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Original Article

Climate change effects on marine renewable energy resources and environmental conditions for offshore aquaculture in Europe

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The development of the marine renewable energy and offshore aquaculture sectors is susceptible to being affected by climate change. Consequently, for the long-term planning of these activities, a holistic view on the effects of climate change on energy resources and environmental conditions is required. Based on present climate and future climate scenario, favourable conditions for wind and wave energy exploitation and for farming six marine fish species are assessed using a suitability index over all European regional seas. Regarding available energy potential, the estimated changes in climate do not have direct impacts on the geographic distribution of potential regions for the energy industry (both wind and wave based), that is they pose no threat to this industry. Long-term changes in environmental conditions could however require adaptation of the aquaculture sector and especially of its exploitation areas. Opportunities for aquaculture expansion of the assessed species are identified. Possibilities for co-location of these activities are observed in the different climate scenarios. The evaluation of potential zones for the exploitation of marine renewable energy resources and offshore aquaculture represents a stepping-stone, useful for improving decision-making and assisting in the management of marine economies both in the short-term and in the long-term development of these sectors.

Keywords: long-term projection, open-sea fish farming, RCP 8.5, suitability index, wave energy, wind energy

Introduction

Renewable energy resources and aquaculture will play a key role in providing energy and food security to meet global demands in the coming decades. The expansion of these activities has been contemplated in public policies at the international, national, and regional levels, such as the European Commission's Blue Growth Strategy (European Commission, 2017). These emergent activities, within the context of Blue Growth, have been increasingly enabled to operate in hostile environments (Bahaj, 2011), justifying their strategic position (European Commission, 2017). The expansion of these industries towards the offshore environment has promoted the development of multi-use platforms during the last decade (Abhinav *et al.*, 2020). This is the case for wind energy, wave energy, and aquaculture activities, which present synergies, mainly structural and operational, that allow the co-location of these activities (e.g. Shiau-Yun et al., 2014; Buck *et al.*, 2017; Weiss *et al.*, 2018a). Currently, renewable resources are part of a large and diversified world energy mix, with a share of renewable marine energy sources of 69 198 GWh in 2018, and a total installed capacity of 28 686 MW in 2019 (IRENA, 2020). Meanwhile, the growth of the aquaculture sector has increased the average consumption of fish and its by-products globally (FAO, 2016a) and is expected to be the main source of aquatic food in the next years (Ottinger *et al.*, 2016). The long-term development of these sectors is however susceptible of being affected by climate change.

The effects of global warming induced by greenhouse gas emissions indicate relevant changes in future climate patterns, with direct impacts on the environment (IPCC, 2014a). In this context, General Circulation Models (GCMs) are essential tools for assessing climate change under future scenarios. The outcomes of currently available GCMs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) are described in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014b). Such projection models take into account Representative Concentration Pathways (RCPs) introduced in the AR5 of the IPCC (IPCC, 2014a). According to this document, the severe increase in greenhouse gas emissions has reached the worst emission scenario proposed by the IPCC, the RCP 8.5 (IPCC, 2014a; Clark *et al.*, 2016). The very high baseline emission scenario, RCP 8.5, is based on the continuity of the current level of CO_2 emissions and is considered the more realistic scenario if no specific mitigation objective is implemented (Riahi *et al.*, 2011; Van Vuuren *et al.*, 2011). However, GCM outputs are limited for wind-wave climate parameters compared to other environmental variables, such as temperature and precipitation.

Since wind-wave climate and environmental conditions (physical–chemical factors) respond to climate variability and changes (Callaway *et al.*, 2012; Hoeke *et al.*, 2013), the main issue is what impact can climate change have on the marine renewable energy and offshore aquaculture sectors? Consequently, another question arises, what are the opportunities (e.g. new areas for exploitation of activities, as well as for co-location) and threats (e.g. currently suitable areas that may be affected by climate change) to these industries in the long-term period?

Several studies have carried out simulations to project ocean wind-wave climate (Camus *et al* 2017; Saha *et al.*, 2017; Morim *et al.*, 2018) and environmental variables (Tinker *et al.*, 2016; De la Hoz et al., 2018; Hand *et al.*, 2019) to respond to different trajectories of increased greenhouse gas emissions throughout the 21st century. More specific studies have assessed the effects of climate change on energy resources and on environmental conditions for aquaculture using climate models (regional and global). Pryor and Barthelmie (2010) and Koletsis *et al.* (2016), for instance, sought to recognize direct changes in wind power potential. In turn, regional wave climate projections over Europe for different scenarios and projected changes in wave energy flux was analysed in Perez *et al.* (2015). Moreover, considerable attention has been focused on climate projections relevant to aquaculture. For instance, Sarà *et al.* (2018) developed an approach to assess spatial and temporal patterns of covariation between maximized environmental cost-benefit changes under present and future climate conditions and narrowing the science-policy communication gap. Merino *et al.* (2012) investigated the feasibility of sustaining current and increased rates of fish consumption per capita in a future scenario, considering economic, climatic, and social aspects.

Although an effort has been made by the scientific community to project climate change, to date, there are no approaches to assess the distribution of potential zones for the exploitation of marine renewable energy resources and for open-sea fish farming in future scenarios. Consequently, to help in long-term planning and the adaptation of the marine renewable energy and offshore aquaculture sectors to future climate conditions, a holistic view of the changes in available energy potential and environmental conditions for open-sea fish farming is required. Furthermore, defining and analysing present and future conditions, including climate and environmental conditions, are two of the most important phases in the marine spatial planning (MSP) process, both included in the United Nations Educational, Scientific and Cultural Organization (UNESCO) methodology (Steps 5 and 6, Ehler and Douvere, 2009). In this sense, this work aims to assess the geographical distribution of potential zones for the exploitation of offshore wind and wave resources, for farming six marine fish species and for the co-location of these activities, due to the climate change. For this purpose, present and projected climate conditions are analysed to recognize areas with favourable conditions for these activities, thus identifying opportunities and threats for these marine economies.

Study area

The study area encompasses the Mediterranean Sea, the Black Sea, the Baltic Sea, and the Northeast Atlantic Ocean (including the North Sea and the Barents Sea). These regions that include all the European regional seas are of particular interest to the offshore renewable energy and aquaculture sectors. Europe has a leading role in the use of marine energies, accounting for >90% of the installed offshore wind capacity in the world (Kalogeri *et al.*, 2017). The enormous wind potential in the North Atlantic sub-basin is evidenced by the advanced development of the wind industry in the North and Baltic Seas. Conversely, this industry is still in its initial developmental phase in the Mediterranean Sea, with some wind farms in operation, but most still under construction or being planned (4COffshore, 2020; Wind Europe, 2020a, b). Another area of special interest for wind and wave energy exploitation is the Black Sea (Rusu *et al.*, 2018). According to Kalogeri *et al.* (2017), the North Atlantic sub-basin also has a high potential for the exploitation of wave energy.

With regard to aquaculture, the Mediterranean Sea is one of the areas with the greatest potential for farming European seabass, Gilthead seabream, Atlantic Bluefin tuna, and Meagre (FAO, 2005a, b, c, 2015; Weiss *et al.*, 2018b), the last three species currently being farmed at commercial scale in Turkey and Greece (FAO, 2017). The African coast of the North Atlantic presents great opportunities for farming Greater amberjack (Weiss *et al.*, 2018b). Elsewhere, Norway and the United Kingdom are the main producers of Atlantic salmon in the North Sea (FAO, 2017).

