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# Extremes and variability of wind and waves across the oceans until the end of the 21st century

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ABSTRACT

The wave model WAVEWATCHIII is used to produce wave information, until the end of the 21st century, covering all ocean areas. Global wind and ice-cover climate data from a total of 120 years are used as input for the wave model. The period is divided into four 30-year slices, where the first (1980–2009) represents the recent past, the second (2010–2039) the near future, the third (2040–2069) the mid-century and the last one (2070–2099) represents the end of the 21st century. For each period, the mean value, the standard deviation and the 99th percentile are computed for significant wave height of total sea, wave energy and cumulative wave energy, and also for the 10-m wind magnitude field, used to force the wave model. Changes from the recent past to the present and to each of the two future periods are obtained and analyzed. The results show an increase in mean significant wave height of total sea, wave energy and cumulative wave energy in the South Atlantic, and an increase in variability and a decrease of mean significant wave height of total sea in the North Atlantic. Other regions also present changes but are less marked and less consistent through time.

## 1. Introduction

The wave climate information is useful for many activities related to the marine and coastal environments, such as planning and managing offshore platforms, ship structures, and wave energy resources (Laugel et al., 2014; Bitner-Gregersen et al., 2018; Guedes Soares et al., 2014). Although the mean conditions can provide important information, extreme waves, storms, and storminess, in general, have a major impact on coastal populations and ecosystems (Li et al., 2014), as the occurrence of such phenomena determine the short-term evolution of coast by beach erosion and destruction of infrastructures (Trifonova et al., 2012). Ships and offshore structures are designed to survive the extreme conditions expected to occur and thus storms and storminess are also critical (Nitta et al., 1992; Guedes Soares, 1996; Guedes Soares et al., 1996, 2014).

Understanding how the wind and wave regimes changed in the past and how they are expected to change in the future is of uttermost importance. According to the Intergovernmental Panel on Climate Change (IPCC) Working Group II, the risks of climate change to coastal populations and ecosystems require the inclusion of a broader range of coastal drivers of changes; one of these key drivers, which has received inadequate attention is wind-waves (IPCC et al., 2007). The Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012), has provided simulations for the earth system using a new generation of Global Climate Models (GCMs) that describe interactions between the components of the global climate system, until the end of the 21st century, but that do not include ocean waves. Their dynamical projections provide a physical response to climate changes in terms of surface winds that are used to force the wave models. The GCMs are driven by the emission scenarios consistent with the four Representative Concentration Pathways (RCPs), namely RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Moss et al.,2010; Van Vuuren et al., 2011).

While present-day climate is often studied using reanalysis or satellite data, future climate, divided into different periods, is usually studied using global or at least large-scale data produced by global wave or statistical models. These two different approaches to obtain sea state information from climate models, the dynamical one where wave models are forced with wind and sea-ice information from climate models, and the statistical one, where relations between atmospheric variables and wave parameters are established have different computational demands. The dynamical approach is more computationally demanding, but it provides a more complete set of information than the

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statistical one, so in the present study the data is produced using this approach.

Intensive research has been placed, in recent years, into assessing global and regional wave climate with the main focus on trends and variability of mean values and high percentiles. The Coordinated Ocean Wave Climate Project (COWCLIP) effort fostered several global studies addressing the global wave climate response to projected future climate scenarios with increase greenhouse gas concentrations (e.g. Hemer et al., 2013; Semedo et al., 2013, Wang et al., 2014).

Morim et al. (2018) analyzed 91 published global and regional scale wind-wave climate projection studies to establish consistent patterns of impacts of global warming on the wind-wave climate across the globe. Bonaduce et al. (2019), assessed the wave climate change of the North Atlantic by the end of the 21st century, using a regional wave climate projection under the RCP8.5 scenario. Meucci et al. (2020), used an ensemble of global wave model runs of a wave model, forced with surface winds simulated by different global climate models, to develop a dataset of storm wave conditions for the end of the 21st century. O'Grady et al. (2021), also evaluated how global climate change will alter wind sea and swell waves, modifying the severity, frequency, and impact.

In the ExWaCli research project, the past (1971–2000) and the future wave (2071–2100) climate was simulated by Aarnes et al. (2017) using the WAM model, while Bitner-Gregersen et al. (2018) summarized the results of the project. Six climate models, including the EC-Earth with three ensemble members and two emission scenarios, RPC4.5 and RPC8.5, were used in these investigations.

Camus et al. (2017) used a statistical approach to produce regional climate projections for coastal impacts. Morim et al. (2018) evaluated the changes in mean annual significant wave height, mean wave period, and mean wave direction using a multi-method ensemble of wave projections, including two emission scenarios RCP4.5 and RCP8.5, two statistical approaches, eight dynamical wind-wave modelling simulations, and two wave models. Historic and future wave conditions were analyzed by Bricheno and Wolf (2018) around the European Atlantic coast, making projections out to the year 2100 under RCP4.5 and RCP8.5 scenarios.

Recently, Meucci et al. (2020) studied changes in extreme wave events, from present-day to the end of the 21st century, at a global scale, evaluating 100-years return periods of Hs (significant wave height) in a seven-member ensemble. In their work, they also investigate changes in the frequency of extreme events. Lobeto et al. (2021) also use the same data to calculate changes in design return periods from the present to the end of the century, applying generalized extreme value distribution parametric models to annual Hs maxima.

Wave energy is very important, and it may play an important role in the planning of energy resources in the future, particularly if adaptation measures force the migration from fuel fossil to renewable energy sources. So, it is of utmost importance to know how this energy resource might change in the future in terms of magnitude but also of variability. Several studies indicate wave energy to be one of the most promising among marine renewable resources. Silva et al. (2018) showed that the higher energy of ocean waves is concentrated off the western coasts of Europe, in the 40°–60° latitude range north and south, due to the prevailing westerly winds. Other assessments provide a good picture of the present conditions (Bento et al., 2018; Goncalves et al., 2018, 2020). However, a global evaluation of the wave climate was presented by Sterl and Caires (2005) using data from the WAM wave model showing that there are other regions, outside this latitude belt that also present interesting wave conditions.

The present work aims to contribute to the state of the art in marine climate change enlarging the ensemble of available global wave climate simulations with a new member. Most published studies regarding future wave climate focus on the last 30 years of the 21st century, comparing it to the present climate. This work wants to evaluate how change occurs during the 21st century, dividing the 120 years of simulation into 4 periods representing the recent past, the present and two future periods. Changes from the recent past climate to each of these periods are assessed enabling the understanding of the more extreme situations described by different authors, at the end of the century.

