year (full period (2000–2023), year or season), the variables (16 options: sea surface temperature, air

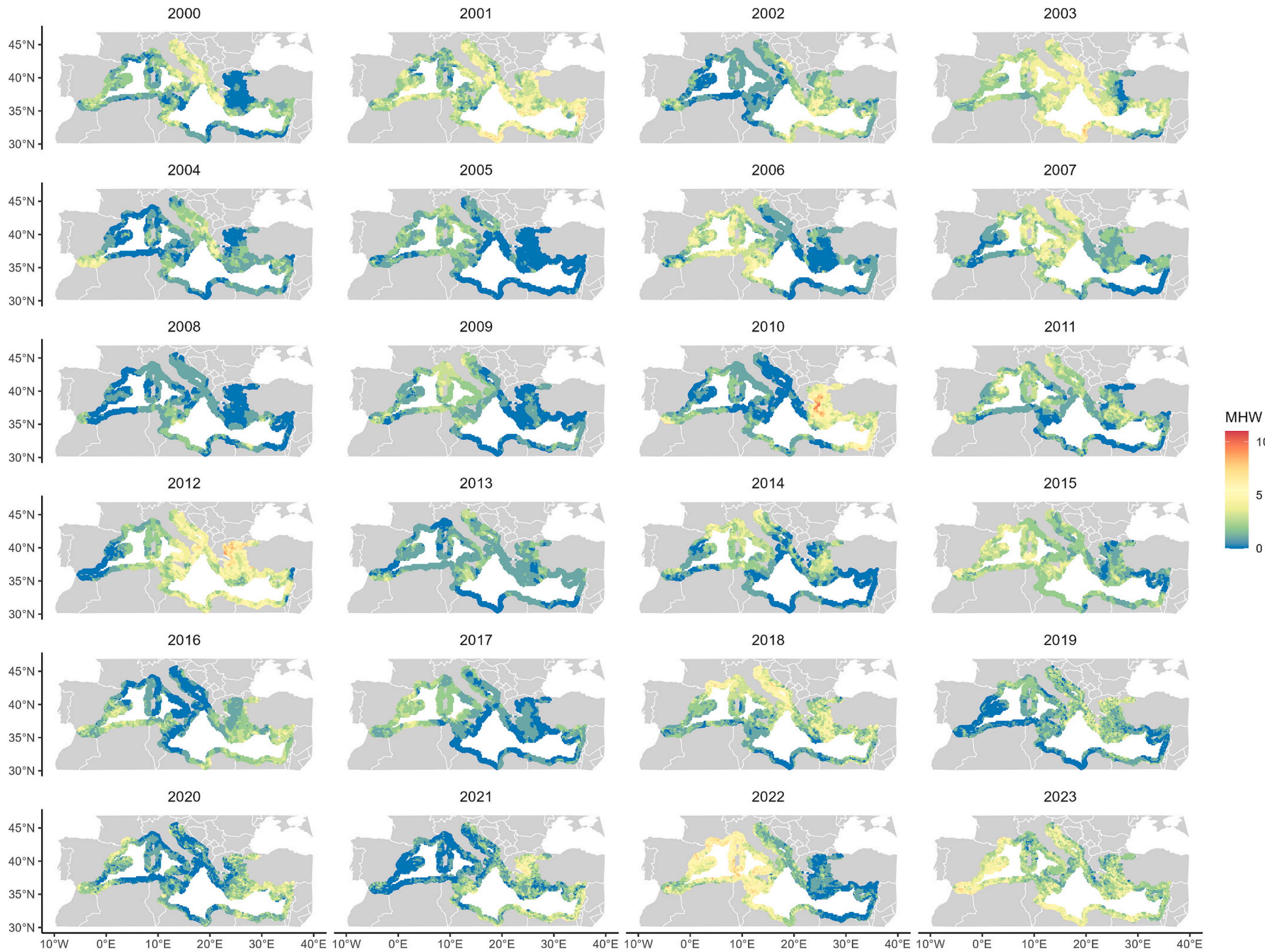

Fig. 4. Yearly evolution of the number of marine heat waves (MHW) in the Mediterranean Sea from 2000 to 2023.