Material and methods

This study analysed present and future spatiotemporal dynamics in met-ocean conditions and oceanic physical–chemical factors for the exploitation of energy resources and open-sea fish farming. The available wind energy potential and wave energy flux are estimated to identify zones with favourable conditions for energy exploitation, and other environmental conditions are analysed to identify zones with optimal conditions for fish growth. The delta change method (delta downscaling or change factor method, Mosier *et al.*, 2014, 2018) is adopted to assess the future changes due to climate change. This method is based on the use of a "change factor", the difference between a mean value in the reference period and future simulations. This "change" is then applied to the historical data series to transform this series set into time series that is representative of the future climate (Figure 1).

The suitability of the study area is estimated using an index [suitability index (SI)] measuring the probability of meeting favourable conditions for each evaluated aspect (*c.f.* "SI

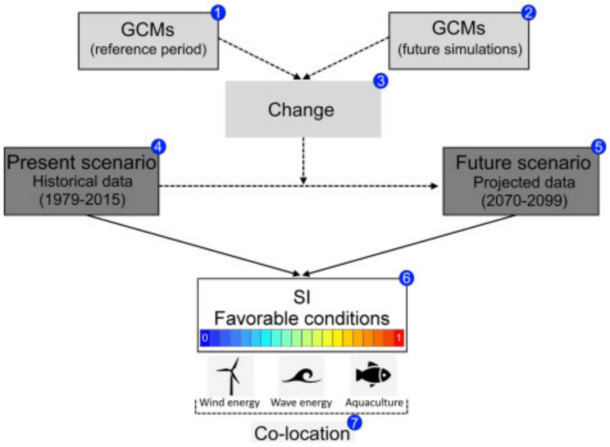

Figure 1. Diagram depicting the various steps followed under the proposed methodological approach. The differences [i.e. *change* (**3**)] in the means between the *reference period* (**1**) and the *future simulations* (**2**) of the GCM data series are applied to the *historical data* (**4**) series, generating the *projected data* (**5**) series. *Historical* and *projected data* [*present scenario* (**4**) and *future scenario* (**5**), respectively] are analysed using a *SI* (**6**) to measure the probability of meeting *favourable conditions* (**6**) for wind energy, wave energy, and aquaculture. The possibilities of *co-location* (**7**) are calculated using the limiting values of the *SI* of each activity (minimum value of suitability).

assessment" section). Figure 1 shows a general overview of the methodology followed in this work, which is explained in more detail in the following sections.

Data

For the present climate, a combination of historical climate data information (21–37 years) at different temporal (hourly, daily, and weekly) and spatial (0.017–0.3°) resolutions is used, depending on the availability of homogeneous datasets (Table 1). As for the future scenario, a long-term (2070–2099) projection, based on the RCP 8.5 from the CMIP5 (Taylor *et al.*, 2012), is considered. GCMs of the baseline scenario (RCP 8.5) are chosen to represent the projections of long-term changes since they correspond to the pathway with the highest greenhouse gas emissions, that is if no specific measure of climate mitigation is included (Riahi *et al.*, 2011; Van Vuuren *et al.*, 2011). To ensure data accuracy, GCMs are selected according to their ability to represent projections in the Northeast Atlantic region (Perez *et al.*, 2014, 2015) and because it is the reference set of the IPCC (IPCC, 2014a) (Table 1).

The variables used to represent the climate in the present and projected scenarios are based on the driving elements for energy production and the limiting factors for fish growth. Wind and wave data are considered to evaluate the availability of a viable resource for energy exploitation. On the other hand, temperature and salinity, two most limiting factors for distribution of marine organisms at a biogeographical scale, are considered to assess favourable environmental conditions for fish farming. These variables allow the mapping of areas with potential for these sectors, thus identifying opportunities and threats due to long-term climate change.

Simulation of long-term projections

The simulation of future climate scenarios for the period 2070–2099 is assessed to apply the delta change method, which is widely used in the literature (Lutz *et al.*, 2014; Mosier *et al.*, 2014; Räty, *et al.*, 2014). As a quality control, data from GCMs during the reference period are compared against historical data for the same period (1985–2005). GCM data with >20% of the values outside the limits of the Mean Squared Errors ($\text{MSE}_{\text{mean}} \pm \text{MSE}_{\text{std}}$) are discarded (Chai and Draxler, 2014). This period is used because historical data overlap with the data available in most GCMs. A detailed description of the data validation procedure is presented in De la Hoz et al. (2018).

To avoid systematic biases, parameters (mean, min, max, std) are calculated for each GCM independently and averaged with the ensemble method (Meier *et al.*, 2011; Arnell *et al.*, 2016; Camus *et al.*, 2017; De la Hoz et al., 2018). Differences in the means between the future simulations (2070–2099) and the reference period (1985–2005) of the GCM data series are applied to the historical data series, generating projected data series (2070–2099). The same bias is assumed in present and future climate conditions, and the spatial and temporal resolutions of the projected data are the same as the available historical data. Because the spatial and temporal resolutions of the GCM outputs are too coarse to allow a direct comparison with the analytical reanalysis, the points with the shortest Euclidean distance among them are considered.

SI assessment

The SI evaluates the favourable conditions of energy resources and environmental conditions for the exploitation of renewable energy and aquaculture activities, respectively. This index measures the percentage of time that the study area is in favourable conditions for these activities, according to the thresholds in Table 2. The percentage of time, explained in more detail in item 3.3.2 for wind and wave energy resources and in item 3.3.3 for aquaculture, is expressed on a standardized scale of probability, where value 1 means the maximum suitability and 0 means the minimum suitability.

Evaluation criteria

The analyses for renewable energy resources are based on reference operating thresholds of large wind turbines and wave devices, considering the feasibility for energy extraction. For aquaculture, optimal environmental ranges are considered for the growth of the six selected marine fish species. Depth limits for energy and aquaculture activities are similar to those established in previous studies (Table 2).

Wind and wave energy resources

The assessment of resource availability is based on the percentage of time during which favourable production conditions occur, for both wind and wave devices (Table 2). Wind energy is evaluated based on the percentage of time the available potential remain above the threshold considered for energy extraction. The available potential is calculated for a height of 90 m, according to the average hub height of wind turbines considered in this study. Therefore, the SI of the wind resource (SI_{Wind}) is defined according to the following equation:

Table 1. Summary of available periods, data sources, resolutions and models for the present and future climate.