## 2. Data and methods

To produce the wave climate information analyzed in this work, the WAVEWATCH III model (hereafter WW3) (Tolman, 1997, 1999) is forced with wind and sea-ice cover information from one CMIP5 model, the EC-Earth, using the RCP8.5 emission scenario. Different marine parameters are analyzed, the near-surface wind magnitude obtained from the EC-Earth and significant wave height of the total sea, wave energy and cumulative wave energy, obtained from the EC-Earth/WW3 simulation.

The EC-Earth (Hazeleger et al., 2010) is an earth-system model developed by a consortium of European research institutions and researchers, based on state-of-the-art models for the atmosphere, the ocean, sea ice and the biosphere. The simulations followed the CMIP5 protocol for long-term simulations (Taylor et al., 2012) which was implemented for the historical period of 1850–2005 and the continuing future period of 2006–2100. The CMIP5 experiments compared with its predecessor CMIP3, include more comprehensive models that are driven by the concentration or emission scenarios consistent with the RCP's described in Moss et al. (2010) and defined in the Fifth Assessment Report of the IPCC.

The EC-Earth system consists of atmospheric and ocean components, i.e., the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF) and the Nucleus for European Modeling of the Ocean (NEMO) developed by Institute Pierre et Simon Laplace (IPSL), which is coupled to the Louvain-la-Neuve sea Ice Model (LIM) embedded in NEMO. All atmospheric and ocean modules are coupled by the OASIS3 software. The EC-Earth community to contribute to the CMIP5 coupled model inter-comparison project with an ensemble of more than 12 simulations. However, for the present work only surface wind and sea-ice cover the simulation produced by the Swedish Meteorological and Hydrological Institute (SMHI) for a RCP8.5 scenario (Van Vuuren et al., 2011), was used to force WW3.

The WW3 is a third-generation spectral wave model that provides an appropriate framework for the current study. In WW3, the ST4 source-term package (Ardhuin et al., 2010) is selected for the wave simulations, which has the wind input source term adapted from Janssen (1991) with adjustments performed by Bidlot et al. (2005, 2007).

The wave power density (P), which is also referred to as the "wave energy flux", is given in W/m of wave crest width at any given water depth, and is calculated as:

$$P = \rho g \int_0^{\pi} \int_0^{\infty} E(f,\theta) C_g(f,h) df d\theta$$

in which E(f,θ) is the directional wave energy spectrum, f is the frequency, and θ is the direction of propagation of the spectral component, $C_g$ is the group velocity, h is the water depth, the seawater density ρ is 1025 kg/m3 and g denotes the acceleration due to gravity.

The wind fields used to force WW3 have a spatial resolution of 0.5° and a time resolution of 3 h. The sea-ice cover data has a monthly resolution, and its coverage differs from the wind field, as it uses a C-grid with a higher horizontal resolution of about one-third of a degree near the equator. Considering that the grid has three poles, one on the South Pole and two near the North Pole (one in Canada and one in Siberia), the horizontal resolution is increased in the vicinity of the North Pole, as described in Hazeleger et al. (2012). The model simulations covered the range between January 1980 and December 2099, covering four periods of 30 years each, adequate to the climate analysis. Stationarity within each of the 30 years periods is assumed.

These simulations have already been presented and validated by Bernardino et al. (2021), followed by a more detailed study on the associated changes in weather types (Lucas et al., 2021). Those studies compared climate simulations for the period 1980 to 2010 with ERA5 reanalysis, for the North Atlantic, and concluded that in general, the simulation performed with the EC-Earth/WW3 model for this period correctly represents the climate of the recent decades regarding mean values of Hs, Tp and Tm. The same was concluded for the wind magnitude obtained from the EC-Earth simulation. Discrepancies found in the extreme values were larger but still within an acceptable range.