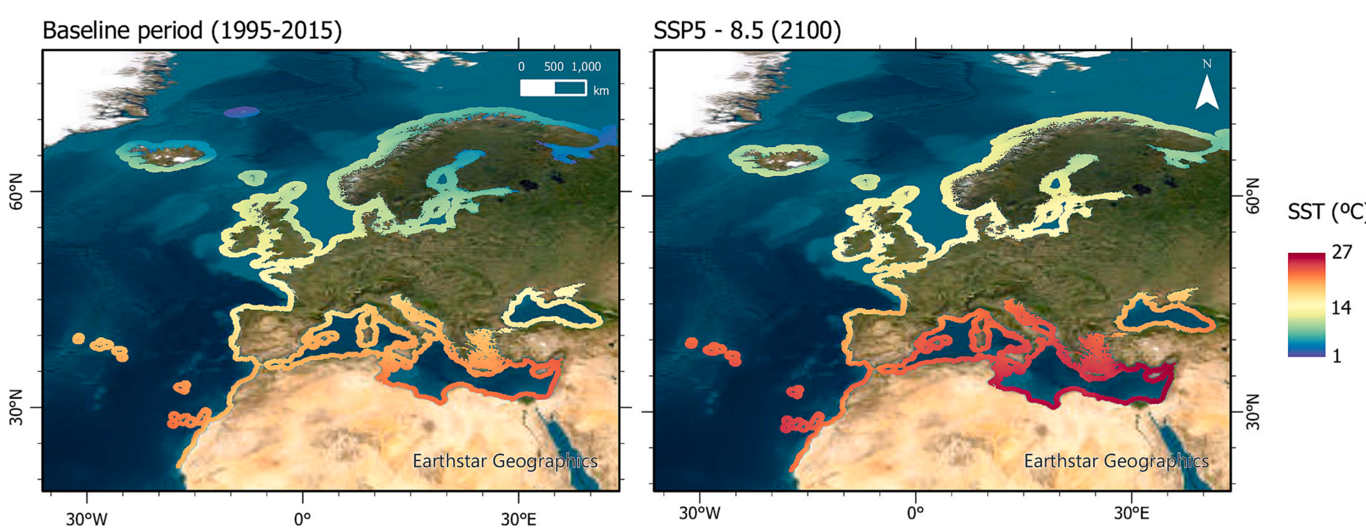

Fig. 5. Sea surface temperature values (SST) in the whole mesh of OCLE for the baseline period used to calculate the projections (1995–2015) in the left panel, and in the climate change SSP5-8.5 for the long term (2100) in the right panel.

temperature, nitrate concentration, pH, salinity, attenuation coefficient, photosynthetically available radiation, significant wave height, wind speed, tidal range, currents speed, bottom orbital speed, sea level, marine heatwaves, marine cold spells, shear stress) and parameters of interest (7 choices: minimum, mean, maximum, percentile 10, percentile 50, percentile 90, standard deviation).