Variable	Available period	Sources of information	Temporal resolution	Spatial resolution (°)	Method
Wind	1979–2010	Saha *et al.* (2010)	Hourly	0.3	Reanalysed data
	2011–2015	Saha *et al.* (2014)		0.2	
	2070–2099	WCRP (2018)	Daily	0.25[a]	Projections CNRM-CM5; GFDL-ESM2G; GFDL-ESM2M; IPSL-CM5A-LR; IPSL-CM5A-MR; MPI-ESMMR
Waves	1979–2015	Perez *et al.* (2017)	Hourly	0.25	Reanalysed data
	1979–2015	Reguero *et al.* (2012)		0.25	
	2070–2099	WCRP (2018)	Monthly	0.25[a]	Projections CNRM-CM5; GFDL-ESM2G; GFDL-ESM2M; IPSL-CM5A-LR; IPSL-CM5A-MR; IPSLCM5B-LR; MPI-ESM-LR; MPI-ESM-MR
Water temperature	1985–2013	Donlon *et al.* (2012)	Daily	0.25	Reanalysed data
	2071–2099	WCRP (2018)	Daily	0.25	Projections CNRM-CM5; GFDL-ESM2G; IPSL-CM5A-LR; IPSL-CM5A-MR; MPI-ESM-LR; MPI-ESM-MR
Salinity	1993–2013	Copernicus (2016)	Weekly	0.25	Reanalysed data
	2079–2099	WCRP (2018)	Monthly	0.25[a]	Projections IPSL-CM5A-LR; IPSL-CM5A-MR; IPSLCM5B-LR; CNRM-CM5; GFDL-EMS2G; GFDL-ESM2M
Bathymetry	2009	Amante and Eakins (2009)	Static	0.017	Satellite measurements

[a] Spatial resolution derived from reanalysis data, c.f. 3.2. *Simulation of long-term projections*.

Table 2. Aspects, species assessed, thresholds, data sources, and criteria.

Aspects/species	Thresholds		Sources of information	Criteria (0–1)
Wind resource				
Available potential (W/m^2)	≥ 400		Jonkman *et al.* (2009, 2012) and Bak *et al.* (2013)	% of time
Wave resource				
Available energy flux (kW/m)	≥ 15		Babarit *et al.* (2012), De Andres *et al.* (2015), and Roberson *et al.* (2016)	% of time
Bathymetry (m)	≤ 500		Weiss *et al.* (2018c)	Boolean
Aquaculture	Temperature (°C)	Salinity (Practical Salinity Unit, PSU)		
European seabass, *Dicentrarchus labrax*	$18\leq$ to ≤ 27	$30\leq$ to ≤ 40	FAO (2005a), Hossu *et al.* (2005), Katavić *et al.* (2005), Kavadias *et al.* (2003), Person-Le Ruyet *et al.* (2004), and Weiss *et al.* (2018b)	% of time
Gilthead seabream, *Sparus aurata*	$18\leq$ to ≤ 26	$30\leq$ to ≤ 40	FAO (2005b), Katavić *et al.* (2005), Seginer and Ben-Asher (2011), and Weiss *et al.* (2018b)	% of time
Atlantic salmon, *Salmo salar*	$6\leq$ to ≤ 16	$30\leq$ to ≤ 35	FAO (2004), Gooley *et al.* (2000), Katavić *et al.* (2005), Nath *et al.* (2000), and Weiss *et al.* (2018b)	% of time
Atlantic Bluefin tuna, *Thunnus thynnus*	$18\leq$ to ≤ 26	$30\leq$ to ≤ 40	FAO (2015), Katavić *et al.* (2005), Ticina *et al.* (2007), Tucker (1998), Weiss *et al.* (2018b) and Wright (2008)	% of time
Meagre, *Argyrosomus regius*	$18\leq$ to ≤ 26	$30\leq$ to ≤ 40	Duncan *et al.* (2013), FAO (2005c), Martínez-Llorens *et al.* (2011), Monfort (2010), Schuchardt *et al.* (2007), and Weiss *et al.* (2018b)	% of time
Greater amberjack, *Seriola dumerili*	$20\leq$ to ≤ 26	$30\leq$ to ≤ 36	Chambers and Ostrowski (1999), FAO (2016b), Jover *et al.* (1999), Tucker (1998), and Weiss *et al.* (2018b)	% of time
Bathymetry (m)	≤ 700		Weiss *et al.* (2018b)	Boolean

$$\mathrm{SI_{Wind}} = \left(\frac{t_{Ap}}{-t}\right), \tag{1}$$

where t_{Ap} is the time, at the temporal resolution of the base variable (wind, Table 1), that the available potential at a height of 90 m (Ap) remained above 400 W/m^2 (Table 2) throughout the analysed time series ($-t$).

The wave energy suitability assessment is based on the percentage of time a site presents waves that could be harvested energetically, considering the flux of wave energy where the availability of resource is viable for energy extraction. The SI for wave resource ($\mathrm{SI_{Wave}}$) according to the following equation is

$$\mathrm{SI_{Wave}} = \left(\frac{t_{Ef}}{-t}\right), \tag{2}$$

where t_{Ef} is the time, at the temporal resolution of the base variable (waves, Table 1), that energy flux (Ef) remained above 15 kW/m (Table 2) throughout the analysed time series ($-t$).

Aquaculture

The assessment of suitable zones for open-sea fish farming is based on two limiting factors for fish growth: sea surface temperature (*sst*) and sea surface salinity (*sss*). The SI for aquaculture ($\mathrm{SI_{Aq}}$) is therefore established according to the percentage of time that *sst* and *sss* remained within the biological thresholds for each species (Table 2) in concomitance (*con*):

$$\mathrm{SI_{Aq}} = con\left(\frac{t_{sst}}{-t}, \frac{t_{sss}}{-t}\right), \tag{3}$$

where t_{sst} is the time, at the temporal resolution of the base variable (temperature, Table 1), that the *sst* remained within the defined thresholds for each fish species (Table 2) throughout the analysed time series ($-t$). Also, t_{sss} is the time, at the temporal resolution of the base variable (salinity, Table 1), that the *sss* remained within the defined thresholds for each fish species (Table 2) throughout the analysed time series ($-t$).

Finally, map results are showing after a Kriging method interpolation (Ghiasi and Nafisi, 2016) on a homogeneous grid with 0.10° spatial resolution.

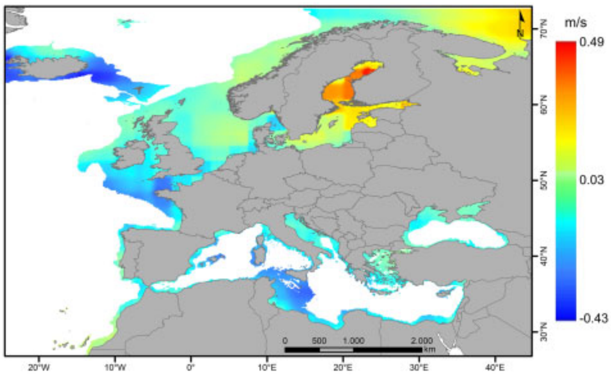

Figure 2. Projected changes in the ensemble mean of the mean wind speed (m/s), i.e. the differences in the means between the reference period and the future simulations of the GCM data series (*c.f.* Figure 1).

Co-location

The SIs for the wind energy (1), wave energy (2), and aquaculture (3) are integrated in a combined maps to identify zones with potential for the co-location of these activities. The integration of the maps is based on the limiting values of each SI (minimum value of suitability, *min*) of the evaluated activities. The potential zones for co-location, in the present and future scenarios, are expressed in a standardized scale of probability ($\mathrm{SI_{Co}}$, 0–1) of the minimum value found for each activity in the study area, at each grid cell:

$$\mathrm{SI_{Co}} = min(\mathrm{SI_{Wind}},\ \mathrm{SI_{Wave}},\ \mathrm{SI_{Aq}}). \tag{4}$$

Different combinations of activities were used for the calculation of $\mathrm{SI_{Co}}$ (e.g. wind + wave; wave + aquaculture; wind + aquaculture; and the three activities).

