Energy Conversion and Management 301 (2024) 118058

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Evolution of the European offshore renewable energy resource under multiple climate change scenarios and forecasting horizons via CMIP6

Egor Barkanov [a], Markel Penalba [a,b,*], Abel Martinez [c], Ander Martinez-Perurena [a], Ander Zarketa-Astigarraga [a], Gregorio Iglesias [c,d]

[a] Fluid Mechanics Department, Mondragon University, Loramendi 4, 20500 Arrasate, Spain
[b] Ikerbasque, Basque Foundation for Science, Euskadi Plaza 5, Bilbao, Spain
[c] MaREI, Environmental Research Institute & School of Engineering, University College Cork, College Road, Cork, Ireland
[d] University of Plymouth, School of Engineering, Computing & Mathematics, Marine Building, Plymouth, UK

A R T I C L E I N F O

Keywords:
Offshore renewable energy resource
Climate change
Shared socioeconomic pathways
CMIP6
Global and local scales
Statistical analysis

A B S T R A C T

The design of the different offshore renewable energy (ORE) technologies depends on the characteristics of wind/wave resources. However, these characteristics are not stationary under climate change. In this study the evolution of European offshore wave/wind resources is assessed under mid- and high-emissions scenarios based on the Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) and three forecasting horizons including the near (2023–2032), mid (2041–2050) and long term (2091–2100). The novelties lie in: (i) the concurrent analysis of wind and wave resources, (ii) the use of data with a 3-hour temporal resolution, and (iii) the local-scale statistical analysis. Results show significant variations along the 21st century, with an overall decline in average wind and wave conditions. Importantly, and somewhat counter-intuitively, much of the Atlantic coast of continental Europe experiences increasing extremes in the high-emissions scenario. For the local-scale statistical analysis, the focus is on five wind farm sites, commissioned or in planning. In the high-emissions scenario, the 99th and 99.99th percentiles decrease in three of them and increase in the other two. The combination of decreasing averages and increasing extremes presents the worst-case scenario for ORE technology developers.

1. Introduction

Climate change is the greatest challenge of the 21st century. Far from being a future problem, climate change is already affecting life in every region on Earth: from the rise in global temperatures (including both atmosphere and ocean temperature) to shifting weather patterns, rising sea levels and intensifying natural disasters like heatwaves, floods and draughts, the potential impacts of climate change are “global in scope and unprecedented in scale” [1]. The energy sector is responsible for 75% of the total CO_2 emissions in the world and is therefore one of the main drivers of climate change [2]. It follows that renewable energy is a key element for the mitigation of climate change [3].

Besides the dramatic consequences of climate change (*i.e.*, higher temperatures, more severe storms, increased droughts, warmer and rising oceans, loss of species, higher health risks, threats to food production, poverty and displacement, etc.), modifications to weather patterns may be expected to affect renewable energy resources, including wind [4–7], wave [8,9] and solar [10,11]. As a consequence, the relationship between climate change and renewable energy is, paradoxically, bi-directional: Renewable energy sources are necessary to mitigate the impact of climate change but, in turn, variations due to climate change may be expected to directly affect the performance and survivability of renewable energy systems [4,12]. This may pose a significant problem not only for the new designs, but also for the renewable energy projects already installed or deployed.

For the reduction of greenhouse gas (GHG) emissions, the implementation of renewable energies is considered to be one of the most efficient actions [13]. While mature and reliable renewable energy technologies like wind and solar power are already prevalent in the market, the scale and rapidity of the required transition suggest a substantial role for emerging renewable technologies. According to the International Renewable Energy Agency (IRENA), an increase of 14 TW in global renewable energy capacity will be necessary by 2050, necessitating a five-fold expansion of the current capacity. This clearly underscores the enormity of the challenge [14]. In fact, the International Energy Agency anticipates that approximately 45% of the reduction in CO_2 emissions by 2050 will originate from technologies

* Corresponding author at: Fluid Mechanics Department, Mondragon University, Loramendi 4, 20500 Arrasate, Spain.
E-mail address: mpenalba@mondragon.edu (M. Penalba).

https://doi.org/10.1016/j.enconman.2023.118058
Received 5 October 2023; Received in revised form 20 December 2023; Accepted 30 December 2023
Available online 5 January 2024

still in development [15]. Offshore renewable energy (ORE) systems are promising options to facilitate this transition. Offshore wind energy is expected to increase global installed capacity thirty-fold over the next three decades [14]. Similarly, wave and tidal energy, while currently in the early stages of development, are also anticipated to make substantial contributions to the future energy landscape. Estimates suggest that they have the potential to fulfil approximately 10% of the future electricity demand [16,17]. Hence, onshore and offshore wind and other marine renewable energy technologies are and will be crucial to ensure the necessary GHG emissions reduction.

In terms of renewable energy implementation, western Europe is expected to lead the global renewable energy growth together with China, representing over 50% of the worldwide installed capacity by 2030 [18]. Europe is committed to leading the development of wind and ORE, with ambitious objectives, such as 400 GW of wind capacity by 2030 (of which over 25% offshore) [19]. Therefore, the accurate understanding of the European wave and wind energy resources under climate change, both onshore and offshore, is crucial in order to ensure the efficient performance and survivability of the technologies installed now and in the next decades.

In order to assess the impact of climate change on the different design and operational aspects related to the different renewable energy technologies, the variation of the resource needs to be analysed under different climate change scenarios. To that end the Intergovernmental Panel on Climate Change (IPCC) provides cutting edge tools, data and recommendations to support the actions against climate change. Global climate models (GCMs) are one of these tools, combining the effort of different professional climate centres all over the globe, which enable researchers and organisations to assess simulations of the possible future of the global climate.

The first scenarios utilised to evaluate future changes in wind resources were the SRES scenarios of cumulative GHG emissions [20], introduced by the International Panel on Climate Change within its third assessment report [21]. These scenarios were applied to anticipate long-term changes in wind speeds using different GCMs and downscaling methods in specific areas of Europe [22–29].

In more recent studies, the evolution of wind resources has been examined within the context of the Representative Concentration Pathways (RCPs) [30], which indicate concentration levels of GHG leading to a specific radiative forcing. Different GCMs and downscaling initiatives in the framework of the fifth Coupled Model Intercomparison Project (CMIP5) were employed to evaluate changes in future wind resources [31–36].

The sixth Coupled Model Intercomparison Project (CMIP6) [37] is the latest phase of their work, which has produced state-of-the-art climate models that simulate past, present and future climate conditions under the new prism of Shared Socioeconomic Pathways (SSPs). These models incorporate a comprehensive range of physical, chemical, and biological processes to project the response of the Earth system to anthropogenic greenhouse gas emissions.

The CMIP6 models have recently been used for forecasting future wind and wave conditions under climate change in different areas of the world. For example, the CMIP6 GCMs are employed to forecast future scenarios of the European wind resource [38–43]. Martinez et al. [38] evaluate the evolution of the resource over Europe using an ensemble model based on the CMIP6 GCMs. Among all the GCMs, the EC-Earth model is demonstrated to be the most accurate compared to the historical ERA5 database. This study is one of the pioneering studies evaluating the evolution of the wind resource using SSP scenarios. In this case, two SSPs are considered, *i.e.* the intermediate SSP2-4.5 and the extreme SSP5-8.5 scenarios, analysing the variability of the resource along the different months. However, the dataset considers a relatively large temporal resolution, *i.e.* daily data, which can significantly mask the variability of the resource and the analysis of the conditions beyond the operational region. In fact, the analysis is restricted to average values ignoring broader statistical analyses and neglecting, for example, the evolution of the extreme events. Similar analyses are conducted by other authors restricting the area of study to smaller regions, such as the North Sea [42], the UK [41], Portugal [44], and even other regions in Asia [45–47,7] and North America [6]. Among all similar studies in the literature, to the best knowledge of the authors, only [41] considers a statistical analysis studying the evolution of the frequency of the different wind conditions. However, this study only includes one forecasting horizon (2015–2050) and the temporal resolution is not specified.

In addition to wind conditions, a few studies consider the evolution of the wave energy resource. Initially, studies focused on the identification of long-term trends based on historical data, demonstrating a relevant increase in wave power worldwide [8]. Other studies analysed local trends in the Gulf of Biscay [48], west Irish coast [49] or South America [50]. Climate change induced ocean warming is suggested to provoke such increases, which is especially demonstrated in [8]. However, it is only more recent studies that focus on the evolution of the future wave resource under different emission scenarios and SSP. Rusu et al. [51] employ a wave modelling system forced with wind fields provided by a regional climate model (RCM), focusing on the mid-term future wave power resource (2021–2050) under two emission scenarios in the Black Sea. Goharnejad et al. [52] study the wave energy potential in the Persian Gulf region, along the southern coasts of Iran. First, historical data is analysed over a timeframe of 30 years, identifying an increasing trend. In contrast, the forecasts for both scenarios contemplated in the paper, *i.e.* high- (RCP8.5) and mid-emission (RCP4.5), reveal descending trends, being slightly milder for RCP4.5. Similarly, [53] investigates the long-term variation of the wave energy resource in the northern part of the Gulf of Oman, analysing the impact of climate change under high-emissions scenario SSP5-8.5 where no mitigation action is considered. A most recent study [54] analyses the future wave energy potential in the Iberian Peninsula, also under the high-emissions SSP5-8.5 scenario, for two forecasting horizons: mid-term (2026–2045) and long-term (2081–2100). Also in this study, a decrease in the wave power resource is observed, with a strong decrease in the mid-term horizon until 2045 that weakens in the long-term horizon until 2100. It should be noted that, to the best knowledge of the authors, all the wave energy forecasting analyses in the previously mentioned studies and other studies in the literature use wind forcing from the CMIP5 as input. It is only in [55] where forcings based on CMIP6 models are used for wave energy forecasting under the effects of climate change. Ibarra-Barasategui et al. [55] presents the most recent forecasting analysis, evaluating wind and wave projections and their impact on energy generation across the whole globe using a single horizon until 2100 and two SSP scenarios. However, monthly means are used, meaning that no statistical analysis, *e.g.* a resource variability study, is considered.

The present study provides simultaneous forecasts of both wind and wave resources analysed independently. In total, two SSP scenarios and three forecasting horizons are evaluated with a 3-hour temporal resolution. Due to the limitations with the data, all SSP scenarios are applied to the wind resource, while only the high-emission SSP5-8.5 is considered for the wave resource. Notably, none of the previous studies in the literature analyses both wind and wave resources and, thus, the present study introduces a novel contribution that is critical for the offshore energy sector, particularly, but not exclusively, for the floating offshore wind sector. In addition, most of the studies only consider one or two forecasting horizons and use a daily temporal resolution. In this sense, the present study represents another novel contribution. The use of three forecasting horizons with a 3-hour temporal resolution enables a deeper statistical analysis of the wave and wind resources than what is available in the literature so far. Furthermore, the global-scale analysis covering the whole of northwestern Europe is complemented by a local-scale analysis for a set of relevant locations with different resource characteristics. Such a local analysis is also an innovation of the present study and allows for extending the statistical investigation that provides a deeper insight into the potential evolution of the resource, including average and extreme conditions. This insight will be particularly relevant for the design of ORE technologies, since occurrence variations of the different conditions may have a relevant impact on critical design aspects like fatigue mechanisms, energy generation or operation and maintenance decisions. Similarly, variations of the extreme conditions can also have a significant impact on the design points that determine the final dimensioning of the platform [56,57]. However, the analysis of the impact of resource variations due to climate change on the most relevant design parameters is out of the scope of the present study.

The remainder of the paper is as follows: Section 2 describes the methodology and presents the case study, including the area of study and the employed GCM, Section 3 shows the main results and a brief discussion on them, and, finally, the main conclusions are drawn in Section 4.