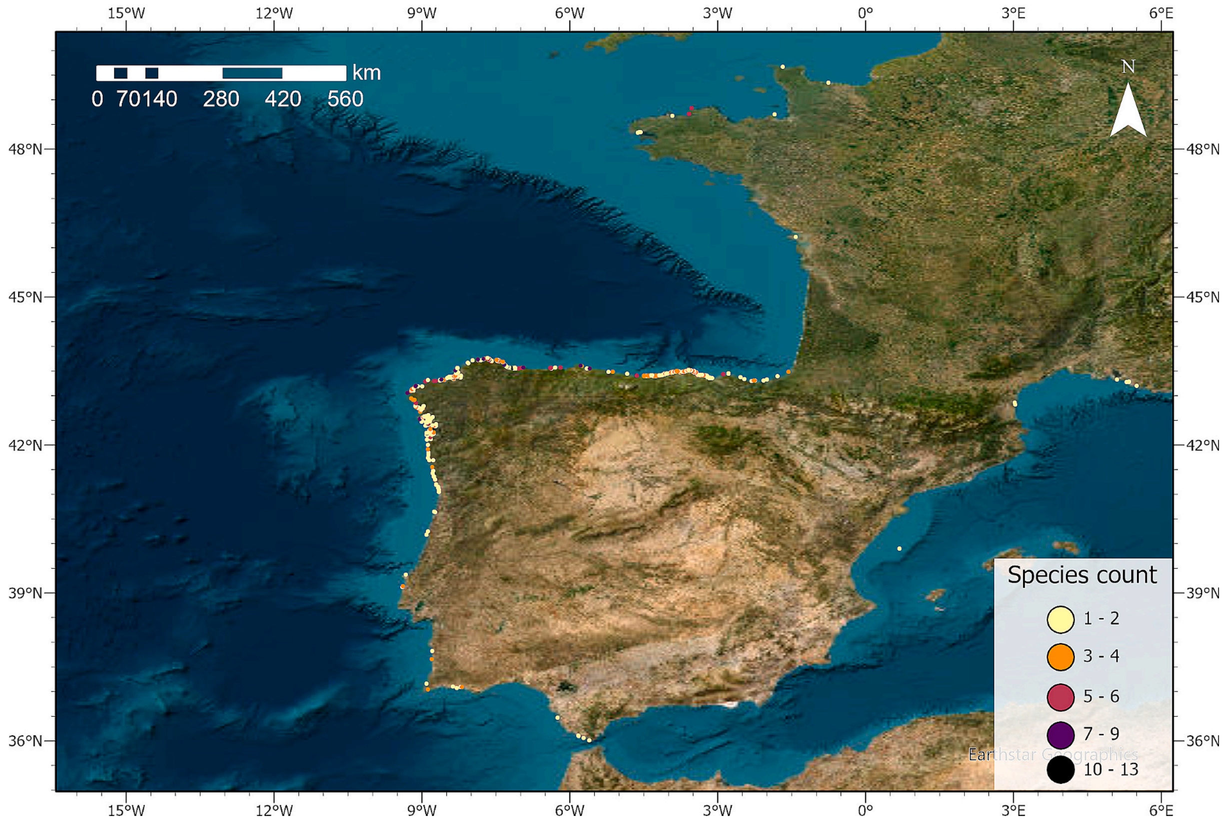

Fig. 6. Number of macroalgae species recorded per sampling point along the NE Atlantic and Mediterranean coasts included in OCLE.

The data provided by OCLE can be downloaded either through the website (Fig. 8) or integrated in the R environment using a function developed specifically for this purpose available to be downloaded in the website (in the downloader section and at https://github.com/IHCantabria/simulit_dowloader). Environmental data is downloaded in NetCDF format by default, but the R function also includes the option to convert the data to ASCII, Rdata or csv format, facilitating their integration into SDMs. Additionally, users can spatially filter areas of interest on the website, enabling the download of information specific to selected regions. This feature ensures efficient data handling by providing only the relevant data needed for specific studies. On the other hand, the biological data is downloaded in JSON format, and its transformation to CSV is also addressed in the R function available on the website.

Additionally, it is possible to access to daily data and customized parameters on request (e.g. number of days a threshold is overpassed). This opens up the possibility to a broad field of work generating more specific parameters.

The website also includes contact information for inquiries, along with a Frequently Asked Questions (FAQs) section and a user tutorial for both the website and the R function. The Tutorials section includes several explanatory videos to guide users through the functionalities and features of OCLE, making it accessible even to those unfamiliar with similar tools.

5. Conclusions

OCLE's integration of ecologically relevant variables represents a significant step forward in improving the assessment systems for littoral communities, both in historical periods and under climate change scenarios. With its extensive spatial coverage and detailed resolution, OCLE enables studies that bridge large-scale ecological patterns with fine-scale processes. Its spatial and temporal homogeneity ensures the reliability and consistency of the dataset, making it a robust foundation for ecological modelling.