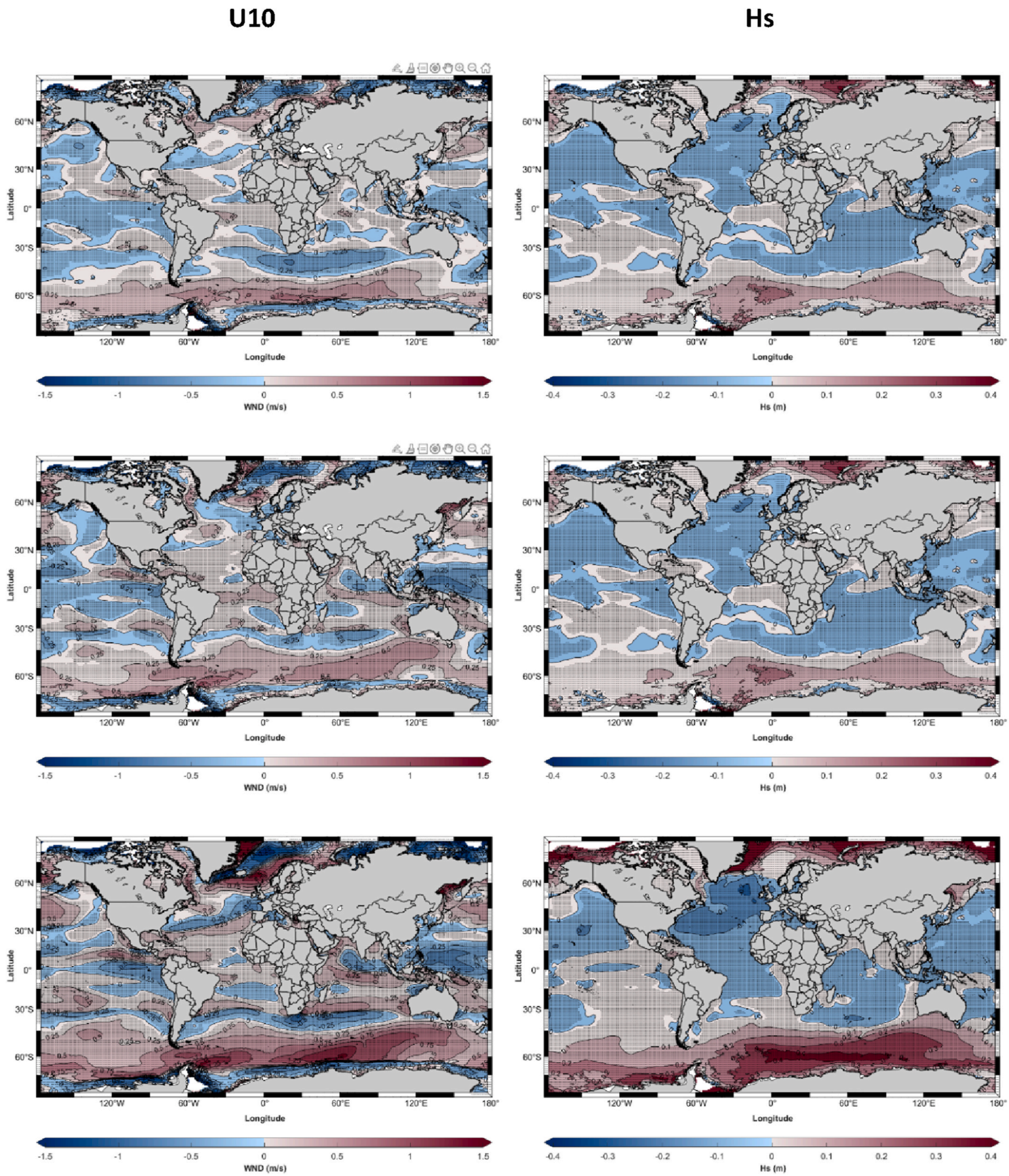


**Fig. 1.** Differences in mean wind magnitude (U10) and mean significant wave height (Hs), from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom). Shadowed areas indicate that the difference is statistically different than zero at a 99% significance level.

The study also concluded that the bias between the presented climate simulations and the ERA5 reanalysis is larger than the one between the recent past and the end of the century simulations. So, in this work, the focus is on changes from the climate of the past decades to each of the present and to the two different future periods and not on the absolute values of the wind and wave fields.

## 3. Results

To investigate the expected evolution of the global wave climate during the 21st century, the 120 years simulation performed with WW3 is divided into four periods of 30 years. The first one (1980–2009) represents the recent past, the second (2010–2039) the present climate, the third (2040–2069) the mid-century and finally the last (2070–2099) represents the end of the 21st century. For each period, the mean value, the standard deviation and the 99th percentile were computed for

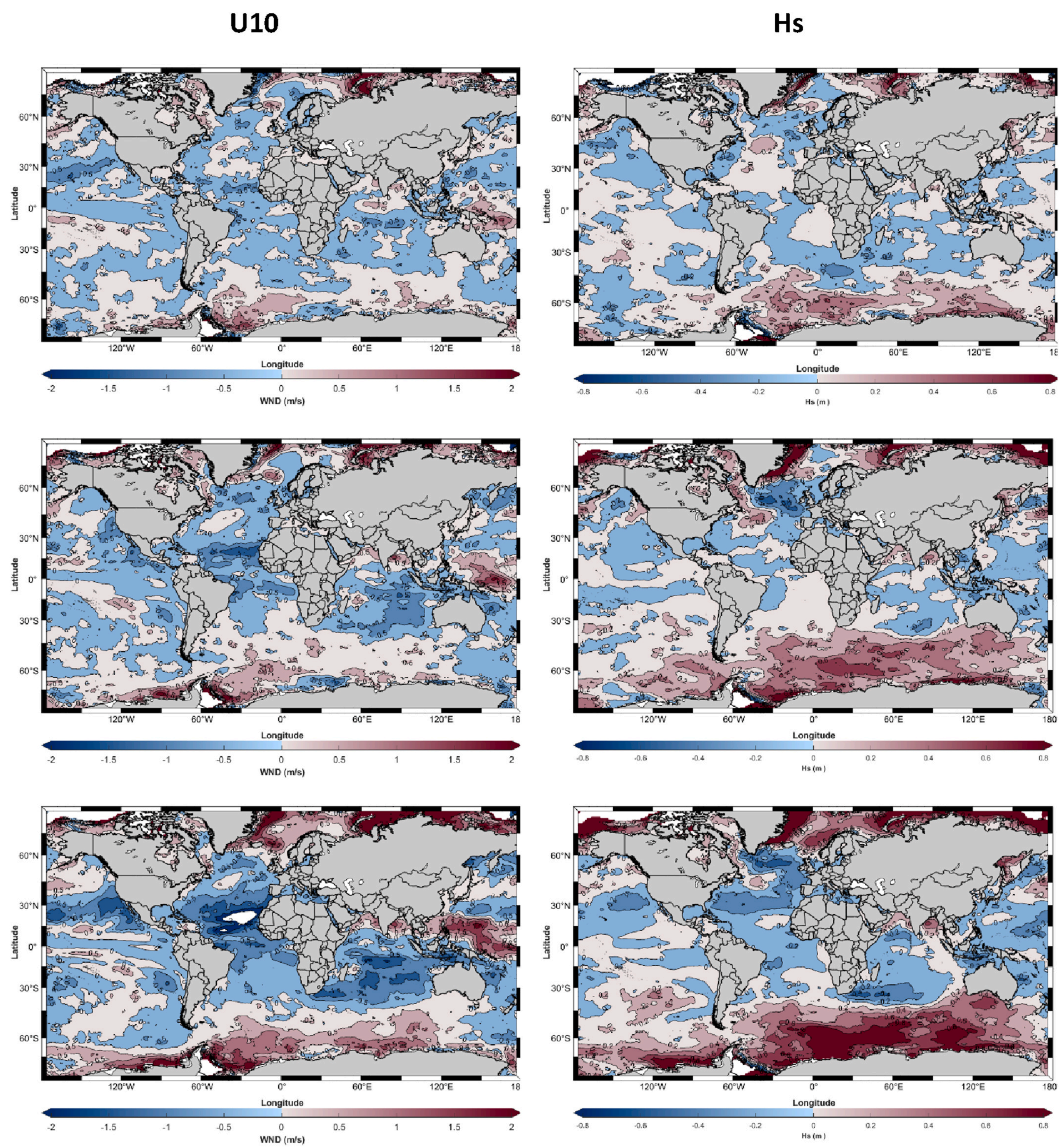


**Fig. 2.** Differences in 99th percentile of wind magnitude (U10) and 99th percentile significant wave height (Hs), from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom).

significant wave height of total sea (Hs) and wave energy (E). The 10-m wind magnitude (U10) field used to force the wave model is also analyzed and the same statistics are computed for each of the four periods. The difference between these statistics from the recent past to each of the present and future periods is computed and is presented in Figs. 1–3.