Results and discussion

Wind energy

The projected long-term changes in the mean wind speed are shown in Figure 2. A decrease of ∼5% in energy potential is found in most of the study area. The projected mean wind speed of the ensemble is generally smaller than that of the present climate conditions, except for that in the Baltic and Barents Seas. The decrease in resource availability in the North Atlantic sub-basin is consistent with the findings of Casas-Prat *et al.* (2018) and Semedo *et al.* (2012). Hemer *et al.* (2013) also predicted a weakening in wind velocities in the North Atlantic sub-basin but of a greater magnitude (−3 m/s) than those observed in this study (−0.43 m/s). These variations in magnitude could be justified by the different scales of analysis and the models and methods used in each study.

For the Mediterranean and Black Seas, the patterns of the changes in wind speed are similar to those calculated by Koletsis *et al.* (2016) and Soukissian *et al.* (2018), showing a negative trend in most parts of both seas. These authors nevertheless found increases in specific areas, such as in the Aegean Sea and in the western part of the Black Sea (Koletsis *et al.*, 2016) and in the Adriatic and Ionian Seas (Soukissian *et al.*, 2018), and these increases are not observed in this study. The increase in wind speed identified for the Baltic Sea shows increases of up to 0.49 m/s in the northern part of the sea. Various studies carried out in this region also have stated that there may be an increase in wind speed (Gräwe *et al.*, 2013); however, other studies have claimed that wind characteristics will not change (Deng *et al.*, 2015).

The available potential (power density) calculated for the present climate is consistent with the conclusions of Zheng and Pan (2014) and Zheng *et al.* (2018) (Figure 3a). In addition, the spatial distribution pattern and values found in this study are similar to those found by Kalogeri *et al.* (2017) (see Supplementary material for wind potential in the different scenarios). The areas with the highest power density are in Iceland, the North Sea, and the Baltic Sea. Among the areas with the highest potential, the North and Baltic Seas are currently the main development areas for the offshore wind industry (4COffshore, 2020). Specific areas in the Mediterranean Sea, such as the coast of France, which is expanding this industry (Wind Europe, 2020b), also stood out as having the potential for wind exploitation. Southwestern regions, such as

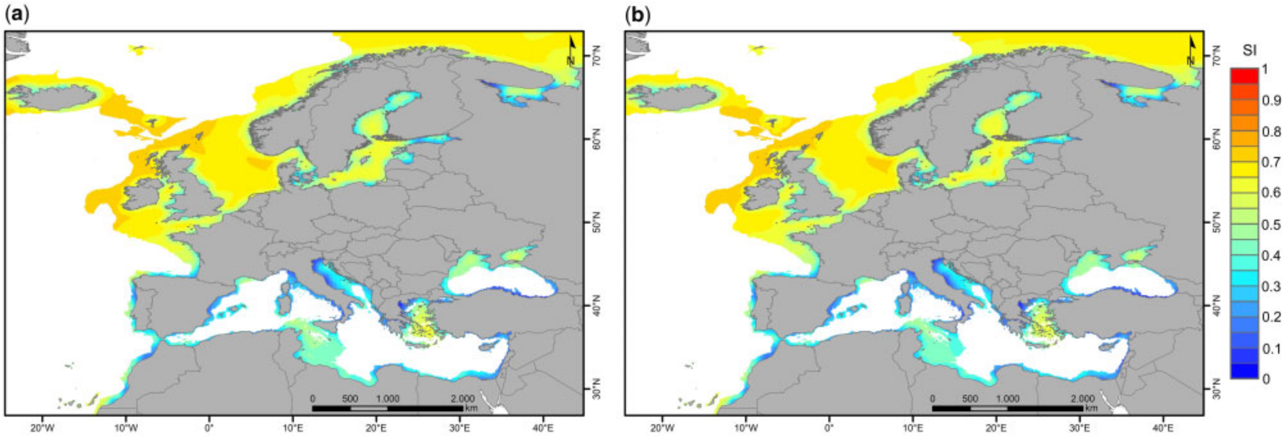

Figure 3. SI for the available wind potential in the (**a**) present climate (1979–2015) and (**b**) future climate scenarios (2070–2099). SI range (1 = maximum suitability, 0 = minimum suitability).

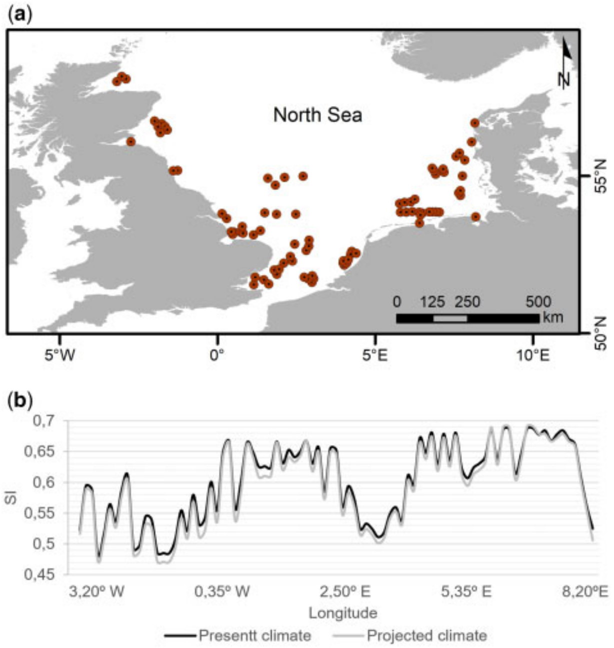

Figure 4. (**a**) Location of the wind projects in the North Sea, classified as either fully commissioned, generating power, under construction, consent authorized, consent application submitted, or early planning (4COffshore, 2018). (**b**) SI for the present climate conditions and future climate scenario in the locations of the represented wind farms according to their longitude. SI range (1 = maximum suitability, 0 = minimum suitability).

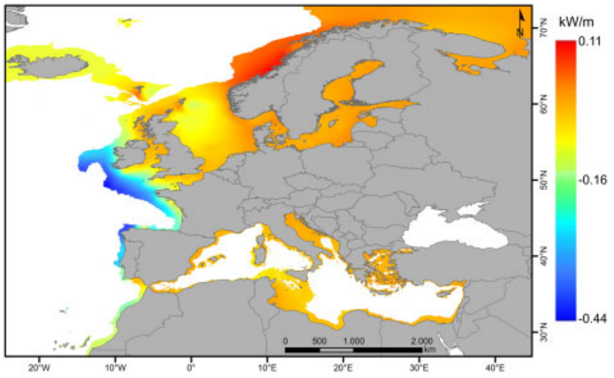

Figure 5. Projected changes in the ensemble mean of the wave energy flux (kW/m), i.e. the differences in the means between the reference period and the future simulations of the GCM data series (*c.f.* Figure 1).

the Canary Islands, also present favourable conditions regarding wind potential (Kalogeri *et al.*, 2017).

The differences between the SI of the present (Figure 3a) and future (Figure 3b) climate scenarios are not relevant enough to affect the availability of a good resource (potential $\geq$400 W/m^2). Therefore, potential zones for wind exploitation tend to maintain favourable conditions, allowing the long-term expansion of this sector.

As an example, Figure 4a shows the location of the offshore wind projects in the North Sea (4COffshore, 2018). The wind farm location sites, whether in the operation, installation, or planning stage, remained under favourable conditions for both scenarios >40% of the time (0.4 of SI, Figure 4b). There is only a slight decrease in the SI$_{\text{Wind}}$ in some locations for the projected scenario, but this decrease does not pose a threat to the future of the North Sea wind sector.