By including a wide array of variables that span physical and geochemical conditions, and metrics for extreme stress conditions, OCLE provides a comprehensive depiction of the environmental factors shaping marine ecosystems. Additionally, the integration of the most up-to-date climate change projections from the IPCC AR6 enhances its capacity to forecast and plan for future ecological changes, offering a forward-looking tool for both research and management.

The open-access nature of OCLE ensures that it is available to researchers and managers alike, facilitating the development of a wide range of studies and applications. From advancing species distribution models to supporting conservation planning and coastal restoration efforts, OCLE's datasets contribute to more informed and effective strategies for biodiversity protection and climate adaptation.

In conclusion, OCLE's focus on the homogeneous spatial precision, variable diversity, and cutting-edge climate information establishes it as a valuable resource for European marine research. Its capacity to address the complexities of both historical conditions and future scenarios positions it as a critical tool in advancing the understanding and management of marine ecosystems, fostering the resilience of these systems in the face of ongoing environmental change.

CRediT authorship contribution statement

Camino F. de la Hoz: Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Conceptualization, Writing – original draft, Validation, Project administration, Funding acquisition. **Elvira Ramos:** Writing – review & editing, Supervision, Methodology, Data curation, Validation, Project administration, Formal analysis, Conceptualization. **Adrián Acevedo:** Writing – review & editing, Validation, Formal analysis, Visualization, Methodology, Data curation. **Melisa Menéndez:** Writing – review & editing, Validation, Formal analysis, Visualization, Methodology, Data curation. **Alejandra G. Cabanillas:** Writing – review & editing, Formal analysis, Visualization,