Fig. 1 shows in the left panel the difference between the arithmetic mean of the wind magnitude obtained for the recent past climate and the arithmetic means obtained for the present (top), mid-century (middle) and end of the century (bottom), periods. An unpaired two-sample *t*-test was performed at a 99% significant level to evaluate if the difference between the means was statisticaly significant. Shadowed regions represent areas where the null hypothesis (difference in the mean is zero) can be rejected, i.e., regions where the difference between the means is different than zero. For the present climate period, it is possible to identify a slight decrease in the mean wind magnitude in mean and low latitudes, with many regions showing no change. The Arctic Ocean, however, shows a significant increase in the mean values of U10 as well

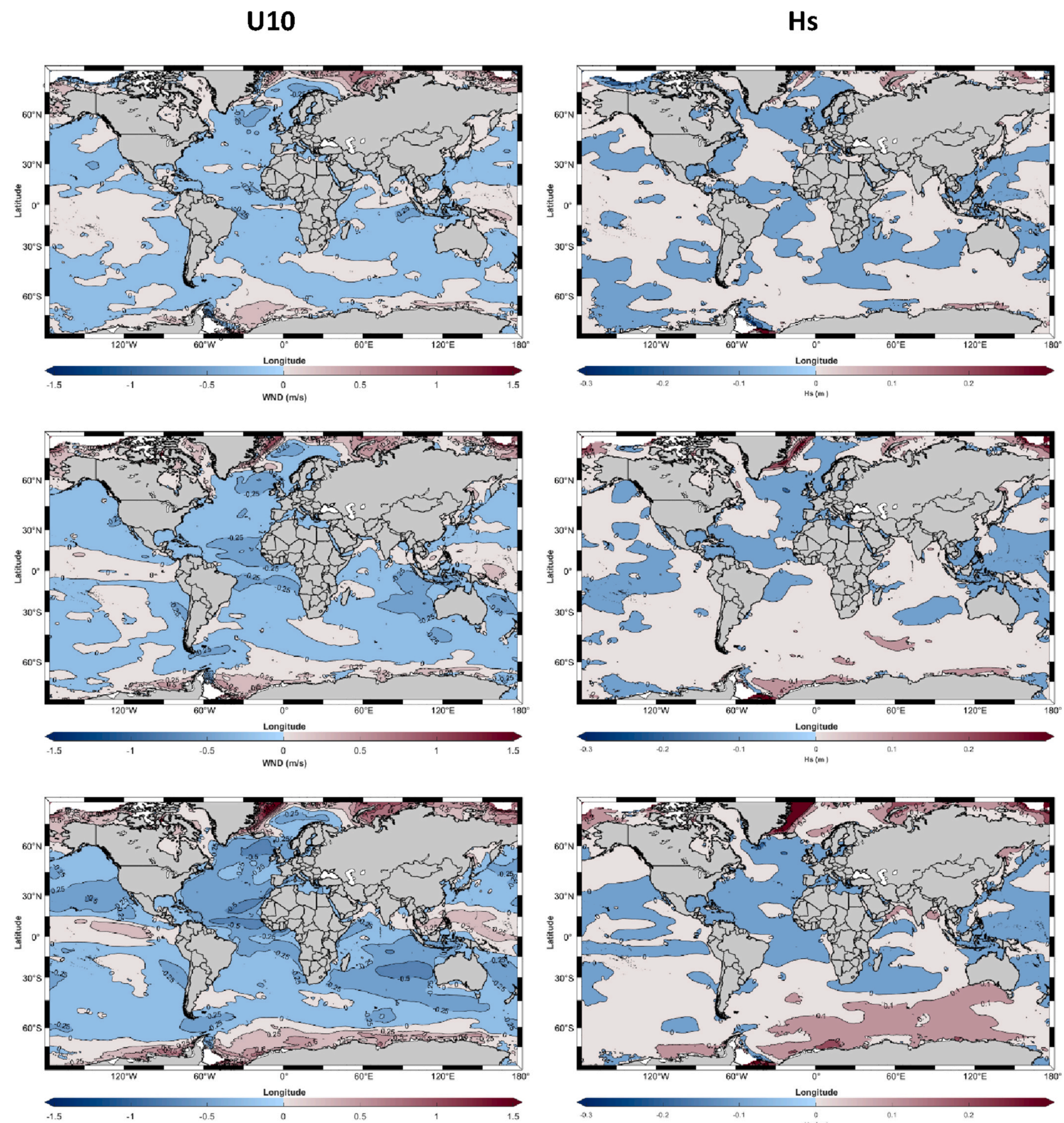


**Fig. 3.** Differences standard deviation of wind magnitude (U10) and standard deviation of significant wave height (Hs), from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom).

as latitudes around 60°N in the North Atlantic Ocean. The changes in the mean U10 panel for the mid-century and end of the 21st century presents similar patterns but with an intensification in magnitude. An increase in the mean U10 in the Arctic Ocean is intensified as the end of the century approaches. It can be observed that the differences are significant in almost all regions. Only locations where the difference is very small, less than 0.1 m/s, is the difference not statistically different than zero. Also, the difference between mean wind magnitude from the recent past to the end of the century presents less areas where this difference is not statistically significant.

In the right panel of Fig. 1, there is a difference in the mean Hs, between the recent past climate and the present and the two future periods. The patterns are like the ones observed for the mean wind magnitude but smoother. Generally, an increase of the mean Hs values is observed in the Arctic and Antarctic regions as well as a decrease (or no change) in other regions. The north hemisphere presents larger areas where the mean Hs decreases through the 21st century in particular in the North Atlantic Ocean where changes are more evident. These differences are significantly different than zero almost everywhere, being only statisticaly zero when the difference in Hs is in the order of a few centimeters. As the magnitude of the differences increases, in more areas these differences are statistically significant.

The left panel of Fig. 2 shows the difference between the 99th percentile of the wind magnitude from the recent past to present climate,mid-century and end of the 21st century periods. As for mean values, there is an increase in the wind extreme values, in the Arctic and Antarctic regions that intensifies through the century. The tropical region of the western Pacific also shows an increase in wind extremes with an intensification towards the end of the century. This area of increased wind extremes extends to the Indian ocean at the end of the 21st century.

The changes in the 99th percentile of Hs suggests an intensification of the extremes in areas where an intensification of the mean values was already observed, mainly in the Arctic and in the Antarctic regions with an intensification towards the end of the century and an enlargement of the areas where Hs extremes increase. Two regions did not show an increase in mean Hs but highlight where the 99th percentile changes positively: in the North Indian Ocean, and the mid-latitudes of the North Atlantic. In the first, the increase in the 99th percentile of Hs is very small in the present climate period but increases in the mid-century and it is marked at the end of the 21st century.