2. Methodology

In the present study, the evolution of the wave and wind energy resources is assessed across the northwestern Europe, with the following specific geographic limits: (25°N, 60°N) for latitude and (25°W, 12°E) longitude. First, the historical wind and wave characteristics across the area of study are assessed using the widely accepted ERA5 re-analysis dataset [59] for the commonly used reference period 2005–2014. In contrast, two different datasets, both framed within the CMIP6 activities, are used for the future projections under the impact of climate change. In the case of the wind energy resource, wind speed data are provided by the EC-EARTH3 GCM [60,61]. The EC-EARTH3 model is demonstrated to provide the best results for the selected area, with over 65% of the gridpoints being statistically similar to the ERA5 reanalysis [38]. This statistical similarity is evaluated by performing a two-sample Kolmogorov–Smirnov test with a significant level of 5%. A similar conclusion is reached in [39] for the same region, where the EC-Earth shows the highest overall performance (over 80%) and the lowest average median difference across all Europe (0.3 m/s).

In the case of the wave resource, the wave climate datasets are provided by researchers at University of Melbourne using the WAVEWATCH III wave model based upon CMIP6 data [62]. The authors present two wave climate datasets derived from two CMIP6 GCMs: The Australian ACCESS-CM2 [63] and the European EC-Earth3 [61] GCMs. In addition, the models are run with the latest observation-based Source Term parametrisation (ST6), using two different values of the wind-drag coefficient parameter (CDFAC): 1 and 1.08. For the present study, the dataset derived from the EC-Earth3 GCM via a CD-FAC parameter of 1.0 is used, as suggested in [62]. Although the evolution of the wind and wave resources is assessed, including the potential similarities between the two, combined effects are not considered, since each resource is analysed independently.

For comprehensively evaluating the evolution of the resource, both for wind and wave resource, the study incorporates three different elements analysed by means of four factors related to the wind speed (U_w) and significant wave height (H_s), respectively. First, the evolution of the mean U_w and H_s is analysed across the area of study. The mean wind speed and wave height are directly related to the power density and, thus, the power production estimation of a potential ORE farm in the same area. The second element considered in the analysis is the variability of the resource, including the variation of U_w and H_s over the whole period illustrated by the coefficient of variance (CoV), and the intra-annual (seasonal) variability illustrated by comparing the mean U_w and H_s values in different seasons. The most common partition for the studies focused on the Northern hemisphere is the following [38,51]: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA) and September–October–November (SON). The last element incorporated into the analysis is related to the extreme conditions, which, in this case, are expressed by the U_w and H_s limit for the 99th percentile.

2.1. Global- and local-scale analysis

Moreover, the study encompasses two distinct geographic perspectives. The first is a global-scale examination, focusing on northwestern Europe as a whole. The second involves a local-scale analysis, focusing on five specific locations within this region, as illustrated in Table 1. The selection of these five locations for detailed scrutiny at the local-scale is based on offshore wind farms that are currently operational or anticipated to be in operation soon [58]. Additionally, these chosen locations are representative of key areas of interest in European waters: the lower North Atlantic Ocean (Portuguese coast), upper north Atlantic Ocean (west coast of Ireland), North Sea (north-east coast of Scotland), the Mediterranean Sea (Tyrrhenian Sea in Italy), and the Gulf of Biscay (the Basque coast). Detailed information about the wind farms' resource characteristics and current status is also compiled in Table 1. It should be noted that, due to the lack of more reliable data (*e.g.* observation data) of the selected locations, no downscaling technique is considered for the local analysis, meaning that raw CMIP6 data is used.

Table 1
Main information of the selected wind farms.
Source: Modified from [58].

Wind farm name	Country	Project phase	Latitude	Longitude	H_s [m]	U_w [m/s]
Hywind	Scotland	Fully commissioned	57.6°N	1.6°W	1.38	9.24
Tramuntana	Spain	Early planning	39.9°N	1.3°E	1.3	6.1
GEROA	Spain	Early planning	43.9°N	3.2°W	1.47	6.01
WindFloat	Portugal	Fully commissioned	42.3°N	10.4°W	2.11	7.89
Clarus	Ireland	Early planning	53°N	9.7°W	2.6	10.1

2.2. Analysed scenarios

In this study, various scenarios are assessed, encompassing SSP scenarios and different forecasting horizons. Specifically, the study focuses on two SSP scenarios, which are the ones that are mostly used in the literature [38–43]: SSP2-4.5 and SSP5-8.5. In addition, the SSP2-4.5 and SSP5-8.5 are the most relevant scenarios for policymakers and practitioners. The first digit in these scenarios represents one of the five narrative pathways, ranging from 1 (sustainable development) to 5 (fossil fuel development). In this context, “2” signifies the “Middle of the road” scenario, characterised by moderate social and economic development aligned with current trends that prioritise economic growth over sustainability. On the other hand, the digit “5” indicates a scenario of fossil fuel development, emphasising economic growth and involving heavy fossil fuel consumption, a peak in global population, and limited efforts to mitigate environmental impact. The second digit in these scenarios represents the radiative forcing levels within a specific SSP storyline, measured in watts per square meter (W/m^2) projected for the year 2100. More specifically, the SSP2-4.5 scenario considers a moderate radiative forcing level around 3.4 W/m^2 by the end of the century, while the SSP5-8.5 scenario refers to a very high radiative forcing level with up to 8.5 W/m^2.

Regarding the prediction periods, horizons have been defined so that each horizon considers a minimum period of 10 years, as indicated in [38], with short (up to 2030), mid (up to 2050) and long term (up to 2100). This distribution is defined so that mid- and long-term horizons refer to the mid- and late-21st century, as is common in the literature when more than one forecasting horizon is considered [38,45,54]: the near future (2023–2032), the middle term (2041–2050), and the distant future (2091–2100). The projections derived from these periods are then contrasted with the baseline, which encapsulates historical data from the reference period 2005–2014 across the same region. Consequently, the evolution of the wind energy resource is illustrated as a percentage deviation from the baseline values for each of the four factors described in the introduction of Section 2.

2.3. Methodology limitations

The limitations of the present study are intrinsic to the limitations of the GCMs considered in the CMIP6 [39]: a coarse spatial resolution hindering the capture of small-scale climate features accurately, and difficulties to reproduce the regional climate variability and extreme events. In addition, inherent uncertainties associated with future projections are also relevant, which may arise from various sources, such as model structure, parameterisations, and future emission scenarios. However, the datasets of the CMIP6 models are widely accepted in the community and it is considered the state-of-the-art in climate modelling, improving the previous version CMIP5 [39].

3. Results & discussion

The results are divided into two main parts, *i.e.* Sections 3.1 and 3.2, dedicated to the analysis of the isolated wind and wave resource, respectively. However, the similarities between the two resources are evident and highly relevant for the deployment of floating wind farms.

3.1. Wind forecasting

Figs. 1–6 illustrate all the evolution of the four factors for the wind resource, which are thoroughly discussed in the following subsections. Hence the evolution of the wind resource is studied by means of the mean U_w, wind variability in terms of the CoV and the inter-annual variability, and the extreme conditions. Finally, the local-scale analysis is explored, including a statistical analysis of the different locations described in Table 1.

3.1.1. Mean wind speed

The historical baseline shown in Fig. 1(a) illustrates the most energetic offshore areas, where the northwest corner region is demonstrated to be the most attractive area with mean U_w values of about 9–10 m/s

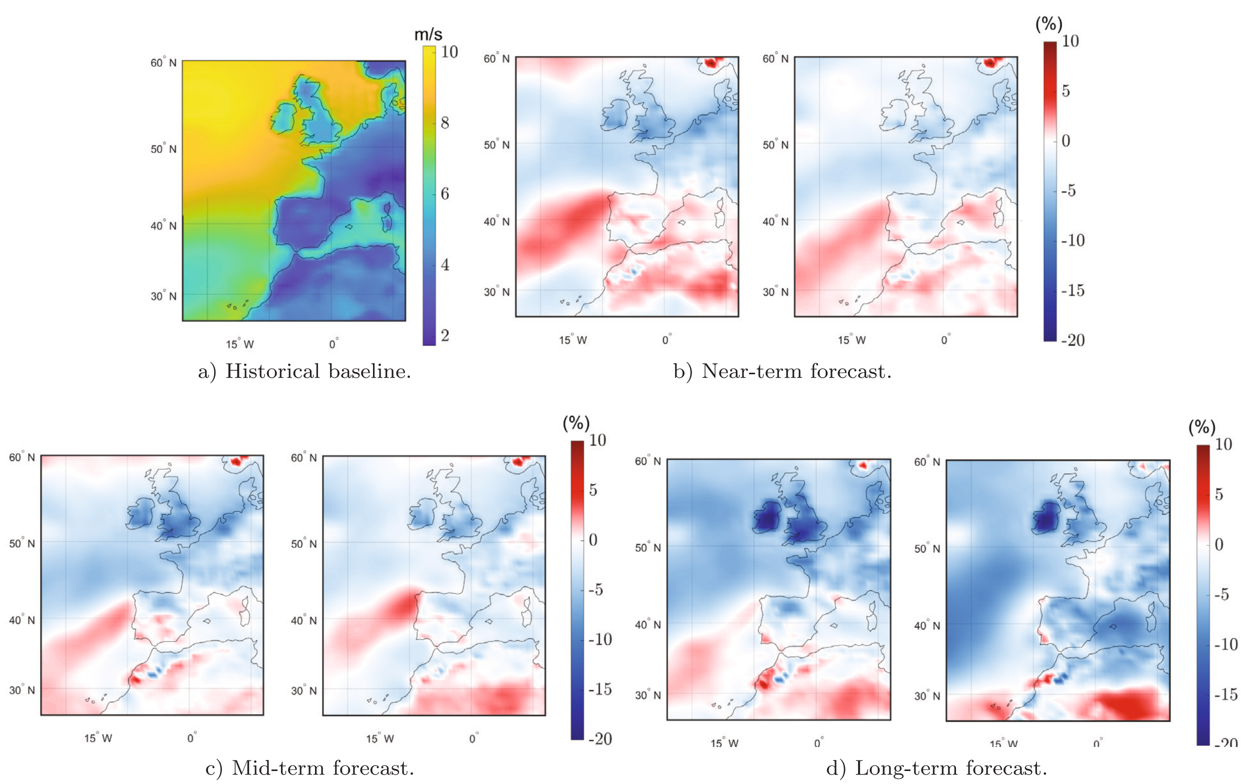


Fig. 1. Evolution of the mean U_w in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP2-4.5 (left) and SSP5-8.5 (right) scenarios.