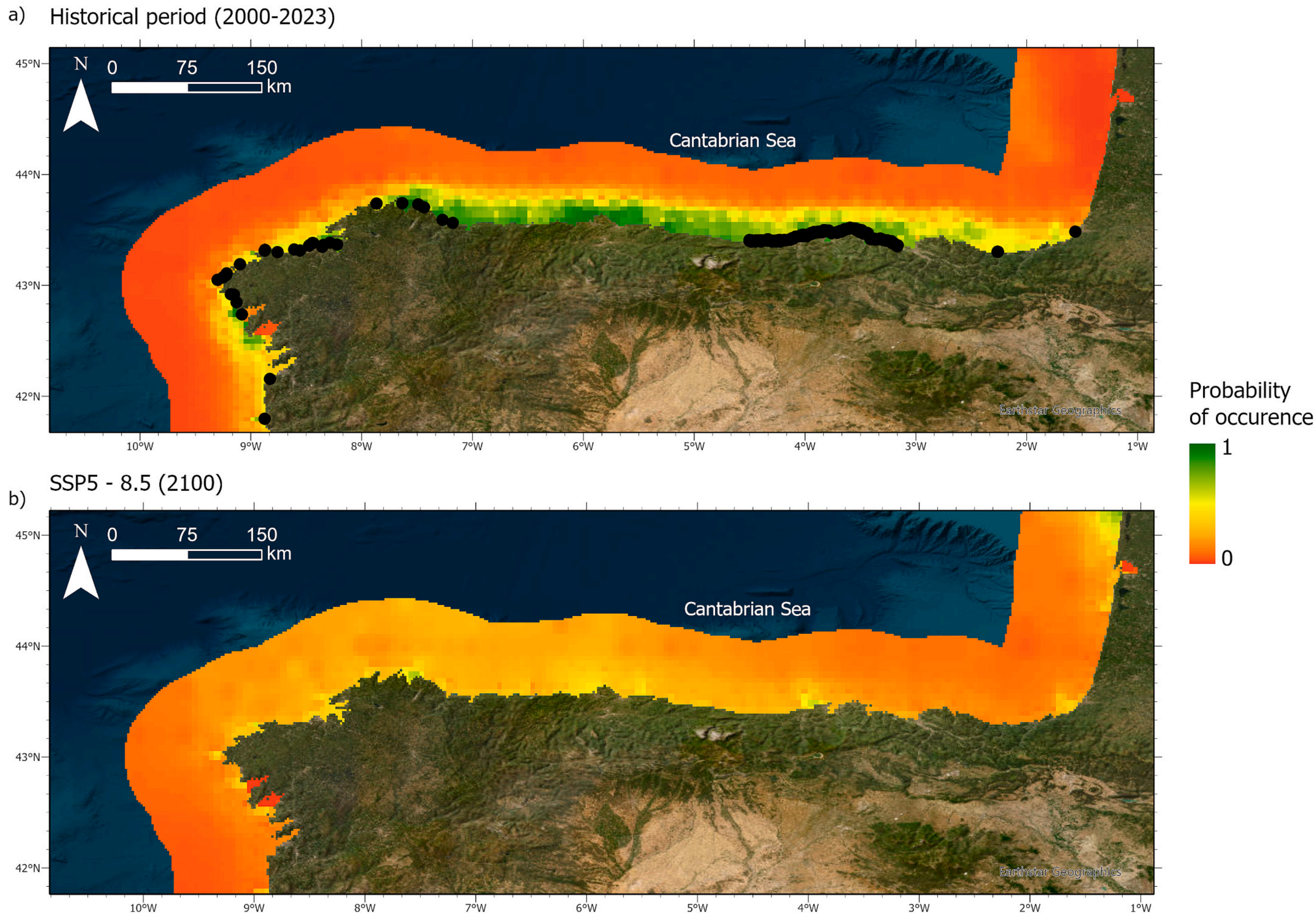

Fig. 7. a) Probability of occurrence during the historical period (2000–2023) of *Gelidium corneum* along the north of the Iberian Peninsula; black dots represent presence records used of *Gelidium corneum* available at ocle. b) Projected probability of occurrence for the year 2100 under the ssp5-8.5 scenario. colours range from green (high probability) to red (low probability).

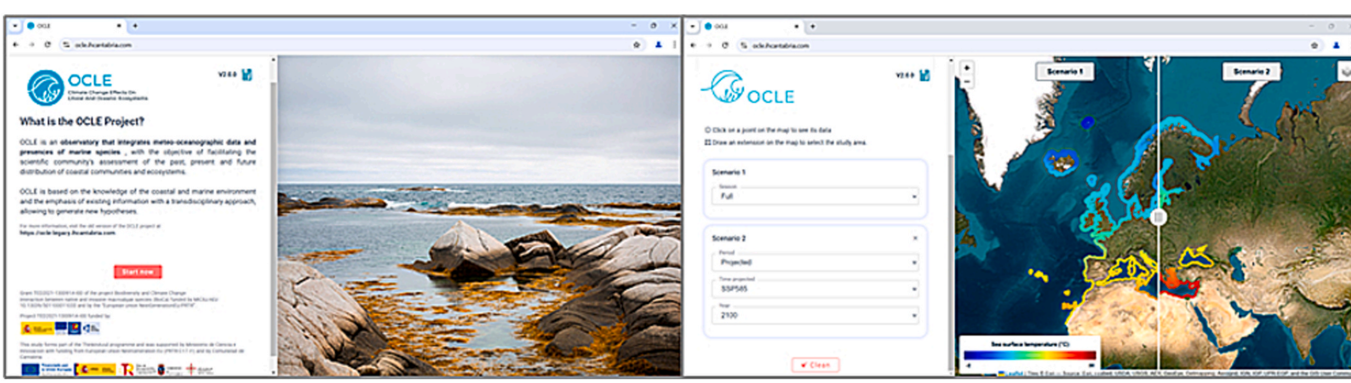

Fig. 8. Aspect of the OCLE website (http://ocle.ihcantabria.com) on its homepage (left) and during the selection of environmental variables (right).

Data curation. **Araceli Puente:** Resources, Writing – review & editing, Conceptualization. **José A. Juanes:** Writing – review & editing, Conceptualization, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2025.103533.

Data availability

The OCLE information is accessible online at http://ocle.ihcantabria.com for download and preview. Additional data will be made available on request.

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