The evolution of changes in the 99th percentile of the Hs in the North Atlantic is not homogeneous. In the present climate period, most of this region shows very small changes up to 20 cm, in the mid-century, a small decrease of 20–40 cm. However, there is a region, around 45°N where a small increase is observed. During the mid-century period, changes in the North Atlantic show a northeast-southwest gradient with an area on the east indicating an increase in Hs extremes, followed by another region in the west showing a very marked decrease. This gradient almost disappears by the end of the century with only a small area around 45°N with an increase in the 99th percentile of Hs and most of the North Atlantic showing a marked decrease in extreme Hs values.

Changes in the variability of U10 and Hs areas have been analyzed by computing the standard deviation of these parameters within each 30 years period and then obtaining the difference between recent past, present climate and each of the two future climate periods. The results are presented in Fig. 4. Regarding U10, the change in variability is small in the present and in the mid-century periods, with a generalized decrease although the exceptions are the Arctic and the Antarctic regions. However, during the periods that include the last 30 years of the 21st century, there is an intensification of the changes, with most of the regions presenting a decrease in variability, particularly in the North Hemisphere. The Arctic and Antarctic regions present an increase as well as the Tropical Pacific. Observing changes in the variability of Hs, presented in the right panel of Fig. 3, indicated that changes from recent past to present and future periods are even smaller than the ones observed for U10.

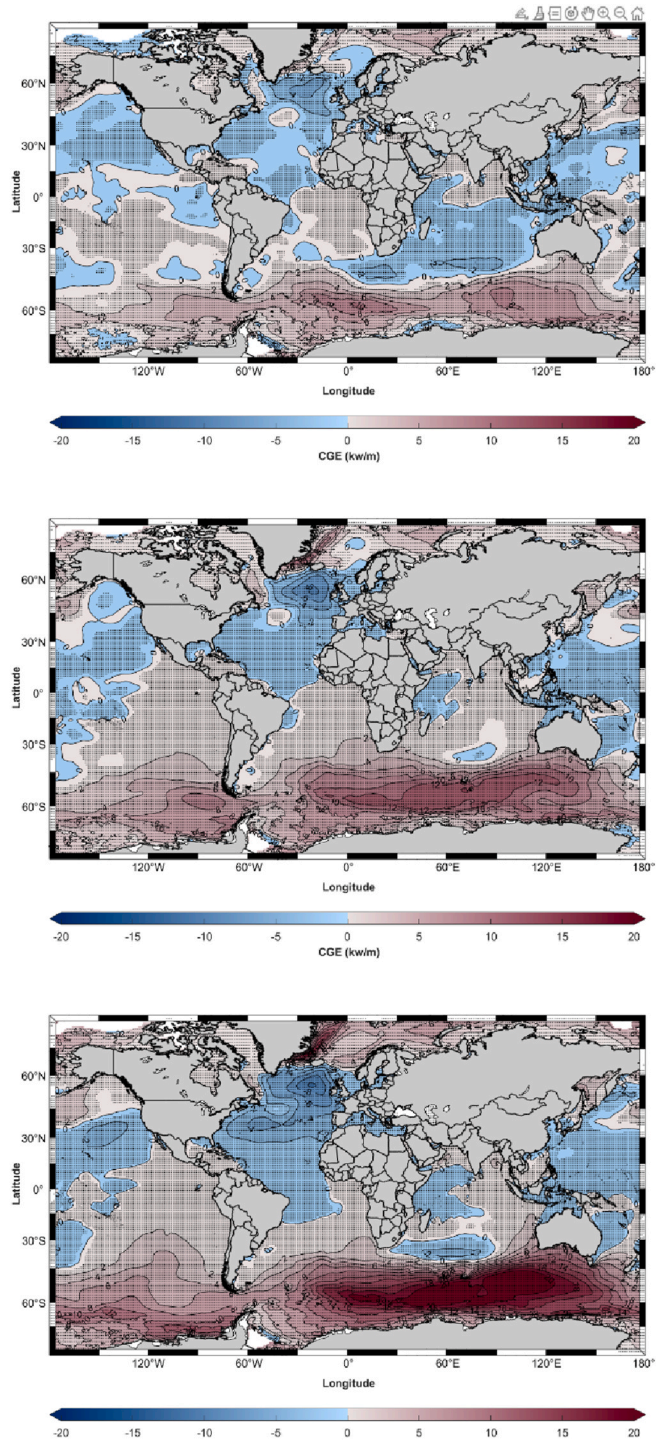


**Fig. 4.** Differences in mean wave energy from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom). Shadowed area indicate that the difference is statistically different than zero at a 99% significance level.

Wave energy was extracted from WW3 simulations for four periods considered in this work, and as for the significant wave height and wind magnitude, the mean, the 99th percentiles for each 30-year were obtained as well as the standard deviation. Then, for each period, the differences between past, and present and future energy potential are obtained and results are shown in Figs. 4–6. As before, an unpaired two-sample *t*-test was performed at a 99% significant level to evaluate if the difference between the means was statisticaly significant and shadowed

