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North Sea Wave Conditions: an analysis of four Transient Future Climate Realizations

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Abstract

The multi-decadal wave conditions in the North Sea can be influenced by anthropogenic climate change. That may lead to the intensification of wave extremes in the future and consequently increasing risks for the coastal areas as well as for on- and offshore human activities. Potential changes caused by alteration of atmospheric patterns are investigated. Four transient climate projections (1961–2100), reflecting two IPCC emission scenarios (A1B and B1) and two different initial states, are used to simulate the wave scenarios. The potential wind-induced changes in waves are studied by comparing future statistics (2001–2100) with the corresponding reference conditions (1961–2000). Generally, there is a small increase in future 99 percentile significant wave height for most eastern parts of the North Sea towards the end of the 21st century. This small increase is superimposed by a strong variability of the annual extremes on time scales of decades. Opposite to the differences in wave height, the change in wave direction to more waves propagating east shows less decadal variability and is more uniform among all realizations. Nevertheless, temporal and spatial differences of the wave height in the four climate projections point to the uncertainties in the climate change signals.

1 Introduction

The knowledge of various aspects of the wave climate on global and regional scales is essential for ocean and coastal applications. Information about past, present and future wave statistics is needed for planning, operating and maintaining offshore and coastal infrastructure and human activities. Studies on extreme wave conditions are important to assess the vulnerability of marine infrastructure like offshore platforms and coastal defenses. The knowledge of mean wave conditions is of interest for ship design, harbor activities and operational service of platforms. An overview of the importance of studies on wave climate is presented by Hemer et al (2012).

Past and present wave conditions can be analyzed from wave observations which are sparse in time and space. Reconstructions or hindcast simulations (e.g. WASA-Group, 1998; Weisse and Günther, 2007; Cieřlikiewicz and Paplińska-Swepel, 2008; Reistad et al, 2011) with wave models are more homogeneous in time and space. They showed their capability of reproducing the observed wave climate and are used for various purposes such as described in Weisse et al (2009).

In the future it is likely that on- and offshore activities will increase (e.g. Berkenhagen et al, 2010; BSH, 2013). In the last decade several studies with wave climate projections for the North Sea became available (e.g. Debernard and Røed, 2008; Grabemann and Weisse, 2008; Lowe et al, 2009; de Winter et al, 2012). Most of them are time slice experiments usually comparing time periods of about 10 to 30 years for the late 20th century and for the end of the 21st century forced with different output of global and regional models. Using time slice experiments only changes between two periods and variations due to different models and emission scenarios can be investigated. The assessment of changes is limited by the scarce information on decadal climate variability inherent in such simulations. To address this issue, transient climate change simulations are required. With today's computational resources long transient model simulations are possible within an acceptable amount of time. Here, a new set of four transient projections for the wave climate in the North Sea is presented. For this set the wave model WAM is forced by wind fields derived from climate simulations with a regional climate model (RCM). The boundary conditions used to drive the RCM were obtained from global simulations with one general circulation model (GCM) incorporating two different initial conditions and two emission scenarios.

For human activities and marine infrastructure both mean and extreme wave conditions are important and will be analyzed using the annual median and the 99 percentile of the hourly wave height. Beside changes of the wave height, changes of the hourly mean wave direction are investigated. Wave directions are described as *going to*. The wave direction is important for e.g. sediment transport, coastal erosion and harbour agitation (e.g. Dreier et al, 2011; Casas-Prat and Sierra, 2012). Changes in the wave conditions are discussed with respect to accordant changes in the wind fields. To allow for a comparison with other time slice studies, changes of the significant wave height for 30-year time periods are shown. Special emphasis is given to the temporal variability of the significant wave height and the wave direction estimated from the transient simulations.