Wave energy

Long-term changes in wave energy flux are noticed for the end of the 21st century (2070–2099, Figure 5). In general, a decrease in wave potential is expected in most of the study area, mainly towards the west (decrease of ∼0.45 kW/m). Wave simulations projected lower waves in the North Atlantic sub-basin than in other areas. These projections are consistent with the results of Hemer *et al.* (2013), Semedo *et al.* (2012), Wang *et al.* (2014), and Casas-Prat *et al.* (2018), who observed a decrease in significant wave height (*Hs*) and wave periods in that region. In comparison to the other areas studies, the Mediterranean Sea, the North Sea and the Baltic Sea showed a higher stability or a moderate decrease in this energy resource. Consistent with the work of Morim *et al.* (2018), a decrease in the North Atlantic and the Mediterranean Sea occurred, although no substantial increase in wave power is observed in the Baltic Sea. The only zone with increased wave energy flux is the Norwegian Sea, in accordance with the results

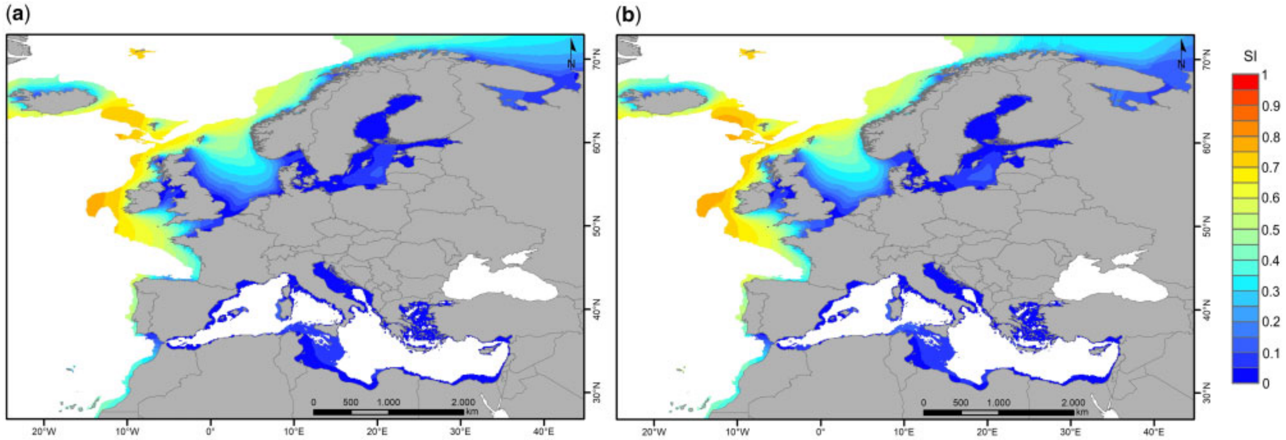

Figure 6. SI for the available wave energy flux in the (**a**) present climate (1979–2015) and (**b**) future climate scenario (2070–2099). SI range (1 = maximum suitability, 0 = minimum suitability).

from the climatological projections for *Hs* determined by Semedo *et al.* (2012), Liu *et al.* (2016), and Casas-Prat *et al.* (2018). Since the selection of the GCMs is based on the models and skills recommended by Perez *et al.* (2014, 2015) for wave climate, the changes in energy flux are similar to those found by these authors. However, changes in greater magnitudes are observed that are mainly negative changes in the North Atlantic sub-basin. The Black Sea is not considered for the energy flux calculations due to the lack of available data to calculate long-term projections.

Wave energy flux shows areas with higher energy potential in the North Atlantic, near Ireland, the United Kingdom, Faroe Islands, and Iceland than in other areas (see Supplementary material for present and projected wave energy flux). The energy flux in the North Atlantic region is ~80 kW/m, as determined by Reguero *et al.* (2011). The energy potential calculated for the present climate follows the same distribution and have similar values as those in previous studies (Kalogeri *et al.*, 2017; Weiss *et al.*, 2018c), which is consistent with the conclusions of Reguero *et al.* (2015). As the changes in wave energy flux are not pronounced (Figure 5), the SIs for the present (Figure 6a) and future (Figure 6b) climate scenarios differed negligibly. Considering the time in which it took the resource to reach values above 15 kW/m, long-term changes in met-ocean conditions should not directly influence energy extraction projects. As with the wind resource scenarios (*c.f.* Figure 3a and b), the availability of energy-efficient resources remained stable, with minor changes at specific points. Therefore, there are opportunities for long-term investments in the wave energy sector in the identified potential zones since there are currently no operational wave farms.

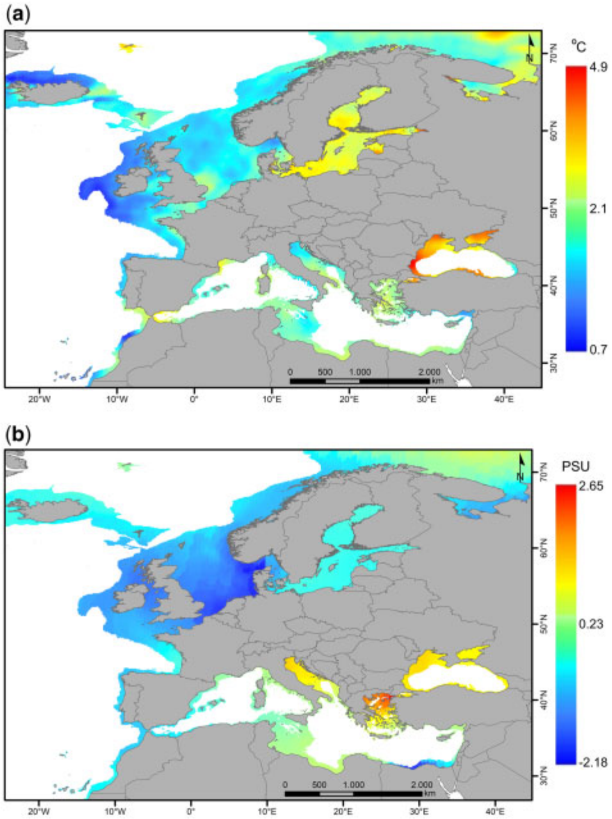

Figure 7. Projected changes in the ensemble mean of the (**a**) water temperature (°C) and (b) salinity (PSU), i.e. the differences in the means between the reference period and the future simulations of the GCM data series (*c.f.* Figure 1).

Aquaculture

In contrast to projections for marine energy resources, water temperature and salinity indicate changes in greater magnitudes, reaching a difference of ~5°C (Figure 7a) and 2.7 PSU (Figure 7b), respectively. The long-term temperature projection showed increases in all European regional seas, coinciding with the findings of De la Hoz et al. (2018). The spatial distribution of these increases followed the same pattern as that found by these authors. The rates of the projected changes in temperature are similar to those found by Tinker *et al.* (2016) and Hand *et al.* (2019) in the North Atlantic sub-basin, with a substantial long-term increase of ~1.3°C. The long-term projections of Meier (2006) in the Baltic Sea also showed an increase in sea surface temperature. In the Mediterranean Sea, the detected changes varied between 1 and 3°C, equal to those found for the same long-term period by Mariotti *et al.* (2015). Larger changes are identified in the Black Sea, with increases over 4°C (Sakali and Başusta, 2018).