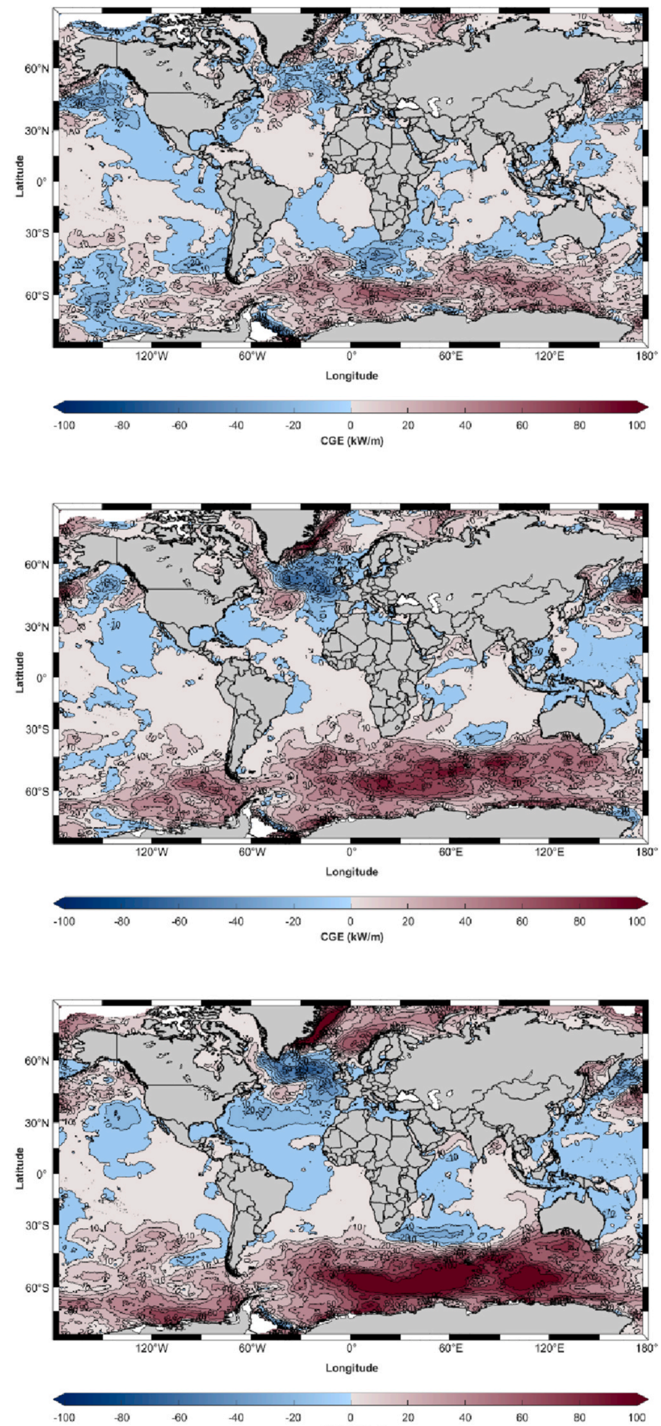


**Fig. 5.** Differences in 99th percentile of wave energy from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom).

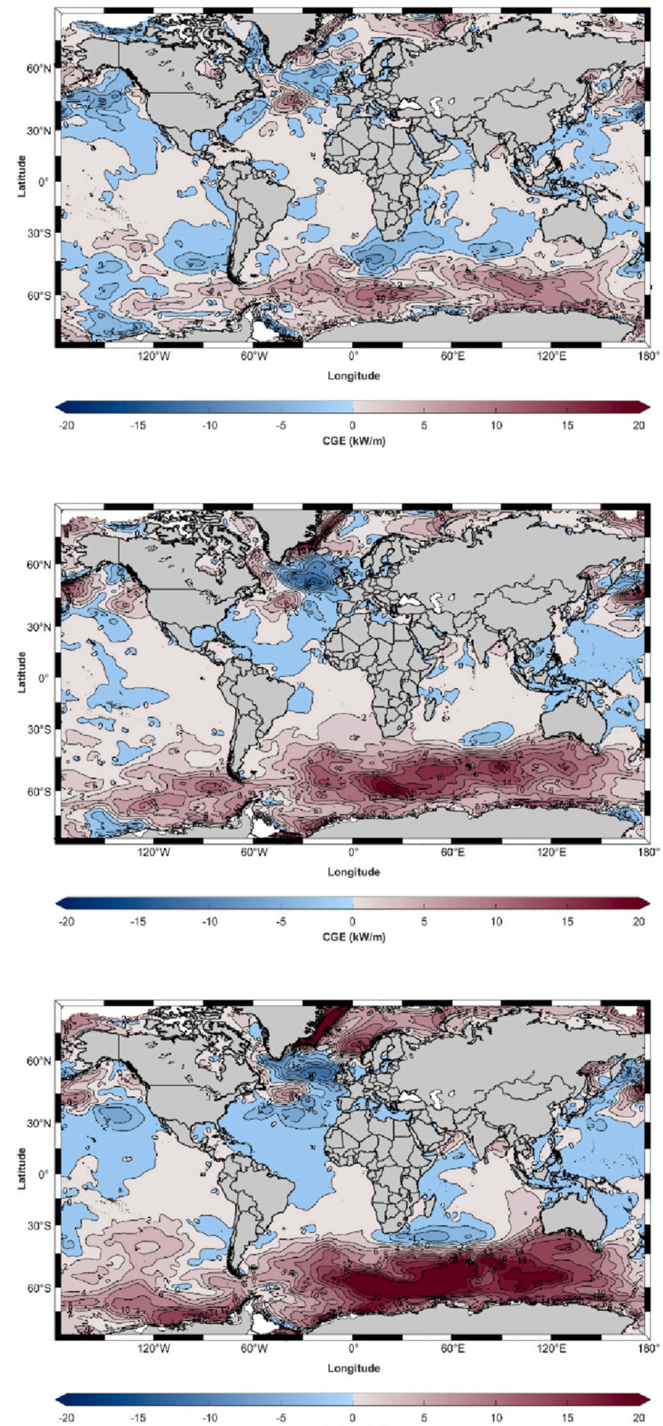


**Fig. 6.** Differences in standard deviation of wave energy from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom).

regions represent areas where this difference is statistically different than zero.

Regarding the mean values of the wave energy, it can be seen that changes from the recent past to the present climate period, are rather small in most places. The exceptions are the Antarctic Ocean where an increase in energy up to 10 kW/m is observed, and the North Atlantic Ocean where a decrease up to 4 kW/m is observed in high latitudes. Observing the changes in mean values obtained using the following 30 years, which represent the mid-century climate, although most of the oceans show no change, although an intensification of the patterns seen in the previous period is present in both the Antarctic Ocean (an increase in wave energy up to 12 kW/m and the area affected by this increase affecting the becomes larger affecting the south of the American continent, South Africa and the southern coast of Australia.

In the North Atlantic, in the area where a decrease is observed in the previous 30 years, the difference between mid-century and present mean wave energy reaches -8 kW/m. The area affected by this change also becomes larger. In high latitudes, above 60° North, there is a slight increase in wave energy probably associated with sea-ice retreat, which can be observed in particular on the eastern coast of Greenland. As the analyzed period reaches the end of the 21st century, an intensification of the areas or values continue to be seen with increasing wave energy (the Southern Ocean and eastern coast of Greenland) and in the North Atlantic, the area affected by the decrease in wave energy expands affecting most of the Atlantic between 30° and 60° N.

As observed for wind magnitude and for significant wave height, changes in mean wave energy are statistically significant almost everywhere. Only in small areas where the change is very small (as some regions of the North Pacific) the change in mean wave energy can be considered statistically zero.

Changes in the extreme values of the wave energy occur approximately in the same regions where changes in mean value are observed and with the same signal. The spatial structure is more complex, and the magnitude of the change is higher. In the northern hemisphere between latitudes 30°N and 60°N, however, there are differences between changes in the mean and changes in the 99th percentile. Regarding the extremes, and especially during the mid-century period, an increase in the magnitude of the 99th percentile can be observed around 45°N, both in the Atlantic and in the Pacific. These patterns smoothen when the end of the 21st century is analyzed, almost disappearing in the North Atlantic. In the Antarctic Ocean, the increase in the 99th percentile of wave energy is very marked, following the increase in the mean.