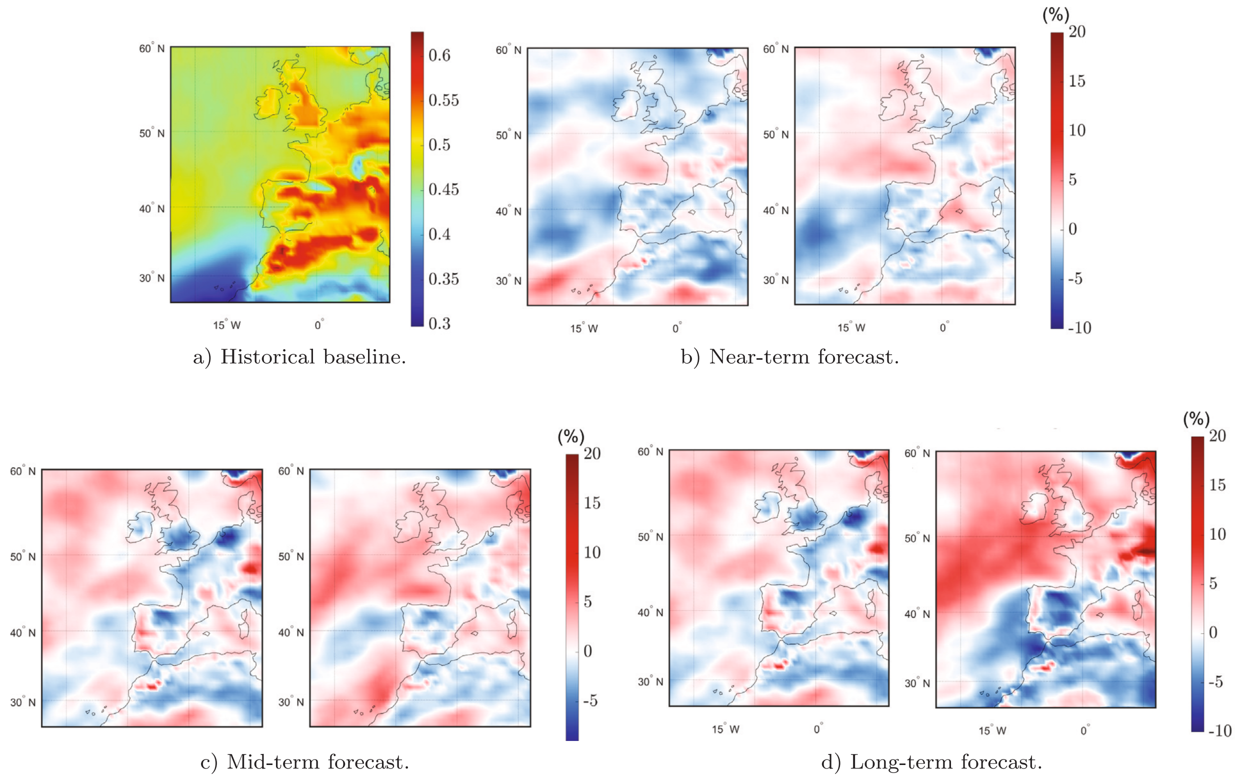


Fig. 2. Evolution of the CoV of the U_w in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP2-4.5 (left) and SSP5-8.5 (right) scenarios.

far-offshore in the north Atlantic Ocean, *i.e.* off the west coast of Ireland and northwest coast of Spain, and the North sea. In addition, coastal areas like the north and south of the Iberian Peninsula also show relatively high wind energy potential with mean U_w values of about 7 m/s, and slightly lower in the Mediterranean Sea with approximately 6 m/s.

Paradoxically, Figs. 1(b)–(d) show that the wind resource in regions with the greatest conditions (*i.e.* norther areas in Europe) is expected to gradually decrease along this century under the effect of climate change, reaching reduction rates of up to 20% in Ireland and the UK coasts. In fact, this decrease seems to be more intense in the milder SSP2-4.5 scenario, although very similar patterns can be recognised. In contrast, the wind resource in the southern areas, such as the west coast of Portugal, the south of the Iberian Peninsula and parts of the Mediterranean Sea, seems to increase significantly. However, this increase is particularly intense in the near-future projections (about 5% increase), while a milder increase is observed in the mid- and, particularly, long-term horizons. These results indicate that the wind resource will follow the increasing trend of the last decades until, approximately, the end of this decade and will start decreasing afterwards until the end of the century. This is consistent with the results shown in the literature [64]. Overall, other regions in the area of study show a relatively regular pattern with mild U_w reductions in the north of the Iberian Peninsula, reaching up to 10% decrease by the end of the century.

3.1.2. Variability

Besides the mean, the variability of the resource is a factor that considerably affects the extraction of the wind resource by means of wind turbines. The variability is crucial for the design of the turbines and the farms, and the analysis of the grid integration, among other aspects. In this sense, the temporal variability of the resource and its evolution along the century are evaluated via the CoV. In addition, the inter-annual variability is also dissected, which provides further insight on the evolution of the wind resource, since seasonal patterns of the wind resource are highly relevant.

Wind data variability. Fig. 2(a) illustrates the variability of the historical wind resource, where a relatively homogeneous CoV of about 0.45 is shown across the whole northwest Atlantic Ocean and North Sea, while this variability is increased to over 0.6 in the Bay of Biscay and the Mediterranean Sea. Connecting with the mean U_w shown in Fig. 1(a), high mean resource regions show lower CoV values and vice versa, showing that higher fluctuations are expected as the average resource decreases.

Once future projections are considered, the CoV seems to increase all over the area of study, except for the west Portuguese coast. In fact, the CoV is shown to gradually intensify the evolution along this century, with the southwestern region exhibiting a decrease of the CoV of up to 10% and the rest of the regions displaying an increase of up to 20%. In contrast to the mean U_w evolution, where both SSP scenarios show a similar distribution, the rate of change of the CoV is shown to intensify under the high-emissions scenario SSP5-8.5.

Intra-annual variability. Seasonal or inter-annual variability of the wind resource is illustrated in Figs. 3 and 4 for the SSP2-4.5 and the SSP5-8.5 scenarios, respectively. The historical baselines shown in Figs. 3(a) and 4(a) are identical and illustrate the mean U_w in each season. Hence, the well-known patterns where Summer months (JJA) are significantly milder, and Spring (MAM) and Autumn (SON) are the most energetic seasons can be observed.

The projections of the seasonal resource seem to be consistent between the two SSP scenarios, although the high-emissions scenario SSP5-8.5 shows more intense variations upon the baseline resource. While there is little overall trending and the variability appears to be non-linear, some relatively clear trends can be observed at both the global (European) and regional scales, with similarities between the two scenarios. Throughout the 21st century, there is a consistent increasing trend of the wind resource in southern areas, while the resource in northern areas decreases. This trend is evident in all seasons and is particularly pronounced in Summer (JJA), where increasing patterns are progressively displaced towards southern areas, and Autumn

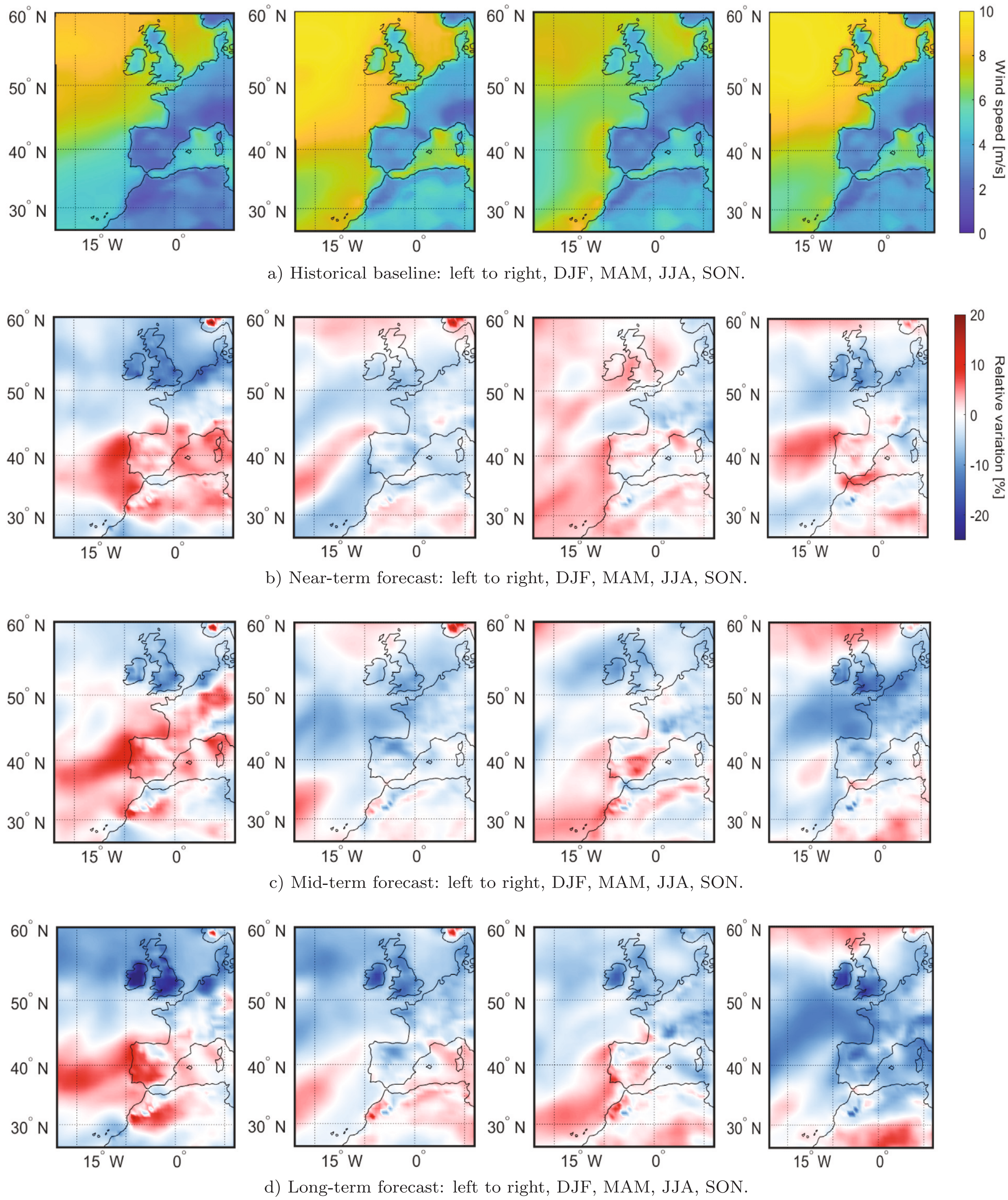
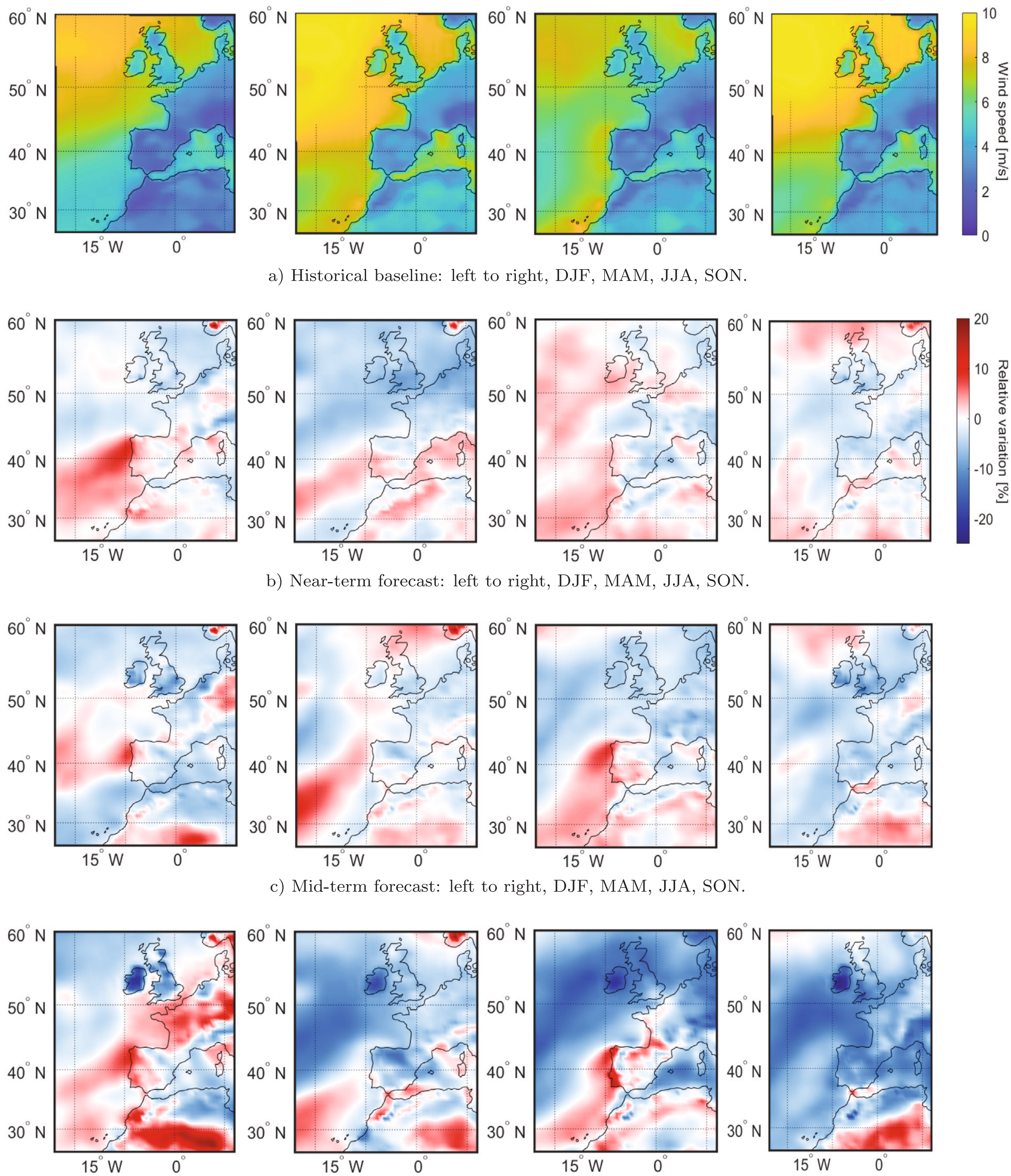


Fig. 3. Evolution of the Inter-annual mean U_w in northwest Europe under the SSP2-4.5 scenario: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts.