2 Model description and experimental setup

2.1 Model setup

2.1.1 The wave model - WAM

The third generation spectral wave model WAM (WAMDI-Group, 1988) is used to simulate the ocean wind waves. This state-of-the-art wave model has been used in several hindcast and future scenario studies (e.g. Weisse and Günther, 2007; Grabemann and Weisse, 2008). Here, the model

Figure 1: Model chain and ensemble setup and the used domains and topographies in the coarse and fine grid runs of the wave model WAM. The four locations used in the analysis are shown in the find grid domain.

version 4.5.3 is used in a nested mode. The coarse grid (Figure 1) has a horizontal resolution of $0.5^\circ \times 0.75^\circ$ (latitude x longitude) which corresponds roughly to a 50 km x 50 km grid. The grid covers most of the Northeast Atlantic and is limited to the boundaries of the output from the driving RCM (see 2.1.2). The area is large enough to take into account wind sea and swell entering the North Sea area from the Northeast Atlantic. The effect of a reduced fetch due to changing sea ice in the northern parts of the coarse grid is considered. The GCM simulations described in 2.1.2 deliver monthly sea ice coverage in the Northeast Atlantic for the coarse grid wave simulations.

The fine grid for the North Sea (Figure 1) has a resolution of $0.05^\circ \times 0.075^\circ$, corresponding to about 5.5 km x 5.5 km. It covers the area from 51°S to 58.5°N and 3.25°W to 10.25°E . The fine grid simulations get the spectral wave information at the boundaries from the coarse grid simulations. The wave spectra for both grids (coarse and fine) are calculated for 25 frequencies (from 0.04177 Hz to 0.41145 Hz) and 24 directions. The model is used in shallow water mode with depth refraction. The integration time step is one minute and wave parameters are stored every hour.

2.1.2 The forcing atmosphere models

The wave simulations are driven by wind fields at 10 m height from simulations with the RCM COSMO-CLM (Consortium for Small-scale Modeling – model in CLimate Mode, hereafter CCLM, Rockel et al (2008)). Simulations with the CCLM are derived within the consortial project (Hollweg et al, 2008). The CCLM simulations are calculated on a $0.165^\circ \times 0.165^\circ$ rotated horizontal grid, which corresponds to about 18 km x 18 km over Central Europe and uses 32 vertical layers. The RCM simulations get the boundary information from Fourth Assessment Report (AR4) simulations with the coupled atmosphere-ocean GCM ECHAM5/MPI-OM (Röckner et al, 2003; Marsland et al, 2003).

Figure 2: Differences of the 40-year mean (1961–2000) of annual median and 99 percentile significant wave height between the C20 and the H20 simulations in [cm] (left: C20_1 minus H20; right: C20_2 minus H20). Only differences for a water depth greater than 10 m are shown. The contour lines display the 40-year mean of corresponding significant wave height in H20 in [m].

2.2 Ensemble setup and model chain

To investigate the future range of possible changes in wave conditions an ensemble of four simulations is used, which consists of two realizations with two emission scenarios. To address the internal variability, the two realizations differ in their initial conditions (starting year 1860). Hereby, two dates chosen from a 550 year long quasi-equilibrium pre-industrial simulation with fixed external forcings and greenhouse gas concentrations from the year 1860 are defined as initial conditions for the two reference simulations of the global climate. These GCM reference simulations for the years 1860 to 2000 are forced by the observed greenhouse gas concentrations. Subsequently, from 2001 to 2100 the simulations are forced with the two IPCC SRES emission scenarios A1B and B1 (Houghton et al, 2001; Nakicenovic and Swart, 2000). The RCM simulations are performed from 1960 to 2100 using these GCM simulations as boundary conditions (Hollweg et al, 2008). The RCM simulations are used to generate two 40 year long wave simulations for the 20th century (1961–2000, hereafter C20_1 and C20_2) and corresponding four 100 year long wave simulations under climate change scenario conditions (2001–2100, hereafter A1B.1, A1B.2, B1.1 and B1.2). A schematic illustration of the model chain and ensemble setup is shown in Figure 1.

3 Results

3.1 Validation

To validate the simulated wave conditions, the results of the two C20 simulations are compared with data from the wave hindcast (hereafter H20) by Weisse and Günther (2007) and with observations at platform K13 (53.22°N, 3.22°E). H20 is taken as a reference for the two 40-year C20 simulations for 1961–2000. For the comparison the C20 simulations are interpolated on the slightly coarser grid (0.05° x 0.1°) of the hindcast. As the domain of the hindcast is smaller, the comparison is limited to the area south of 56°N. Figure 2 shows the differences between the hindcast and the two C20 simulations for the 99 percentile of the significant wave height. For large areas in the North Sea the C20 simulations underestimate the hindcast wave conditions by 10 to 30 cm (2-6%). Along the British Coast and in the southernmost parts of the North Sea the C20 simulations overestimate the hindcast up to 40 cm (10%). The median wave conditions show a slightly different pattern compared to extreme conditions (not shown) and are underestimated

Figure 3: As Figure 2 but for the differences of the 40-year mean (1961–2000) wave direction.

by about 2 to 6 cm in the northern parts of the domain and are overestimated up to 8 cm in the southern parts compared to the hindcast wave conditions. The percentage deviations of the median are comparable to those for the extreme conditions and range between -3% and +8%.