In general, comparing the changes observed in the mean values and in the extremes, of wind magnitude, Hs and wave energy, it can be seen that there are regions with small changes, both in the mean and in the extremes, but in regions where the mean suffers larger changes, the changes in the extremes are even larger. This may be explained by changes in the statistical distribution. Only changes in the mean were statistically evaluated.

To evaluate changes in wave energy variability the difference between the standard deviation in present and each of two future climate periods, and the recent past have been computed. Moving from the present to the end of the 21st century, it can be observed that at the beginning of the century, differences from the recent past are small and that there are areas that show an increase in the variability close to areas that show a decrease. In the southern hemisphere, an almost zonal behaviour can be seen, with an increase in the variability of wave energy close to Antarctica and an area of a small decrease around 45° S.

Between 30°S and 30°N, almost no change is observed. In the northern hemisphere, in latitudes above 30°N, most of the Pacific shows a decrease in the standard deviation of the wave energy but the northeast side of the basin shows a small increase. In the North Atlantic, the pattern is complex, with a decrease and increase of variability in adjacent areas. In the mid of the century, the patterns that represent changes in the variability of wave energy are more organized. In most regions south of 40°S, the standard deviation values increase in comparison with the present climate more strongly than in the first 30-years period.

During the end of the 21st century period, there is an intensification of the patterns already present in the previous period. The variability strongly increases in the Southern Ocean and the Atlantic above 60° N. In other regions the patterns and values that represent changes in variability are similar to the ones observed during the mid-century period.

Cumulative wave energy is an important parameter in the planning of offshore structures wave energy farms (Rodriguez-Delgado and Bergillos, 2021). This parameter was computed for each 30-year period and the difference between the recent past and the present climate periods was obtained, as well as the difference between recent past and near future and end od the century periods. Results can be observed in Fig. 7.

It can be seen in the top panel of Fig. 7 that the cumulative wave energy over 30 years suffers a decrease during the present climate period in comparison to the recent past in most of the oceanic regions between 60° S and 60° N. Except in the North Atlantic, this decrease is not very marked (less than 0.4 GW/m in magnitude). In polar regions above 60° S and 60° N, in particular in the Antarctic Ocean, an increase in the

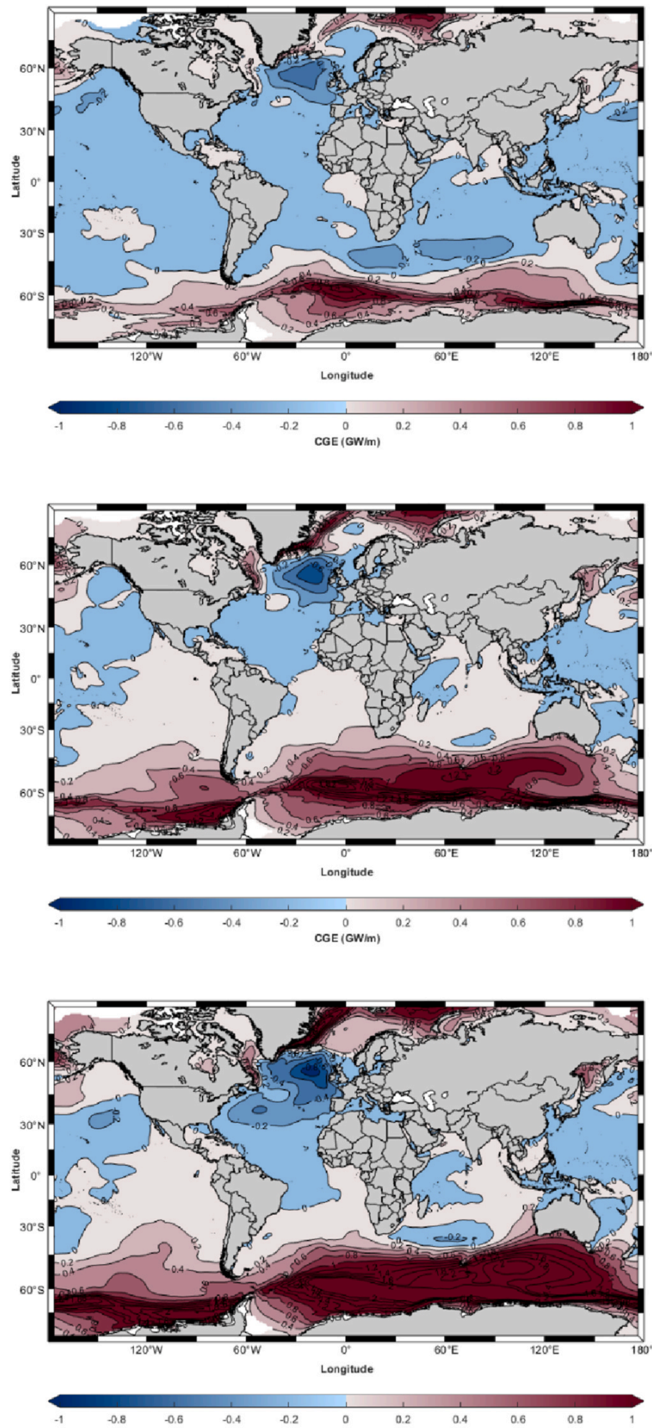


**Fig. 7.** Differences in cumulative wave energy from the recent past to the present climate (top), mid-century (middle) and end of the century (bottom).

cumulative wave energy is observed with values reaching as high as 0.8 GW/m. Observing the changes in cumulative wave energy from the recent past to the near future (mid panel of Fig. 7), it is clear that the areas with a positive change have spread to lower latitudes, especially in the southern hemisphere. Only in the north Atlantic there are regions with a marked decrease in this parameter. In most of the world oceans, the change in cumulative wave energy over 30 years, compared with the recent past, takes values between −0.2 and + 0.2 GW/m. As the end of the century approaches, we can see an intensification of the patterns observed in other periods. In the Arctic and Antarctic oceans a strong (higher than 0.8 GW/m) increase in cumulative wave energy compared with the recent past period. In the north Atlantic, the regions where a decrease was visible in previous periods, has spread affecting most of the North Atlantic up to 60 o N. Some regions of the north Pacific and in the south of the Indian Ocean, also present a decrease in the cumulative wave energy, with a magnitude higher than 0.2 GW/m.