(SON), where the reduction of the resource dominates across all the European waters with the exception of the very southern areas. The intensity of the increasing trends is greater under the SSP5-8.5 scenario, while decreasing trends are more intense under the SSP2-4.5 scenario, where the highest decreasing rates (up to 25%) are observed.

In Winter (DJF), the trends are less recognisable, with discontinuous patterns. The increasing trend seems to expand over northern regions in the mid-term horizon under the SSP2-4.5 scenario, while under the SSP5-8.5 scenario, the decreasing trend dominates most of the region in the mid-term horizon, with an expansion of the increasing trend in the longer-term horizon, significantly extending to northern regions.

In the regional context, certain areas show consistent trends across different scenarios, horizons and seasons. For example, the southwestern area of the European waters, particularly off the western coast of the Iberian Peninsula, exhibits a consistent increasing pattern that intensifies towards the end of the century. Conversely, the resource over the northern areas, especially Ireland and the British islands, consistently shows reductions, with the most intense reductions occurring at the end of the century.



a) Historical baseline: left to right, DJF, MAM, JJA, SON.

b) Near-term forecast: left to right, DJF, MAM, JJA, SON.

c) Mid-term forecast: left to right, DJF, MAM, JJA, SON.

d) Long-term forecast: left to right, DJF, MAM, JJA, SON.

Fig. 4. Evolution of the Inter-annual mean U_w in northwest Europe under the SSP5-8.5 scenario: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts.

3.1.3. Extreme conditions

Although the CoV of the resource somewhat accounts for the extreme values by quantifying the deviation of the dataset, this deviation is normalised against the mean, which may results in masking the evolution of the extreme conditions. For example, if the mean of the U_w increases in the same proportion as its deviation, the CoV remains the same and the increase of the extreme conditions results overlooked. In fact, the correlation between the reduction of the mean U_w and the increase of the CoV indicates that assuming a direct relationship between the CoV and the extreme conditions may not be judicious. In fact, this is demonstrated by the considerable differences shown between Figs. 2 and 5.

Therefore, the evolution of the extreme events is characterised by assessing the U_w data belonging to the 99th percentile, as illustrated in Fig. 5. The historical baseline of the extreme conditions depicted in Fig. 5(a) shows an almost identical pattern of the mean U_w baseline illustrated in Fig. 1(a). The only exceptions are the region in the south of France and the Canary Islands for opposite reasons. While the Canary Islands show a relatively high mean U_w and average extreme conditions, the south of France shows a rather mild mean U_w and

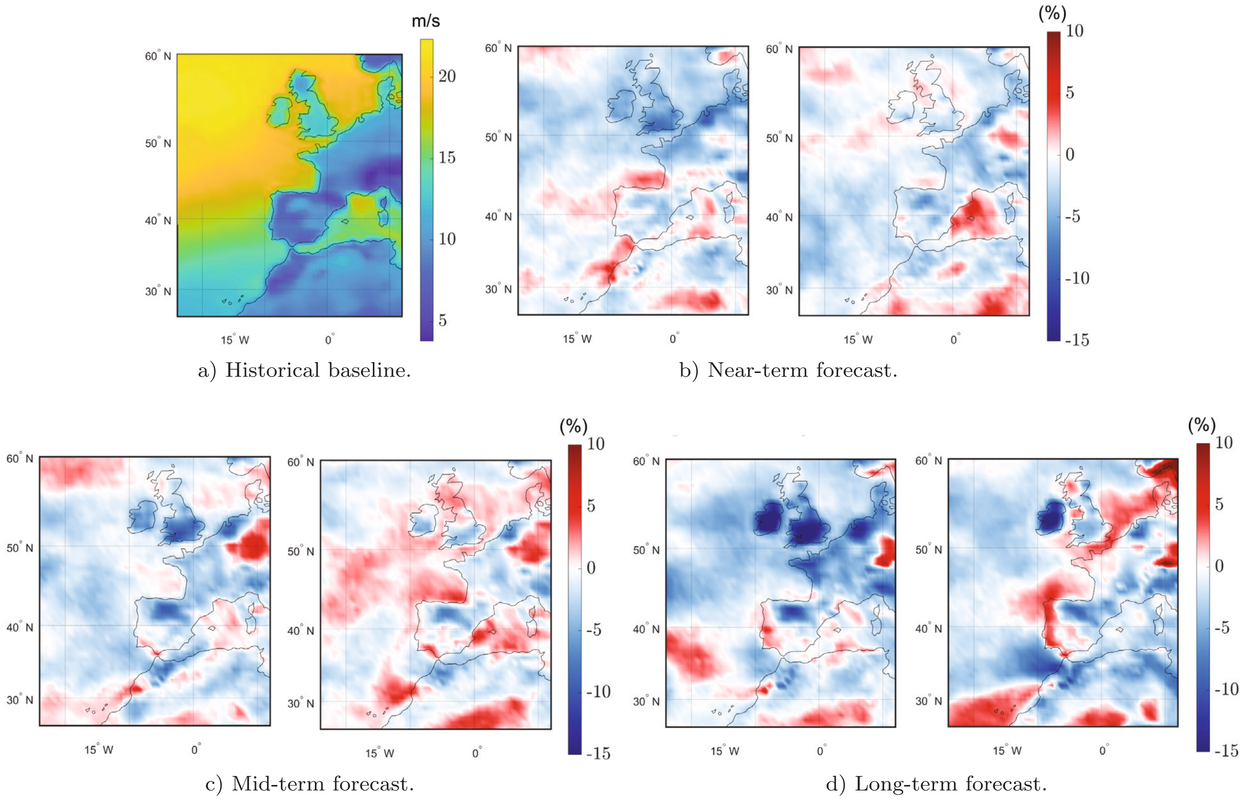


Fig. 5. Evolution of extreme U_w in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP2-4.5 (left) and SSP5-8.5 (right) scenarios.

considerably harsh extreme conditions. Note that the later is the worst case scenario, since energy extracting capabilities are reduced, while a further reinforcement of the system is necessary to survive the extreme events.

However, the projections of the extreme conditions show that extreme conditions will vary independently from the evolution of the mean U_w and the CoV. In this case, each SSP scenario shows different patterns. Under the mid-emissions scenario SSP2-4.5, extreme conditions seem to reduce significantly (reaching up to 15% reduction) in the northwestern area of Europe, especially off the Irish and British coasts, which is consistent with the evolution of the mean U_w. In contrast, a mild increase (up to 5%) is observed in some areas of the Mediterranean Sea. Besides, the Gulf of Biscay displays an increase of over 5% in the near-term horizon, but gradually reduces in longer horizons. In the case of the high-emissions scenario SSP5-8.5, an intense increasing pattern is observed around the Iberian Peninsula and the North Sea, with an increase of up to a very significant 10% by the end of the century. These cases are particularly interesting due to the decreasing trends of the mean U_w shown in Fig. 1, which results in the catastrophic situation mentioned earlier.

3.1.4. *Local-scale evolution*

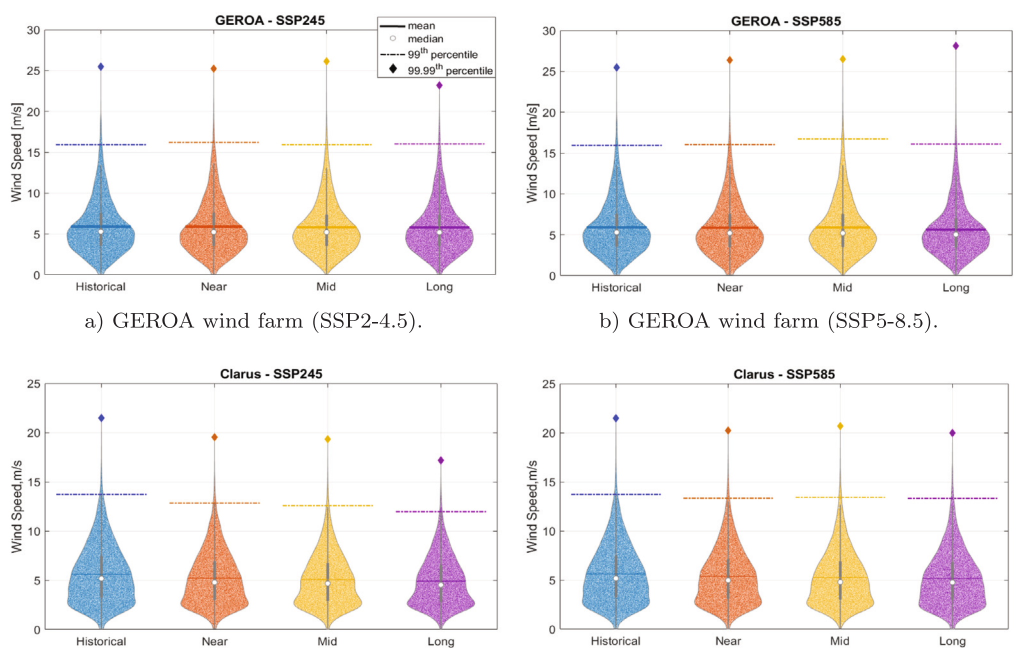
The global-scale analysis is relevant for the recognition of geospatial patterns and the understanding of the overall trends. However, a statistical analysis of the resource is unfeasible due to the large amount of data to be considered. Therefore, such a statistical analysis of the resource is carried out in the local scale, more specifically, in the 5 locations presented in Table 1. The evolution of the resource is analysed in terms of mean and extreme (99th percentile) conditions, as illustrated in Table 2. The same values are also depicted in Fig. 6, where the lower and upper lines in each violin plot indicate, respectively, the mean and extreme conditions. Fig. 6 illustrates the probability density function (PDF) of the resource, providing further insight for two of the most interesting locations, *i.e.* the GEROA and Clarus wind farms.

Hence, Figs. 6(a) and (b) represent the evolution of the resource in the area where the GEROA farm is planned, showing that the mean U_w is expected to decrease under the emissions scenarios and forecasting horizons considered, while the extreme conditions are likely to increase, particularly in the high-emissions SSP5-8.5 scenario. In general, the distributions corresponding to the longer horizons show that the tails of the distributions become thinner while a higher number of points accumulate close to the peak of the distribution. This effect can be observed in both scenarios, although it is more relevant in the high-emissions SSP5-8.5 scenario. In the case of the extreme conditions, represented by the 99.99th percentile, opposite trends are observed in the mid- and the high-emissions scenarios. While the distribution tails are shown to decrease in the SSP2-4.5 scenario, these tails are shown to increase in the SSP5-8.5 scenario, demonstrating that global warming has a direct impact on the evolution of the extreme conditions. It should be noted that this conclusion can only be identified because a local-scale analysis is carried out using a 3-hour resolution. In fact, using a finer resolution, such as 1-hour intervals, would likely yield statistically more significant results. Finer resolutions help to avoid smoothing effects that can mask statistically important variations and extreme events.