Changes in sea surface salinity for the future climate scenario showed both increases and decreases in the study area (Figure 7b). The different estimated spatial change patterns in salinity compared to those in temperature are due to adjective processes and local freshwater inputs (Tinker *et al.*, 2016). The salinity projection is validated with OCLE (Observatory of Climate change effects on Littoral Ecosystems) data (http://ocle.ihcantabria.com/, De la Hoz et al., 2018), which showed the same climate change spatial patterns. The increases found in this study are, however, higher than those observed in the OCLE project. A decrease in salinity is predicted mainly for the North Atlantic sub-basin, concentrated in the North Sea, and with differences of up to -2.18 PSU. Tinker *et al.* (2016) also observed a decrease in this region, although with declines in ∼0.41 PSU. The Baltic Sea also shows a salinity decrease in relation to the present climate conditions, as documented by Meier (2006). Conversely, increases (of up to 2.5 PSU in the Aegean Sea) are observed in most of the Mediterranean Sea, although particular areas showed decreases (approximately −1.8 PSU on the Egyptian coast and −0.7 to the extreme west of the Mediterranean Sea). Projections for the Black Sea identified increases of ∼1 PSU.

The effects of climate change on marine environmental conditions are evident (Hand *et al.*, 2019), with direct and indirect impacts on aquaculture (Barange and Cochrane, 2018) and seafood quality (Barbosa *et al.*, 2017) and implications for the growth rate of farmed species (Sarà *et al.*, 2018). In this context, changes in environmental conditions suitable for open-sea fish farming tend to drive the long-term spatiotemporal evolution of this industry. In the study area, changes in these conditions are mainly associated with the increase in suitable areas for aquaculture, providing long-term opportunities for this sector. Evidence indicating long-term threats to the current potential farming areas has been identified for small areas in the central west and east of the United Kingdom and eastern Ireland for Atlantic salmon farming (Figure 8c).

Due to the similarity in temperature and salinity thresholds (euryhaline and eurythermal species), Gilthead seabream, Atlantic Bluefin tuna, Meagre, and European seabass show a similar distribution of suitable zones (Figure 8a and b). The areas with the greatest SIs for these species are concentrated mainly in the Mediterranean Sea and along the North Atlantic coast of Morocco and the Canary Islands. However, there is a considerable increase in the SI for the RCP 8.5 scenario at the end of the century over the Moroccan coast and the southern part of Spain and Portugal. Smaller increases occurred in the southern Mediterranean and the Aegean Sea between Greece and Turkey (main producers of Atlantic Bluefin tuna, Gilthead seabream and Meagre, FAO, 2017), mainly due to changes in temperature (Figure 8a and b).

With increasing water temperatures, suitable zones for farming Atlantic salmon will be redistributed to higher latitudes, as evidenced on the Norwegian coast (Figure 8c). However, salinity projections demarcated higher SIs along the North Atlantic sub-basin latitudes. The spatial redistribution of favourable conditions for Atlantic salmon farming demonstrated both the resilience of the current industry (production of Atlantic salmon in Norway and the United Kingdom, FAO, 2017) and new market opportunities. No suitable zones are identified for farming Greater amberjack under the present climate conditions, mainly due to temperature and salinity thresholds to the north and south of the study area, respectively (Figure 8d). The SI for the projected climate scenario increased along the coast of Morocco, southern Spain, the Canary Islands, and the Bay of Biscay, for this species (Figure 8d).

The identified climate change effects will require adaptation by the aquaculture sector, mainly regarding exploitation areas. While long-term changes are apparently positive (i.e. enabling farming of certain species in other regions), the long-term development of this sector requires preventive management and planning. In this context, assuming that climate change will have a direct impact on wild fish resources (Frost *et al.*, 2012; Barbosa *et al.*, 2017), the aquaculture sector can contribute to food security throughout this century since it can adapt to changes in the environmental conditions suitable for fish farming.

As an example, the SI means of the present and future scenarios for Meagre, Gilthead seabream and Atlantic Bluefin tuna are presented in the Major Fishing Areas of the Mediterranean Sea (Figure 9a and b; FAO, 2018a). The largest increases in SI have been predicted for Divisions 1.1 and 1.2, indicating opportunities for the long-term expansion of Meagre and Gilthead seabream farming in France (production of 600 and 700 tonnes in 2016, respectively) and Meagre, Gilthead seabream, and Atlantic Bluefin tuna farming in Spain (production of 1661, 10 128, and 910 tonnes in 2016, respectively) (FAO, 2018b). Opportunities for new markets have been identified in Algeria and Morocco for the three species and in France for Atlantic Bluefin tuna (FAO, 2018b). Increases in SI have also been observed in Divisions 2.2, 3.1, and 3.2. The main production zone of these three species (FAO, 2017), Division 3.2, indicates a continuity of favourable conditions, thus favouring the long-term expansion of this industry. The zones in Divisions 1.3 and 2.1 will maintain present environmental conditions, with SIs for both scenarios being similar (with a 0.01 and 0.004 difference, respectively). Therefore, the continuity of aquaculture activities for these species does not seem to be threatened by the predicted increase in ocean temperature and changes in salinity.

Co-location

The increasing and often conflicting uses of marine resources have driven the search for technological solutions to the co-location of different activities. Thus, and due to the massive development trend towards the open ocean, multipurpose and hybrid platforms can be an alternative for the sustainable development of marine economies (Christensen *et al.*, 2015). Multipurpose concepts combining aquaculture with wind energy were proposed by Buck *et al.* (2017). Hybrid platforms were developed for the combined exploitation of offshore wind and wave energy, such as the W2Power hybrid system (Pelagic Power, 2010). Different approaches to combine energy exploitation, aquaculture, and related maritime transport have been analysed by the FP7-funded TROPOS project (Shiau-Yun et al., 2014).

The co-location of these activities has significant potential in economizing CAPEX (capital expenditure) and operational costs by means of concerted long-term spatial planning and infrastructure sharing (Abhinav *et al.*, 2020). Moreover, the process of planning and building offshore farms and platforms takes a long time and has a long-projected lifespan, thus requiring essential climate change information.