It should be observed that the cumulative wave energy is proportional to the mean wave energy, so the patterns found for both variables are the same, but the absolute values are different. Nevertheless, the cumulative wave energy is more interesting in terms of planning purposes than the mean wave.

## 4. Discussion

The results obtained in this paper are in agreement with the ones found by Bitner-Gregersen et al. (2018) and Aarnes et al. (2017) who analyzed six climate models, also EC-Earth and two emission scenarios RPC4.5 and RPC8.5 and found, in a general agreement between all models, that the mean significant wave height is expected to decrease by the end of the 21st century in the north-eastern Atlantic, more strongly in the RCP8.5 scenario. Bricheno and Wolf (2018) analyzing wave conditions around the European Atlantic coast until the end of the 21st century also found a decrease in mean significant wave height of the order 0.2 m across most of the European coast.

Morim et al. (2018) analyzed 91 published global and regional scale wind-wave climate projection studies and found consensus amongst studies regarding an increase of the mean significant wave height Hs across the Southern Ocean, tropical eastern Pacific, and Baltic Sea, and conversely, a decrease of Hs over the North Atlantic and the Mediterranean Sea.

Meucci et al. (2020), found that the magnitude of a 1 in 100-year significant wave height (Hs) event increases by 5–15% over the Southern Ocean by the end of the 21st century, compared to the 1979–2005 period. Their results for the North Atlantic show a decrease at low to mid-latitudes (≈5–15%) and an increase at high latitudes (≈10%). These results are also corroborated by Lobeto et al. (2021), who conclude that the Southern Ocean is the region where the most robust increase in extreme Hs is projected, showing local increases of over 2 m regardless of the analyzed return period under RCP8.5 scenario but that, the tropical north Pacific shows a robust decrease in extreme Hs, with local decreases of over 1.5 m.

In general changes in extreme values are more marked than changes in the mean, but the signal of the change is not the same everywhere. Changes in standard deviation are small and in general indicate a decrease in variability. An increase in variability is usually found in regions where a significant increase in the 99th percentil was observed, as the Antarctic Ocean.

The decrease in the Hs in the North Atlantic Ocean by the end of the 21st century is attributed by several authors to the strongest warming of the arctic region compared to the extratropical region (Overland et al., 2014) due to climate change. This unequal warming reduces the temperature gradient between the two regions, leading to a reduction in baroclinic instability and cyclogeneses (Seiler and Zwiers, 2016), leading to fewer and weaker storms.

Increases in Hs and wave energy in the Antarctic region may be related to the observed increase in wind. Also, the expected increase in the moisture content of the atmosphere, resulting from an increase in temperature, can potentially lead to more explosive cyclones, explaining the increase in variability in these regions. Changes in fetch, resulting from changes in ice coverage may influence the wave fields.

It should be stressed that the large variability of the surface winds in different climate model simulations representing the end of the 21st century, together with ice cover uncertainty, transfers uncertainties into the wave fields. Having a large collection of climate simulations using different climate models, with more diverse emission scenarios and different wave models available, allows a better awareness and preparation to address these uncertainties.

## 5. Conclusions

This work has the objective of contributing to the state-of-the-art knowledge of the present and future wave climate, providing global wave simulations obtained from the WW3 wave model forced by wind and sea ice-cover from a CMIP5 model RCP8.5 integration. Four data sets of 30 years each representing the recent past climate (1980–2009), present climate (2010–2049), the mid-century (2050–2069) and the climate at the end of the 21st century (2070–2099) are produced, and changes in the mean values, 99th percentile and standard deviation of U10, Hs, wave energy and cumulative wave energy from the recent past to the present climate and to two future periods are evaluated.

In the present climate period, it is possible to identify a slight decrease in the mean wind magnitude in mean and low latitudes, with many regions showing no change. The Arctic Ocean, however, showed a significant increase in the mean values of U10 as well as latitudes around 60°N in the North Atlantic Ocean. Mid-century and end of the 21st century presented similar patterns but with an intensification in magnitude.

Regarding Hs, patterns are similar to the ones observed for the mean wind magnitude but smother. In general, an increase of the mean Hs values in the Arctic and Antarctic regions, as well as a decrease (or no change) in other regions, is found. In the north Atlantic the mean Hs decreases through the 21st century while in other regions, no significant change was observed.

Changes in mean wind magnitude and Hs, were statistically evaluated and are found to be different from zero in almost all regions.

There is an increase observed in the wind extreme values (99th percentile), in the Arctic and Antarctic regions and the tropical region of the western Pacific, that intensified through the century. This area of increased wind extremes extends to the Indian ocean at the end of the 21st century.

The evolution of changes in the 99th percentile of the Hs is not homogeneous. In the present climate, most of the North Atlantic shows very small changes up to 20 cm, in the mid-century, a small decrease of 20–40 cm, the exception being a small region around 45°N that shows an increase. Moving to the end of the century, changes in North Atlantic show a northeast-southwest gradient with an area on the east indicating an increase in Hs extremes, later, this gradient disappears and most of the North Atlantic shows a marked decrease in extreme Hs values. In the Arctic and the Antarctic regions an intensification of extreme values is visible towards the end of the century as well as an enlargement of the areas where these extreme values are increasing. Changes in the mean value and the 99th percentile of wave energy and follow the changes observed in Hs.

Changes in the variability U10 show a small decrease in the present climate and the mid-century periods, except for the Arctic and the Antarctic regions. However, in the last 30 years of the 21st century, there is an intensification of the changes, with most of the regions presenting a decrease in variability, particularly in the North Hemisphere. The Arctic and Antarctic regions present an increase as well as the Tropical Pacific. Changes in the variability of Hs, are even smaller than the ones observed for U10. During the period representing the beginning of the century, differences in wave energy variability compared with the present climate are small. During the period covering the mid of the century, the patterns that represent changes in the variability of wave energy are more organized and in most regions south of 40°S, the standard deviation values increase in comparison with the recent past more strongly than in the first 30-years period. As the end of the 21st-century approaches, there was an intensification of the patterns that represent these changes with variability strongly increasing in the Southern Atlantic and the Atlantic above 60° N. Changes in wave energy and in cumulative wave energy are in general small except for the Antartic region and for the North Atlantic. In these regions an intensification of the change is observed, from present until the end of the 21st century.

## CRediT authorship contribution statement

**M. Bernardino:** Writing – original draft. **M. Gonçalves:** Formal analysis, Visualization, Writing – original draft. **R.M. Campos:** Review writing. **C. Guedes Soares:** Writing – review & editing.

## 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

No data was used for the research described in the article.

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