The case for the area where the Clarus farm is planned to be installed also shows reductions of the mean U_w under both SSP scenarios, gradually decreasing throughout the century. Moreover, the variations in the PDF distributions along the century are dramatic under both SSP scenarios. The PDF almost turns into a double peak distribution when approaching to the end of the century, where the lower peak becomes clearly dominant. This lower peaks appear at values well below the mean U_w, resulting in lower fatigue damage and power generation capabilities. In contrast to the evolution of the resource in the GEROA wind farm, extreme conditions are shown to decrease in both scenarios, both in terms of the 99th percentile and the tail of the PDF. However, this reduction is significantly milder under the high-emission scenario SSP5-8.5.

Table 2
Summary of the local wind resource evolution.

Forecasting horizon	Mean U_w		Extreme U_w - 99th		Extreme U_w - 99.99th	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
Hywind						
Near-term	8.4 (−1.2%)	8.4 (−1%)	18.9 (−1.5%)	19.3 (0.6%)	27.48 (−10.9%)	27.7 (−10.1%)
Mid-term	8.4 (−1.2%)	8.4 (−1.4%)	19.1 (−0.8%)	19 (−0.8%)	28.4 (−7.9%)	31.2 (1%)
Long-term	8.2 (−3.2%)	8.2 (−3.7%)	18.9 (−1.6%)	18.6 (−2.9%)	29.8 (−3.4%)	30.3 (−1.9%)
Tramuntana						
Near-term	6.2 (1%)	6.2 (0%)	15.5 (−0.6%)	15.5 (−0.3%)	21.3 (1.7%)	21.9 (4.8%)
Mid-term	6.1 (−1.1%)	6.1 (−0.9%)	15.4 (−1.2%)	15.5(−0.3%)	20.2 (−3.5%)	21.5 (2.8%)
Long-term	6.1 (−1.5%)	5.8 (−5.7%)	15.1 (−3.7%)	15.2 (−2.6%)	22.6 (8.1%)	21.1 (−0.7%)
GEROA						
Near-term	5.9 (0.1%)	5.9 (−0.7%)	16.2 (1.8%)	16 (0.7%)	25.2 (−0.9%)	26.4 (3.6%)
Mid-term	5.8 (−1.4%)	5.9 (−0.2%)	15.9 (0%)	16.7(5%)	26.1 (2.7%)	26.5 (4%)
Long-term	5.8 (−1.9%)	5.6 (−4.8%)	16 (0.5%)	16.1 (1%)	23.2 (−8.9%)	28.1 (10.5%)
WindFloat						
Near-term	8.1 (3.3%)	7.9 (0.9%)	17.5 (1.2%)	17 (−2%)	27.2 (0.65%)	24.1 (−11.1%)
Mid-term	7.8 (0.5%)	8.1 (3.4%)	17.1 (−1.1%)	17.6(1.4%)	26.4 (−2.5%)	24.3 (−10.2%)
Long-term	7.8 (0.7%)	7.8 (−0.2%)	17.3 (−0.1%)	17.7 (2.2%)	26.6 (−1.8%)	27.9 (3%)
Clarus						
Near-term	5.2 (−7.1%)	5.4 (−4.2%)	12.8 (−6.4%)	13.3 (−2.8%)	19.5 (−9.1%)	20.2 (−5.8%)
Mid-term	5.1 (−9.7%)	5.2 (−6.7%)	12.6 (−8.3%)	13.4 (−2.3%)	19.3 (−10%)	20.7 (−3.8%)
Long-term	4.9 (−12.5%)	5.2 (−7.9%)	12 (−12.8%)	13.3 (−3%)	17.2 (−20.1%)	20 (−6.9%)



a) GEROA wind farm (SSP2-4.5). b) GEROA wind farm (SSP5-8.5).

c) Clarus wind farm (SSP2-4.5). d) Clarus wind farm (SSP5-8.5).

Fig. 6. Evolution of the local wind resource: (a) and (b) at GEROA wind farm for the SSP2-4.5 and SSP5-8.5 scenarios, respectively, and (c) and (d) at Clarus wind farm for the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

Overall, although the results in Table 2 do not show clear trends, the impact of climate change is evident, particularly in the extreme conditions. In general, the mean U_w is shown to decrease up to 2100. In certain areas, however, trends change over time. For example, the mean U_w under the SSP5-8.5 at the Windfloat site is shown to increase until mid-century and to decrease afterwards (see also Fig. 1). Such changes, which are rather common in climate projections, may be attributed to the inherent complexity of the climate system, the uncertainties surrounding climate modelling, emission scenarios and other external forcings, and climate internal variability [39,65].

Extreme wind speeds (represented by the 99th and 99.99th percentiles) decrease in three of the study sites and increase in the other two in the high-emissions scenario.

Hence, two main impacts from global warming may be identified in the projections. First, opposite tendencies are found for the mean and extreme U_w values. Whereas an overall decreasing tendency is expected for the mean U_w, the evolution of extreme conditions presents great spatial variability. Second, these trends are projected to strengthen as global temperatures increase, with the SSP5-8.5 scenario showing lower means and more intense extremes than the SSP2-4.5 scenario.

3.2. Wave forecasting

The evolution of the wave climate is evaluated only under the high-emissions SSP5-8.5 scenario due to the limitations of available data. Similarly to the wind resource assessment, Figs. 7–11 illustrate

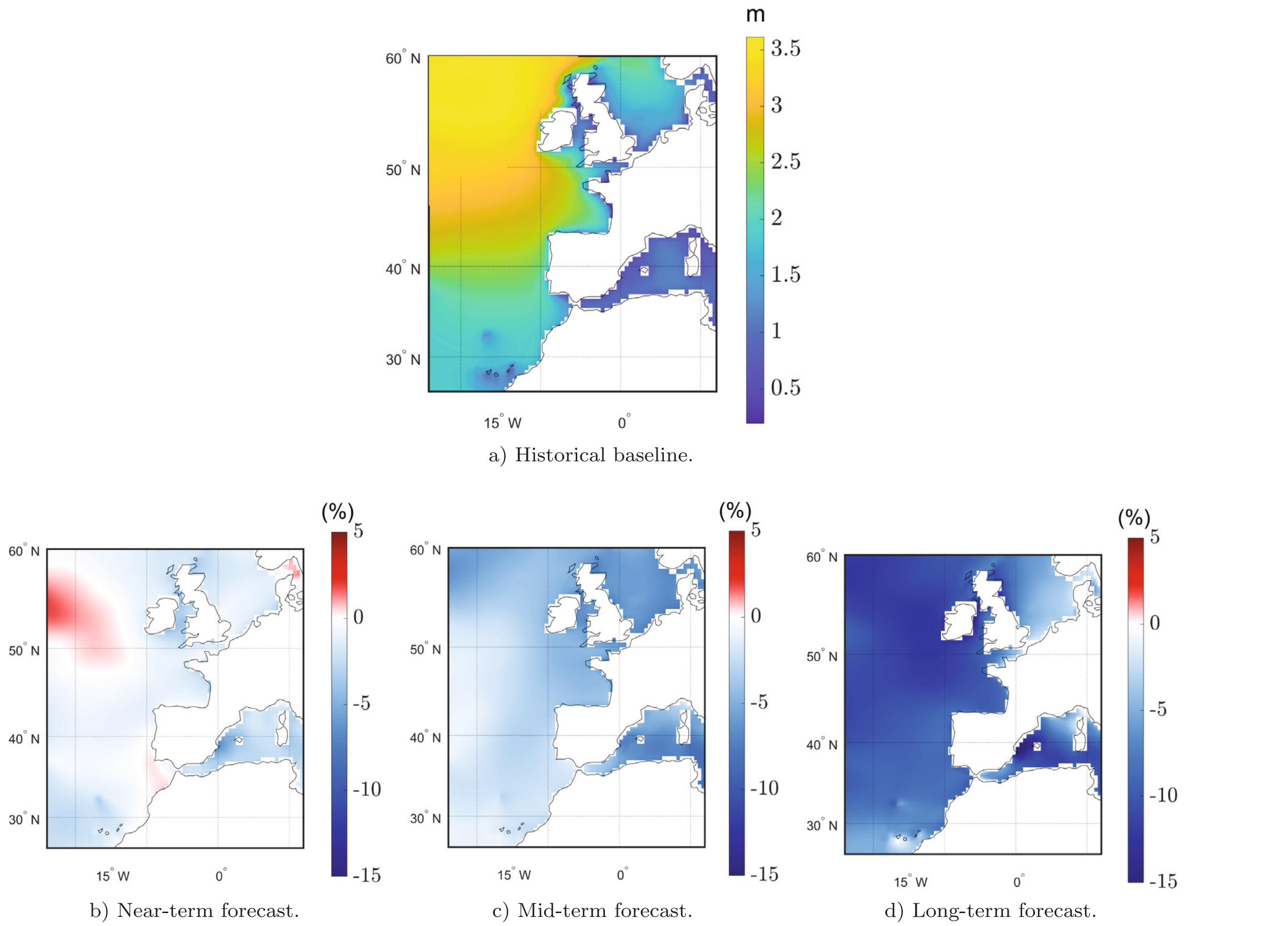


Fig. 7. Evolution of the mean H_s in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP5-8.5 scenario.

all the evolution of the four factors for the wave resource, which are thoroughly discussed in the following subsections. In this case, H_s is the main variable for studying the evolution in the wave climate, analysing the evolution of the mean, the variability and extremes.

3.2.1. Mean wave height

Previous studies show that the worldwide wave climate has evolved along the 20th century with increasing wave energy density [8], including specific locations in Europe, particularly off the west coast of Ireland [49] and the Bay of Biscay [48]. In the 21st century, beyond 2030 (the subject of this analysis), a clearly decreasing trend in significant wave height prevails over the entire area of study, reaching 15% by 2100 in regions such as the west coast of Ireland and the Balearic Sea (Fig. 7). A similar decline is observed for the wind resource in northern European areas (Fig. 1), where the decreasing trend is well established by the second half of the 21st century, particularly under the SSP5-8.5 scenario.

3.2.2. Variability

The variability of the wave resource is also evaluated by means of the CoV and the inter-annual variations as in Section 3.1.2.

Wave data variability. Similarities on the evolution patterns of wind and wave resources also exist in terms of variability. Fig. 8 illustrates that the wave climate is expected to become more variable, especially by the end of the century, where almost all the area of study shows an increase of 10%. It should be observed that the areas with the highest CoV in the baseline scenario, *e.g.* the Mediterranean Sea, are not the areas where the highest increase is expected. In contrast, the Atlantic Ocean off the west coast of Portugal and the Bay of Biscay, which are characterised by a relatively low CoV, are the areas where the highest increases are expected. Similarities with the wind resource evolution presented in Fig. 2 are evident, especially in the near- and mid-term horizons, where the Southern regions in the area of study illustrate a clear decreasing trend in both wind and wave resources. In addition, the northern areas, especially the Bay of Biscay and the mid western regions of the Atlantic Ocean, show a gradually increasing pattern that is repeated both in the wind and wave resource evolution.

Intra-annual variability. Two main aspects can be highlighted from the inter-annual analysis of the historical baseline wave climate illustrated in Fig. 9(a). First, the conditions are shown to be significantly harsher in Winter, Spring and Autumn in the Atlantic Ocean. In contrast, the Mediterranean Sea appears very consistent along the year, with relatively low wave heights in all seasons.

The future trends show an overall decreasing pattern across the whole area of study and seasons, although some particularities should be noted. Similarly to the pattern illustrated in Fig. 7, positive trends are more relevant in the near-term horizon and mostly appear in northern regions, leading to less energetic conditions across the whole area of study as the forecasting horizon increases. Exceptions include the southern regions in Summer and Autumn, following the pattern recognised in the near-term horizon, the North Sea in Spring, and the Mediterranean Sea in Winter. Similar patterns are also found in the evolution of the wind resource, as illustrated in Fig. 4.