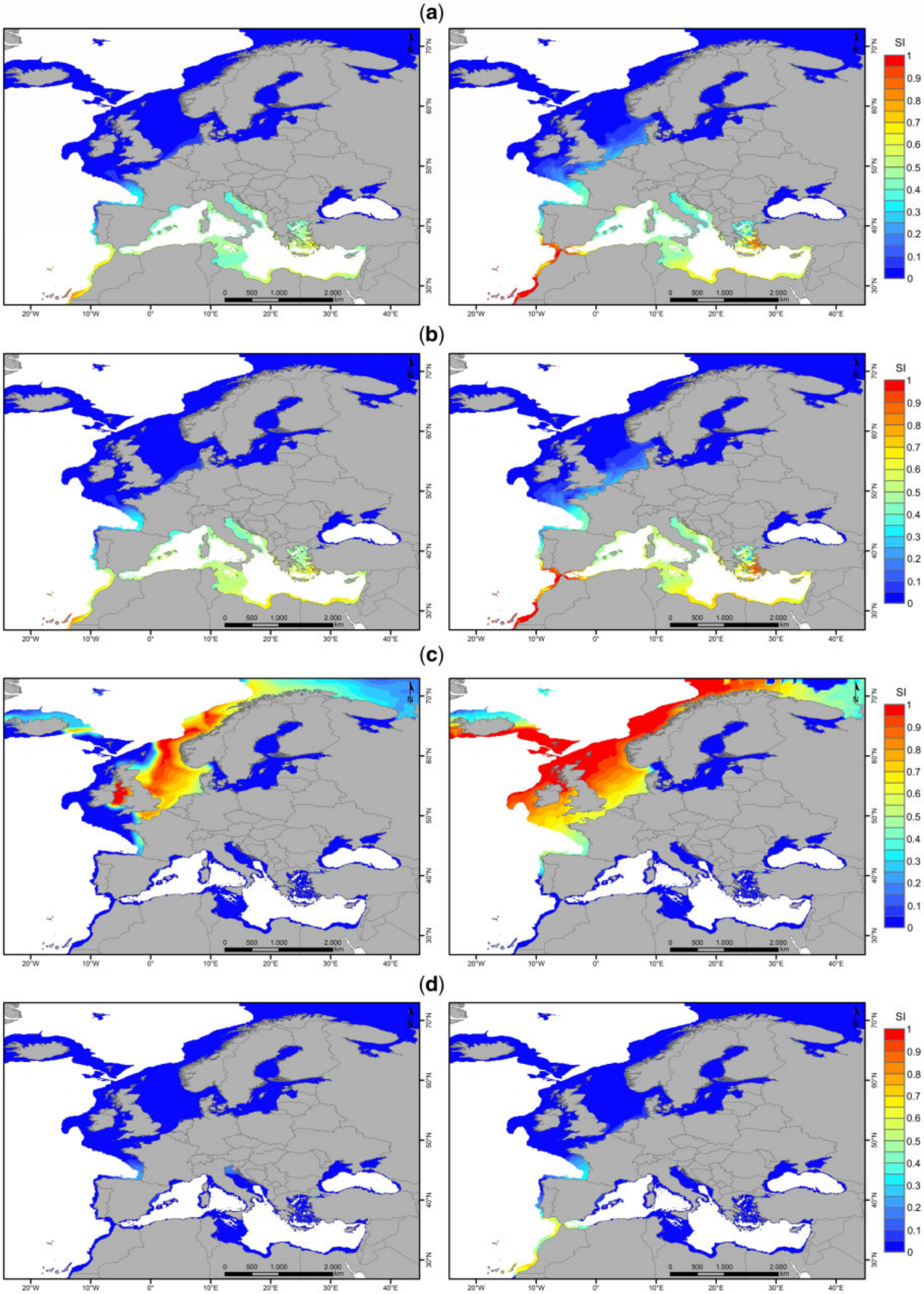

Figure 8. SI for (**a**) Meagre, Gilthead seabream, and Atlantic Bluefin tuna; (**b**) European seabass; (**c**) Atlantic salmon; and (**d**) Greater amberjack under present (left column) and future (right column) climate conditions. SI range (1 = maximum suitability, 0 = minimum suitability).

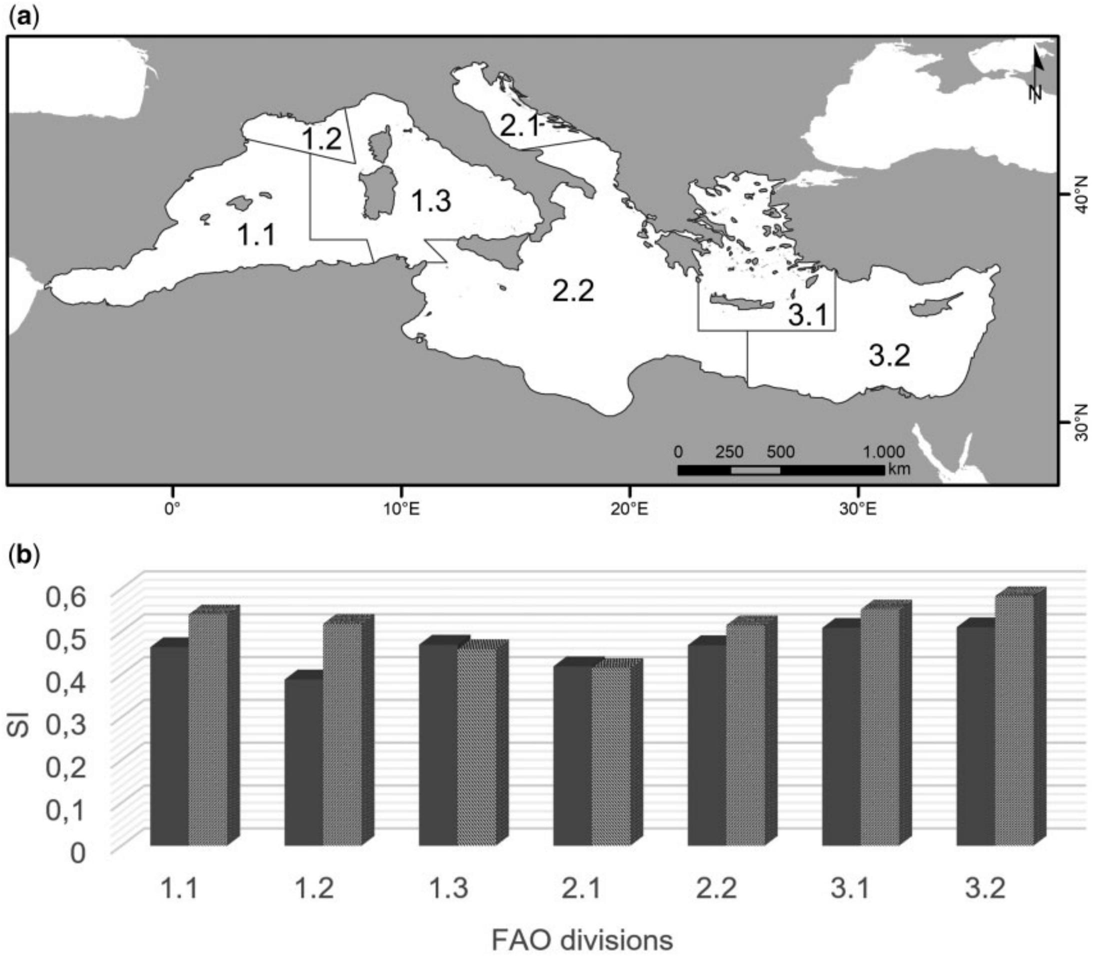

Figure 9. (**a**) Mediterranean Sea FAO Major Fishing Area with its respective divisions (FAO, 2018a). (**b**) SI means for the present climate conditions and future climate change scenario in each division as proposed by the FAO. SI range (1 = maximum suitability, 0 = minimum suitability).

In this contribution, long-term climate changes show opportunities for the co-location of energy activities and aquaculture of some fish species assessed in this study. Different combinations of activities are shown in Figure 10; moreover, all possibilities for co-location are in the Supplementary material. The possibilities for co-location of wind and wave energy exploitation devices are similar under both scenarios (Figure 10a). The potential zones for the combined exploitation of these resources are concentrated in the Norwegian and North seas, on the coast of Ireland and the United Kingdom, and between Iceland and the Faroe Islands.