3.2.3. Extreme conditions

Extreme wave conditions are observed to decrease overall, as illustrated in Fig. 10, following the pattern of the mean H_s. However,

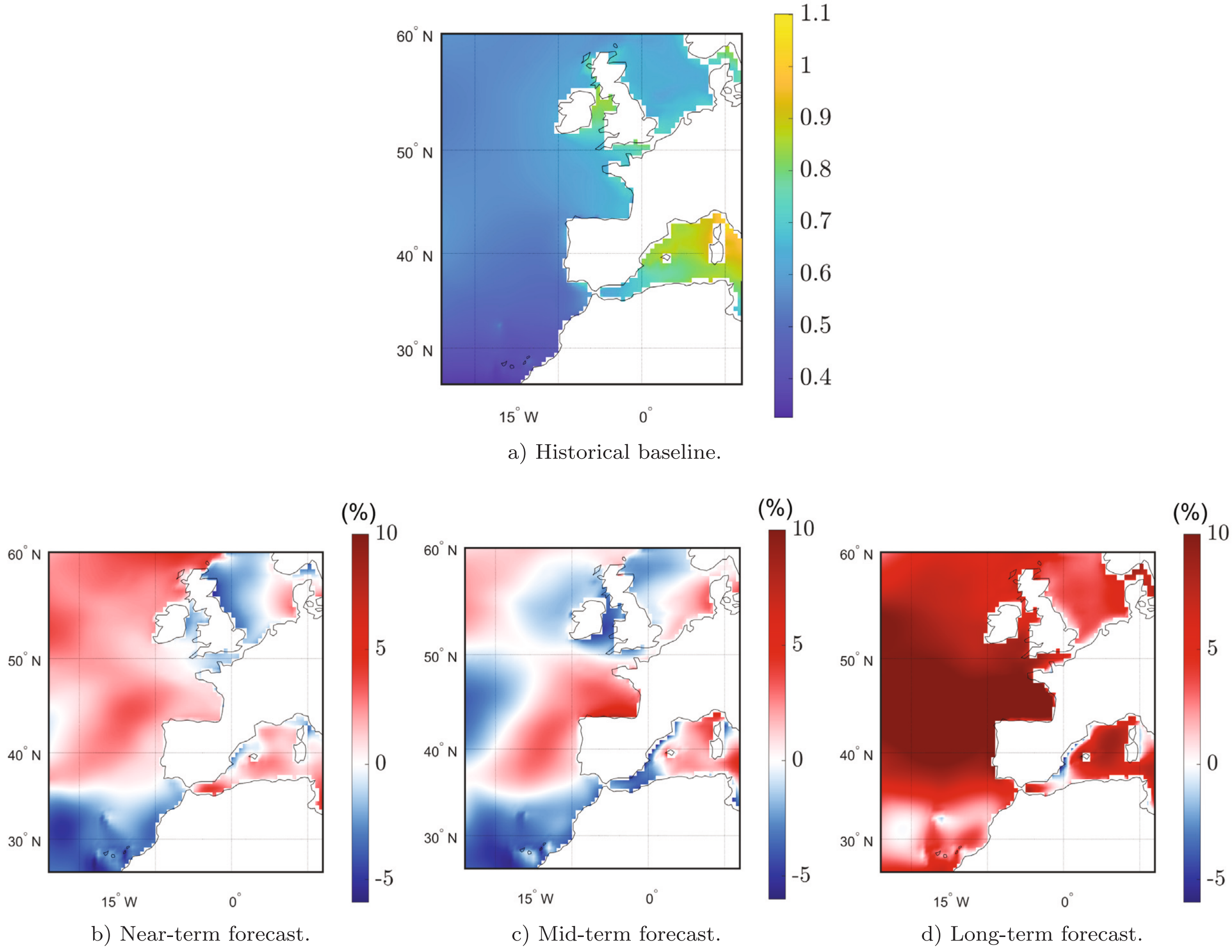


Fig. 8. Evolution of the CoV of the H_s in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP5-8.5 scenario.

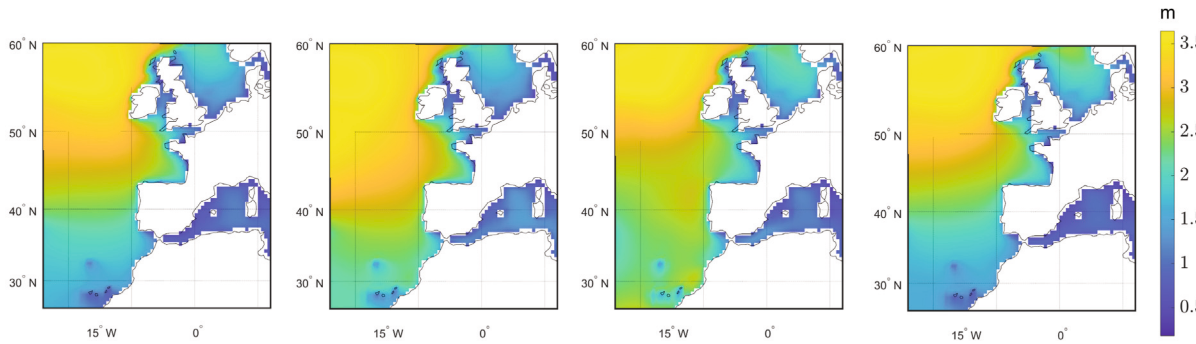
the Atlantic watershed of the Iberian Peninsula shows a significant increasing trend that also appears in Fig. 5 for the wind resource. However, in the near-term horizon, extreme wave conditions seem to increase considerably in the northern Atlantic Ocean, which is not the case in the predictions of the wind resource. In contrast, the mid-term horizon for wave and wind shows the opposite patterns, with the extreme wave conditions being milder and extreme wind conditions expected to increase significantly. It is in the long-term horizon where wind and wave predictions show the largest similarities.

3.2.4. Local-scale evolution

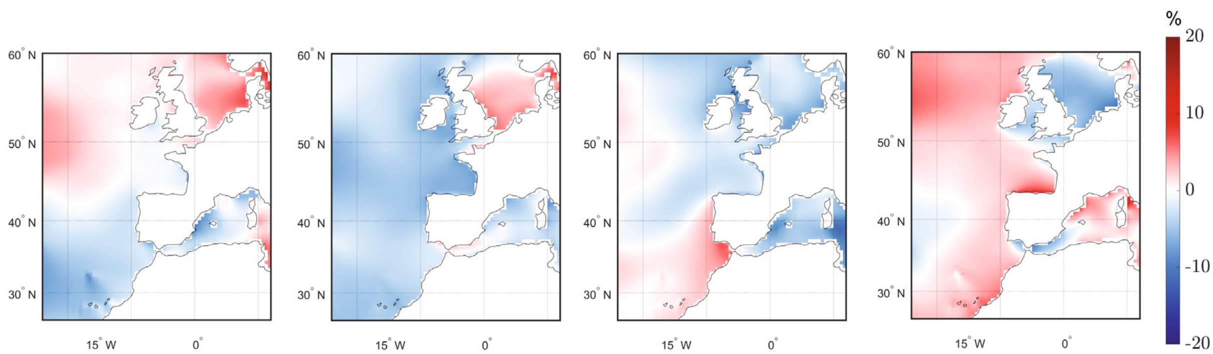
Finally, the local-scale analysis of the wave resource is presented in Table 3 for all the locations analysed in this study. In addition, Figs. 11(a) and (b) illustrate the same analysis for the GEROA and Clarus wind farms projects, respectively, using violin plots. For the GEROA project, the mean H_s is shown to decrease along the 21st century, while H_s for the 99th percentile is shown to increase, which is consistent with the results shown in Figs. 7 and 10, respectively. However, the representation of the data in violin plots enables a further understanding of the evolution that is masked in the global-scale analysis. On the one hand, one can observe that more and more data are gathered around lower H_s values, resulting in PDF distributions with wider peaks that are placed lower and thinner tails. On the other hand, it is remarkable that, besides the 99th percentile value, the highest value of the PDF distribution reaches significantly higher values, moving from 9 m in the historical baseline case study to a remarkably high value of 12 m (over 30% of increase). This is particularly catastrophic, as in the case of the wind resource, since the different components,

Table 3
Summary of the local wave resource evolution.

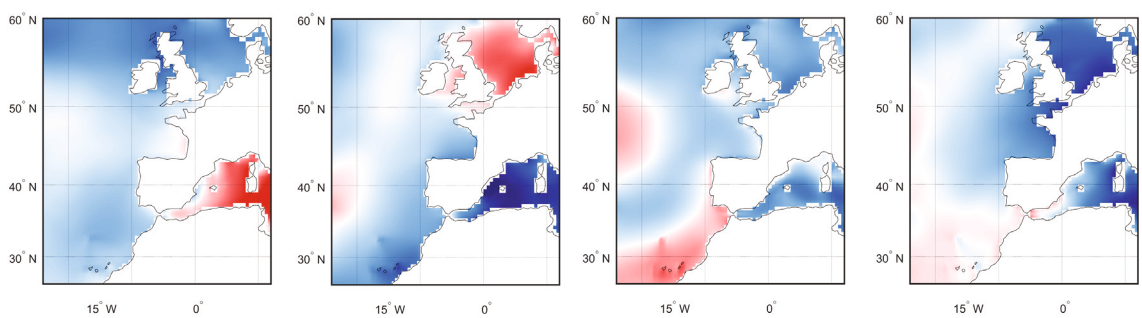
Forecasting horizon	Mean H_s	Extreme H_s 99th	Extreme H_s 99.99th
Hywind			
Near-term	1.5 (−2.1%)	4.7 (−5.8%)	8.8 (4.5%)
Mid-term	1.4 (−6.2%)	4.5 (−8.6%)	8.5 (1.3%)
Long-term	1.4 (−9.9%)	4.4 (−10.1%)	7.7 (−8.4%)
Tramuntana			
Near-term	0.74 (−2.8%)	2.9 (−4.6%)	6.1 (13.8%)
Mid-term	0.72 (−5.1%)	3 (−4.6%)	5.8 (9.1%)
Long-term	0.68 (−11.1%)	2.9 (−5.4%)	5.4 (1.5%)
GEROA			
Near-term	2.1 (−1%)	6.8 (1.3%)	11.5 (−4.8%)
Mid-term	2 (−4%)	6.8 (2.3%)	12.2 (0.5%)
Long-term	1.8 (−9.6%)	6.9 (2.9%)	14.6 (20.5%)
WindFloat			
Near-term	2.3 (−0.8%)	6.6 (0.5%)	10.1 (−5.3%)
Mid-term	2.2 (−3%)	6.5 (−0.7%)	10.4 (−1.6%)
Long-term	2.1 (−8.9%)	6.9 (5.9%)	14 (41%)
Clarus			
Near-term	3.1 (−1%)	9.22 (−1.1%)	16.3 (−4.1%)
Mid-term	3 (−4.1%)	8.8 (−5.7%)	16.1 (−5%)
Long-term	2.8 (−12.1%)	8.6 (−7.9%)	14.8 (−12.8%)



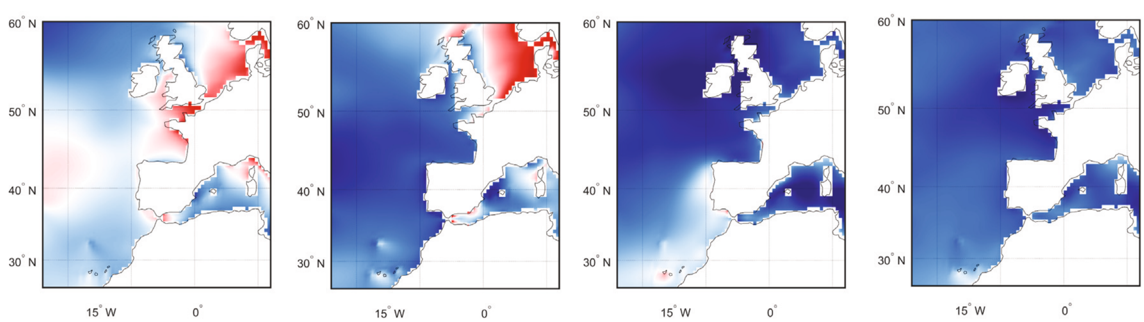
a) Historical baseline: left to right, DJF, MAM, JJA, SON.



b) Near-term forecast: left to right, DJF, MAM, JJA, SON.

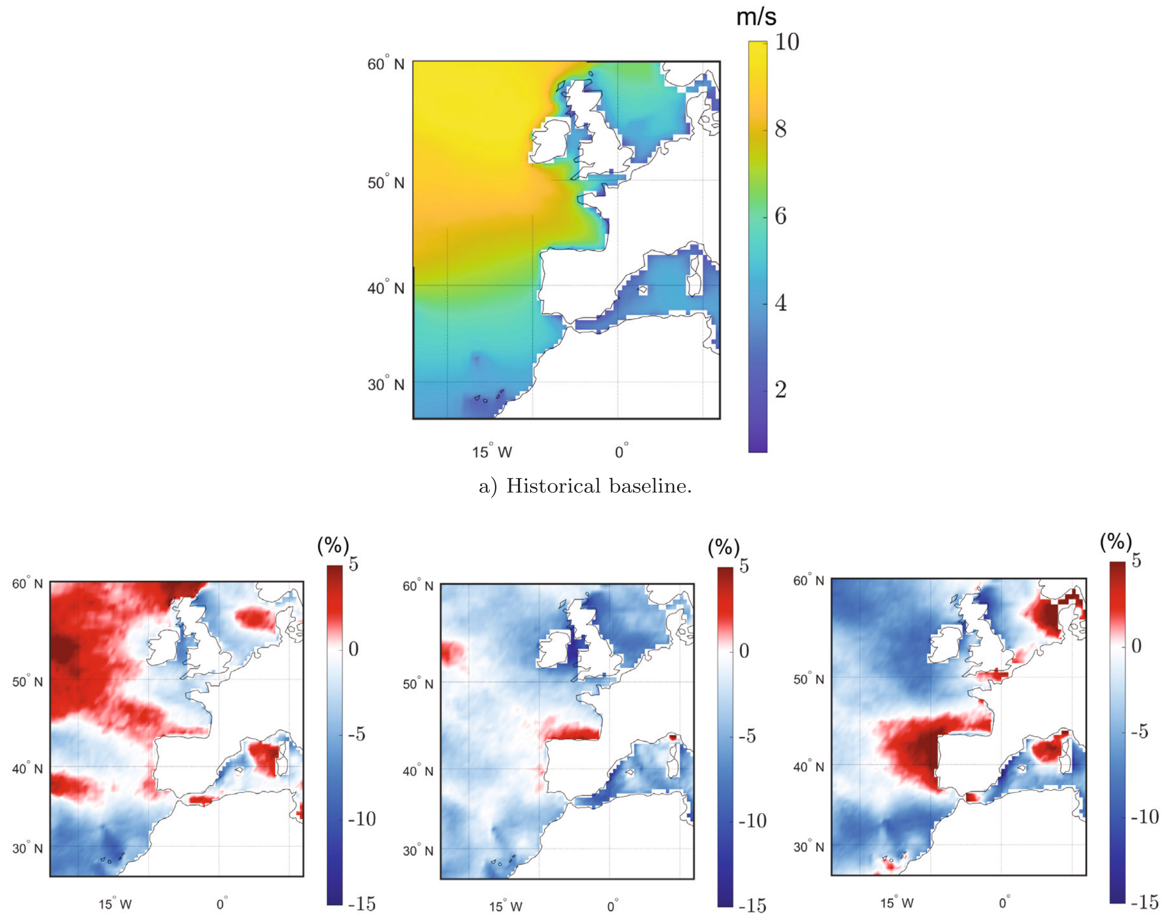


c) Mid-term forecast: left to right, DJF, MAM, JJA, SON.



d) Long-term forecast: left to right, DJF, MAM, JJA, SON.

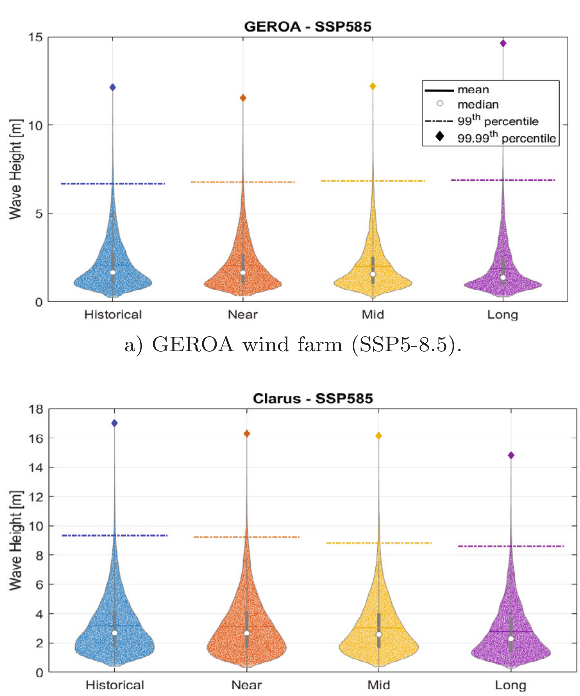
Fig. 9. Evolution of the inter-annual mean H_s in northwest Europe under the SSP5-8.5 scenario: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts.



a) Historical baseline.

b) Near-term forecast. c) Mid-term forecast. d) Long-term forecast.

Fig. 10. Evolution of extreme H_s in northwest Europe: (a) Historical baseline, and (b) near-, (c) mid- and (d) long-term forecasts for the SSP5-8.5 scenario.



a) GEROA wind farm (SSP5-8.5).

b) Clarus wind farm (SSP5-8.5).

Fig. 11. Evolution of the local wave resource at (a) GEROA and (b) Clarus wind farms for SSP5-8.5 scenario.

such as floating wind platforms, mooring lines and blades, need to be designed to survive such harsh conditions.

Similar trends can also be found in Fig. 11(b) for the area where the Clarus wind farm is planned to be installed, except that the very extreme conditions also decrease in this case. The wave climate evolution shows a decrease in mean H_s, with the peak of the PDF being moved towards lower H_s values. The 99th threshold is also shown to decrease in time, as in Fig. 10.

4. Conclusions

The present paper assesses the evolution of the wind and wave resources across European waters under the impact of climate change, considering two scenarios (*i.e.* mid and high emissions) and three forecasting horizons (*i.e.* near, mid and long term). The dataset used for the assessment is based on the Coupled Model Intercomparison Project Phase 6 (CMIP6), which provides state-of-the-art climate models. The novelties of the present study lie in: (i) considering wave and wind data including their similarities, (ii) using a high temporal resolution, (iii) combining global and local scales for the resource assessment, and (iv) carrying out a comprehensive statistical analysis with probability density functions (PDFs). All these novelties include aspects that are critical to the offshore renewable energy (ORE) industry, since they enable a more thorough analysis of the evolution of the resources and its implications for the design of ORE technologies.

On average, both wind and wave resources are expected to decrease gradually in the next decades, particularly in the northern regions and under the high-emissions SSP5-8.5 scenario. In southern regions a very mild increase and a mild decrease is projected in the SSP2-4.5 and

SSP5-8.5 scenarios, respectively. In fact, the local-scale analysis confirms the long-term decreasing trend, with initially narrow, dense PDF peaks which are gradually displaced towards lower values, resulting in thinner tails. Similar patterns are also observed for the wave climate, with the caveat that in the northern regions the resource seems to increase in the near-term horizon. In both wind and wave resources, it is very clear that the increasing trends observed in the literature for the 20th century are totally reversed almost everywhere before 2050.

Besides the variations in the average resource, extreme conditions also vary considerably. The values of the 99th percentiles show different trends depending on the region, with much of the Atlantic waters off continental Europe experiencing increases by 2100, whereas much of the Mediterranean waters, Great Britain and Ireland experience decreases.

These trends are confirmed by the local-scale analysis. More specifically, in two of the five study sites, a significant extension of the PDF tails towards higher wind speeds and, especially, larger wave heights is projected by 2100. This effect is particularly relevant in SSP5-8.5. Under this scenario the displacement of the PDF tails can have significant repercussions, especially when combined with reductions in the mean wind speed and significant wave height values – it would imply higher survivability requirements while assuming lower energy production. This evolution of the extremes is more dramatic in the high-emissions scenario. In any case, further investigation considering the downscaling of wind/wave data to capture the local geographical and topographical characteristics is recommended.

All the wind and wave resource variations presented in this study reinforce the idea that the designs of future ORE technologies should consider these effects in order to better suit the future resource characteristics. To that end, future studies should evaluate the impact of the resource variations on the most relevant design parameters as in [57], incorporating aspects like power generation, structural integrity to fatigue and extreme events, and operation and maintenance.

CRediT authorship contribution statement

Egor Barkanov: Visualisation, Software, Investigation, Formal analysis, Data curation. **Markel Penalba:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Abel Martinez:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Ander Martinez-Perurena:** Writing – review & editing, Visualization, Investigation, Data curation. **Ander Zarketa-Astigarraga:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Gregorio Iglesias:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgements

The research leading to these results has partly received funding from the European Union Horizon Europe programme under the agreement 101136087 (INF4INITY Project). This publication is also part of the research project PID2021-124245OA-I00 funded by MCIN/AEI/10.13039/501100011033 and by ERDF A way of making Europe, and the research project funded by the Basque Government's ELKARTEK 2022 program under the grant No. KK-2022/00090. Finally, the authors from the Fluid Mechanics research group at Mondragon University are also supported by the Basque Government's Research Group Program under the grant No. IT1505-22.