Since available energy resources remain stable (*c.f.* Figures 3 and 6), the main factor driving the long-term possibilities of co-location of energy and aquaculture activities is the increase in the SI for fish species. This is the case for the combination of wind energy, wave energy, and Atlantic salmon (Figure 10b). The opportunities for co-location of these activities are related to the increase in areas with favourable conditions in the future scenario. The main areas with increased SI are between Iceland and the United Kingdom and on the Irish coast. Zones with the potential for co-location between wind energy and aquaculture are documented in the study area, as is the case for Greater amberjack farming (Figure 10c). Due to the increase in the Greater Amberjack's SI for the projected climate scenario (*c.f.* Figure 8d), possibilities of combined exploitation with wind energy are identified in the Canary Islands, on the Atlantic and Mediterranean coasts of Morocco, in southern and northern Spain, and in southern Portugal and western France. Opportunities for the co-location of wave energy and Meagre, Gilthead seabream, and Atlantic Bluefin tuna farming increased in the future scenario (Figure 10d). Higher values of SI are found on the Portuguese coast and in the Gulf of Biscay.

Conclusion

A regional downscaling of the atmospheric conditions for multivariate wind-wave climate and environmental conditions is developed and applied over the European regional seas. The methodological approach used is based on the delta change method to simulate future met-ocean and environmental conditions based on the continuity of the current level of CO_2 emissions (i.e. RCP 8.5). The application of this method allows improving the spatial and temporal resolution of the GCM outputs, generating a projected time series between the years 2070 and 2099 that enabled SI calculations for the different activities in future scenarios with a higher robustness. Climate projections using the very high baseline emission scenario (RCP 8.5) indicate that the energy potential for both wind and wave energy will not

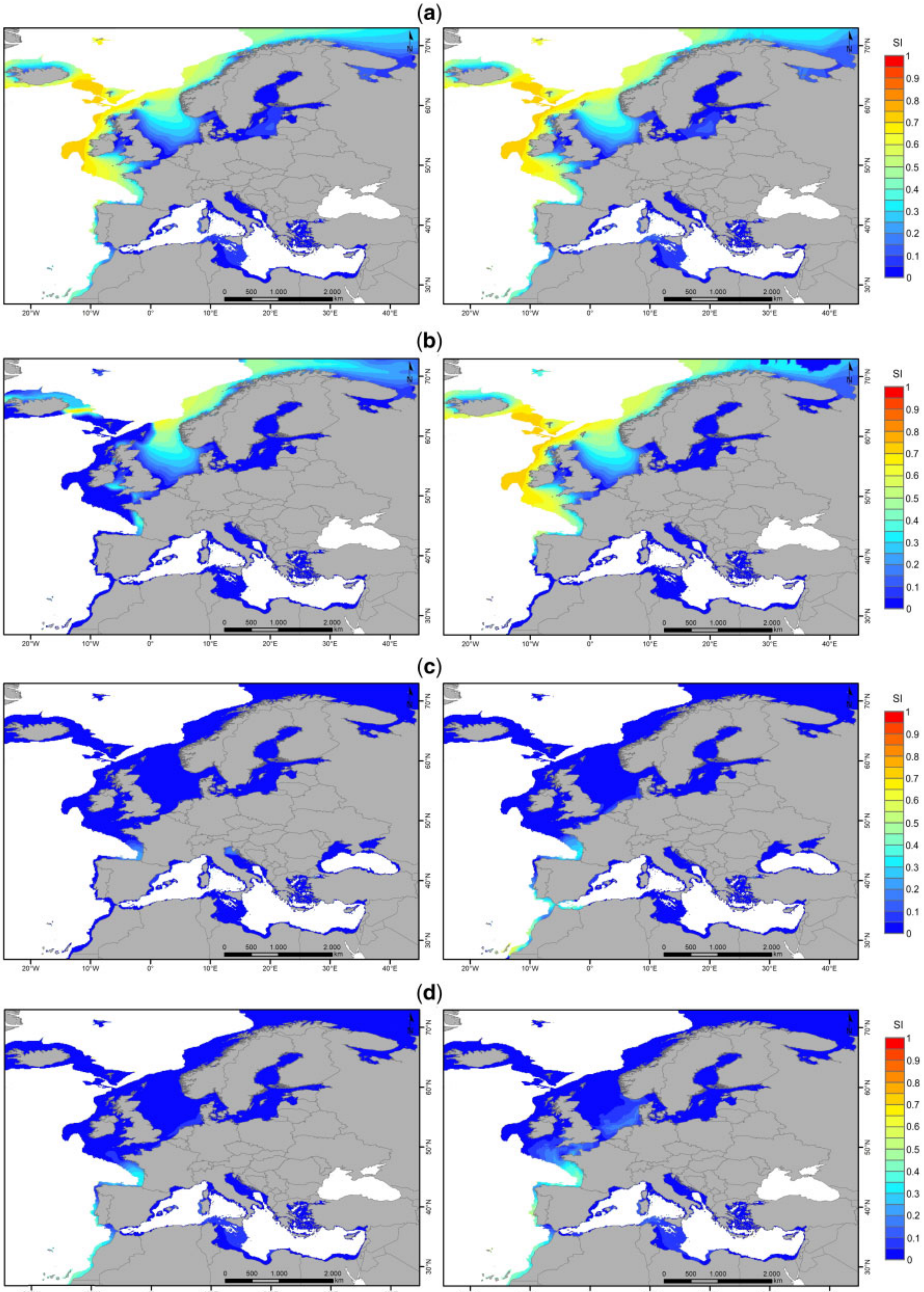

Figure 10. SI for the co-location of activities, considering the combination of (**a**) available wind potential, available wave energy flux and Atlantic salmon; (**b**) available wind potential and available wave energy flux; (**c**) available wind potential and Greater amberjack; and (**d**) available wave energy flux and Meagre, Gilthead seabream, and Atlantic Bluefin tuna, under present (left column) and future (right column) climate conditions. SI range (1 = maximum suitability, 0 = minimum suitability).

be negatively impacted by climate change. In fact, both resources showed a relative stability between historical and projected climate situations. In the case of environmental conditions for open-sea fish farming, a considerable long-term change is predicted. The increase in temperature (Figure 7a) and differences in salinity (Figure 7b) will require an adaptation of the aquaculture sector regarding the geographical location of the farms. In any case, management responses should be implemented in advance to reduce the impacts of unfavourable conditions and maximize opportunities in areas suitable for aquaculture. Opportunities for co-location of these activities increase in the future scenario, such as the combination of wind energy, wave energy, and Atlantic salmon farming (Figure 10b). Projections to assess the effects of climate change on emerging marine economies assist in strategic management and long-term planning of the marine space, i.e. the MSP process. In this sense, a holistic view of spatial displacement trends in the energy and aquaculture industries, within a Blue Growth perspective, highlights opportunities and threats for these sectors. It also identifies potential pressures from these activities in areas that are not yet prepared for such development (e.g. the expansion of the aquaculture industry for European seabass farming along the Morocco coast). Moreover, a strategic vision is important to ensure the sustainable development of these sectors from a perspective of coexistence (e.g. multi-use offshore platforms), thus optimizing the use of space and reducing impacts on the marine environment. Therefore, the assessment of potential zones for the exploitation of marine renewable energy resources and fish farming represents a useful stepping-stone for improving decision-making and confirming the long-term resilience of such activities in the study area, both for individual and co-location exploitation.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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