References

[1] IPCC. Global warming of 1.5 °C. Tech. Rep., Intergovernmental Panel on Climate Change (IPCC); 2018.
[2] Olivier JG, Schure K, Peters J, et al. Trends in global CO2 and total greenhouse gas emissions. Tech. Rep. 2674, PBL Netherlands Environmental Assessment Agency; 2017.
[3] IPCC. Mitigation of climate change. Working group III contribution to the sixth assessment report of the intergovernmental panel on climate change. Tech. Rep., Intergovernmental Panel on Climate Change (IPCC); 2022.
[4] Martinez A, Iglesias G. Global wind energy resources decline under climate change. Energy 2023;129765.
[5] Pryor SC, Barthelmie RJ, Bukovsky MS, Leung LR, Sakaguchi K. Climate change impacts on wind power generation. Nat Rev Earth Environ 2020;1(12):627–43.
[6] Martinez A, Iglesias G. Climate change impacts on wind energy resources in North America based on the CMIP6 projections. Sci Total Environ 2022;806:150580.
[7] Fournier A, Martinez A, Iglesias G. Impacts of climate change on wind energy potential in Australasia and South-East Asia following the shared socioeconomic pathways. Sci Total Environ 2023;882:163347.
[8] Reguero BG, Losada IJ, Méndez FJ. A recent increase in global wave power as a consequence of oceanic warming. Nature Commun 2019;10(1):205.
[9] Iwasaki S. Increase in the wave power caused by decreasing sea ice over the Sea of Okhotsk in winter. Sci Rep 2023;13(1):2539.
[10] Yin J, Molini A, Porporato A. Impacts of solar intermittency on future photovoltaic reliability. Nature Commun 2020;11(1):4781.
[11] Hou X, Wild M, Folini D, Kazadzis S, Wohland J. Climate change impacts on solar power generation and its spatial variability in Europe based on CMIP6. Earth Syst Dyn 2021;12(4):1099–113. http://dx.doi.org/10.5194/esd-12-1099-2021, URL https://esd.copernicus.org/articles/12/1099/2021/.
[12] Rusu E, Onea F. Expected dynamics of the European offshore wind sector in the climate change context. 2023.
[13] Lee H, Romero J. Climate change 2023: Synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change. Tech. Rep., Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC); 2023, http://dx.doi.org/10.59327/IPCC/AR6-9789291691647.
[14] IRENA. Future of wind: Deployment, investment, grid integration and socio-economic aspects (A Global Energy Transformation paper). Tech. Rep., Abu Dhabi: International Renewable Energy Agency; 2019, Available in https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.
[15] Bouckaert S, Pales AF, McGlade C, Remme U, Wanner B. Net zero by 2050: A roadmap for the global energy sector. Tech. Rep., Paris: International Energy Agency; 2021, p. 224, URL https://www.iea.org/reports/net-zero-by-2050.
[16] Ocean Energy Europe. 2030 ocean energy vision. Tech. Rep., 2020, URL https://www.oceanenergy-europe.eu/wp-content/uploads/2020/10/OEE_2030_Ocean_Energy_Vision.pdf.
[17] NREL. Marine energy in the United States: An overview of opportunities. Tech. Rep. February, 2021, URL https://www.nrel.gov/docs/fy21osti/78773.pdf.
[18] Bahar H, Moorhouse J. Renewable energy market update - May 2022. Tech. Rep., Paris: International Energy Agency; 2022, URL https://www.iea.org/reports/renewable-energy-market-update-may-2022.
[19] WindEurope. Wind energy and economic recovery in Europe. Tech. Rep., 2020, URL https://windeurope.org/intelligence-platform/product/wind-energy-and-economic-recovery-in-europe/.
[20] Nakicenovic N, Swart R. Emissions scenarios-special report of the intergovernmental panel on climate change. 2000.
[21] Smithson PA. IPCC, 2001: climate change 2001: the scientific basis. contribution of working group 1 to the third assessment report of the intergovernmental panel on climate change. Cambridge, UK, and New York, USA: Cambridge University Press; 2002, 2001. No. of pages: 881. Price £ 34.95, us 49.95, isbn0-521-01495-6(paperback). £90.00, us 130.00, isbn 0-521-80767-0 (hardback),
[22] Koletsis I, Kotroni V, Lagouvardos K, Soukissian T. Assessment of offshore wind speed and power potential over the Mediterranean and the black seas under future climate changes. Renew Sustain Energy Rev 2016;60:234–45.
[23] Räisänen J, Hansson U, Ullerstig A, Döscher R, Graham L, Jones C, et al. European climate in the late twenty-first century: Regional simulations with two driving global models and two forcing scenarios. Clim Dyn 2004;22:13–31.
[24] Pryor S, Barthelmie R, Kjellström E. Potential climate change impact on wind energy resources in northern Europe: Analyses using a regional climate model. Clim Dynam 2005;25:815–35.
[25] Hueging H, Haas R, Born K, Jacob D, Pinto JG. Regional changes in wind energy potential over Europe using regional climate model ensemble projections. J Appl Meteorol Climatol 2013;52(4):903–17.
[26] Tobin I, Vautard R, Balog I, Bréon F-M, Jerez S, Ruti PM, et al. Assessing climate change impacts on European wind energy from ensembles high-resolution climate projections. Clim Change 2015;128:99–112.

[27] Cradden LC, Harrison GP, Chick JP. Will climate change impact on wind power development in the UK? Clim Change 2012;115:837–52.
[28] Nolan P, Lynch P, McGrath R, Semmler T, Wang S. Simulating climate change and its effects on the wind energy resource of Ireland. Wind Energy 2012;15(4):593–608.
[29] Nolan P, Lynch P, Sweeney C. Simulating the future wind energy resource of Ireland using the COSMO-CLM model. Wind Energy 2014;17(1):19–37.
[30] Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, et al. The next generation of scenarios for climate change research and assessment. Nature 2010;463(7282):747–56.
[31] Carvalho D, Rocha A, Gómez-Gesteira M, Santos CS. Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. Renew Energy 2017;101:29–40.
[32] Reyers M, Moemken J, Pinto JG. Future changes of wind energy potentials over Europe in a large CMIP5 multi-model ensemble. Int J Climatol 2016;36(2):783–96.
[33] Moemken J, Reyers M, Feldmann H, Pinto JG. Future changes of wind speed and wind energy potentials in EURO-CORDEX ensemble simulations. J Geophys Res: Atmos 2018;123(12):6373–89.
[34] Alvarez I, Lorenzo MN. Changes in offshore wind power potential over the Mediterranean Sea using CORDEX projections. Reg Environ Change 2019;19:79–88.
[35] Lira-Loarca A, Ferrari F, Mazzino A, Besio G. Future wind and wave energy resources and exploitability in the Mediterranean Sea by 2100. Appl Energy 2021;302:117492.
[36] Davy R, Gnatiuk N, Pettersson L, Bobylev L. Climate change impacts on wind energy potential in the European domain with a focus on the Black Sea. Renew Sustain Energy Rev 2018;81:1652–9.
[37] Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, et al. Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 2016;9(5):1937–58.
[38] Martinez A, Iglesias G. Wind resource evolution in Europe under different scenarios of climate change characterised by the novel Shared Socioeconomic Pathways. Energy Convers Manage 2021;234:113961.
[39] Carvalho D, Rocha A, Costoya X, DeCastro M, Gómez-Gesteira M. Wind energy resource over Europe under CMIP6 future climate projections: What changes from CMIP5 to CMIP6. Renew Sustain Energy Rev 2021;151:111594.
[40] Hahmann AN, García-Santiago O, Peña A. Current and future wind energy resources in the North Sea according to CMIP6. Wind Energy Sci 2022;7(6):2373–91.
[41] Moradian S, Akbari M, Iglesias G. Optimized hybrid ensemble technique for CMIP6 wind data projections under different climate-change scenarios. Case study: United Kingdom. Sci Total Environ 2022;826:154124.
[42] Martinez A, Murphy L, Iglesias G. Evolution of offshore wind resources in Northern Europe under climate change. Energy 2023;269:126655.
[43] Martinez A, Iglesias G. Climate-change impacts on offshore wind resources in the Mediterranean Sea. Energy Convers Manage 2023;291:117231. http://dx.doi.org/10.1016/j.enconman.2023.117231, URL https://www.sciencedirect.com/science/article/pii/S0196890423005770.
[44] Claro A, Santos JA, Carvalho D. Assessing the future wind energy potential in Portugal using a CMIP6 model ensemble and WRF high-resolution simulations. Energies 2023;16(2):661.
[45] Wu J, Shi Y, Xu Y. Evaluation and projection of surface wind speed over China based on CMIP6 GCMs. J Geophys Res: Atmos 2020;125(22). e2020JD033611.
[46] Deng H, Hua W, Fan G. Evaluation and projection of near-surface wind speed over China based on CMIP6 models. Atmosphere 2021;12(8):1062.
[47] Zhang S, Li X. Future projections of offshore wind energy resources in China using CMIP6 simulations and a deep learning-based downscaling method. Energy 2021;217:119321.
[48] Ulazia A, Penalba M, Ibarra-Berastegui G, Ringwood J, Saénz J. Wave energy trends over the Bay of Biscay and the consequences for wave energy converters. Energy 2017;141. http://dx.doi.org/10.1016/j.energy.2017.09.099.
[49] Penalba M, Ulazia A, Ibarra-Berastegui G, Ringwood J, Sáenz J. Wave energy resource variation off the west coast of Ireland and its impact on realistic wave energy converters' power absorption. Appl Energy 2018;224:205–19. http://dx.doi.org/10.1016/j.apenergy.2018.04.121, URL https://www.sciencedirect.com/science/article/pii/S0306261918306895.
[50] Ulazia A, Penalba M, Rabanal A, Ibarra-Berastegi G, Ringwood J, Sáenz J. Historical evolution of the wave resource and energy production off the Chilean coast over the 20th century. Energies 2018;11(9):2289. http://dx.doi.org/10.3390/en11092289, URL http://www.mdpi.com/1996-1073/11/9/2289.
[51] Rusu L. Evaluation of the near future wave energy resources in the Black Sea under two climate scenarios. Renew Energy 2019;142:137–46.
[52] Goharnejad H, Nikaein E, Perrie W. Assessment of wave energy in the Persian Gulf: An evaluation of the impacts of climate change. Oceanologia 2021;63(1):27–39.
[53] Pourali M, Kavianpour MR, Kamranzad B, Alizadeh MJ. Future variability of wave energy in the Gulf of Oman using a high resolution CMIP6 climate model. Energy 2023;262:125552.
[54] Majidi AG, Ramos V, Giannini G, Santos PR, das Neves L, Taveira-Pinto F. The impact of climate change on the wave energy resource potential of the Atlantic Coast of Iberian Peninsula. Ocean Eng 2023;284:115451.
[55] Ibarra-Berastegui G, Sáenz J, Ulazia A, Sáenz-Aguirre A, Esnaola G. CMIP6 projections for global offshore wind and wave energy production (2015–2100). Sci Rep 2023;13(1):18046.
[56] Penalba M, Aizpurua JI, Martinez-perurena A. On the definition of a risk index based on long-term metocean data to assist in the design of Marine Renewable Energy systems. Ocean Eng 2021;242(March):110080. http://dx.doi.org/10.1016/j.oceaneng.2021.110080.
[57] Penalba M, Zarketa-astigarraga A, Branson P, Robertson B. Impact of resource uncertainties on the design of wave energy converters. In: 15th European wave and tidal energy conference. Bilbao, Spain; 2023, p. 529. http://dx.doi.org/10.36688/ewtec-2023-paper-529.
[58] Konuk E-B, Centeno-Telleria M, Zarketa-Astigarraga A, Aizpurua J-I, Giorgi G, Bracco G, et al. On the definition of a comprehensive technology-informed accessibility metric for offshore renewable energy site selection. J Mar Sci Eng 2023;11(9):1702.
[59] Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, et al. The ERA5 global reanalysis. Q J R Meteorol Soc 2020;146(730):1999–2049.
[60] EC-Earth Consortium (EC-Earth). EC-Earth-consortium EC-Earth3 model output prepared for CMIP6 scenariomip ssp370. 2023, URL https://www.wdc-climate.de/ui/entry?acronym=C6_4422882.
[61] Döscher R, Acosta M, Alessandri A, et al. The EC-Earth3 earth system model for the coupled model intercomparison project 6. Geosci model dev 15 (7): 2973–3020. 2022.
[62] Meucci A, Young IR, Hemer M, Trenham C, Watterson IG. 140 years of global ocean wind-wave climate derived from CMIP6 ACCESS-CM2 and EC-Earth3 GCMs: Global trends, regional changes, and future projections. J Clim 2023;36(6):1605–31.
[63] Bi D, Dix M, Marsland S, O'farrell S, Sullivan A, Bodman R, et al. Configuration and spin-up of ACCESS-CM2, the new generation Australian community climate and earth system simulator coupled model. J South Hemisphere Earth Syst Sci 2020;70(1):225–51.
[64] Carreno-Madinabeitia S, Ibarra-Berastegi G, Sáenz J, Ulazia A. Long-term changes in offshore wind power density and wind turbine capacity factor in the Iberian Peninsula (1900–2010). Energy 2021;226:120364. http://dx.doi.org/10.1016/j.energy.2021.120364, URL https://www.sciencedirect.com/science/article/pii/S0360544221006137.
[65] Andres-Martin M, Azorin-Molina C, Shen C, Fernández-Alvarez JC, Gimeno L, Vicente-Serrano SM, et al. Uncertainty in surface wind speed projections over the Iberian Peninsula: CMIP6 GCMs versus a WRF-RCM. Ann New York Acad Sci 2023;1529(1):101–8.