The comparison of the mean wave direction (Figure 3) for the period 1961–2000 between the C20 and the H20 simulations shows over large areas a counterclockwise deviation between 5 to 10 degrees. These more easterly wave directions are in accordance with the more pronounced westerly winds in the ECHAM5 GCM simulations over Europe discussed by e.g. Bengtsson et al (2006) and Pinto et al (2007).

In Figure 4 a comparison of the wave simulations with observations is displayed. The left panel shows a quantile-quantile plot of the two C20 simulations and the H20 data against wave observations at the platform K13 for the years 1980–2000. To account for possible gaps in the observations, the comparison with the hindcast is only carried out for time steps where observations are available, whereas all time steps for the years 1980–2000 of the C20 simulations are used for the comparison. For wave heights above 3 m all model simulations (H20 and C20) overestimate the observations, for more moderate conditions the model simulations fit the observations adequate. The right panel presents the directional distribution using the same data as for the quantile-quantile plot. The H20 and the C20 simulations overestimate the frequency of zonal directions and underestimate meridional directions.

Compared to the H20 simulation the wave heights and the frequency of easterly directions of the C20 simulations show less overestimation relative to the observations at K13. At other locations with less observational data or only hindcast data the results are similar to the comparison at K13, hence the C20 simulations can be used as an adequate reference climate to investigate future wave conditions under climate change scenarios.

3.2 Wave conditions in the climate change scenarios

Here, spatial changes of the significant wave height and wave direction are presented for the three consecutive time periods 2011–2040, 2041–2070 and 2071–2100. Besides comparing time periods, the transient simulations enable investigations of the temporal variations within the simulated 140 years. Thus, multi-decadal variations are shown on the basis of three locations in the North Sea: CNS (56.4°N, 2.375°E) is located in the central part of the North Sea and NOR (53.8°N, 6.875°E) and SYL (54.9°N, 8°E) are situated in the southern and eastern parts of the German Bight, respectively (see Figure 1). All changes are presented relative to the reference period 1961–1990 and are mentioned as climate change signals.

Figure 4: Left: Quantile-quantile plot of tenth percentiles wave height (0, 0.1, 0.2, ..., 99.8, 99.9, 100) of C20_1 (blue), C20_2 (cyan) and H20 (green) versus observations at K13. Percentiles are generated from 21 years (1980–2000) three hourly significant wave heights. Right: Wave rose for the same data as the quantile-quantile plot with the directional distribution in [%].

3.2.1 Spatial variability in consecutive time periods

Figures 5 and 6 display the spatial changes in 30-year averaged annual median and 99 percentile significant wave height for all realizations relative to the corresponding control climate for the three consecutive time slices. Climate change signals are tested for their statistical significance on a 95%-level with a student's *t* test with Welch correction to take into account for the possible unequal population variances and are marked in the figures. However, also not significant changes are discussed.

In the first period (2011–2041) changes in the median significant wave height are spatially heterogeneous in all realizations (Figure 5). A1B.1 and B1.1 show a zonal gradient of changes with a statistically significant decrease of -8 cm in northwestern parts in A1B.1. In A1B.2 and B1.2 a more meridional gradient with an increase towards the eastern parts of the North Sea is evident. In the second period (2041–2070) a meridional gradient of changes is evolved in all realizations with a decrease in the western parts and an increase in the eastern parts. The largest changes are in A1B.1 and range from -8 cm to $+8$ cm. At the end of the 21st century (2071–2100) a pronounced meridional gradient of changes has established in all four realizations. The eastern parts of the North Sea show a general increase of median wave height with a maximum of $+6$ cm to more than $+8$ cm in the Skagerrak and around $+2$ cm to $+4$ cm in the German Bight, except in B1.2 where changes are smaller. In the western parts of the North Sea especially along the British Coast a decrease of the median wave height of -4 cm to below -8 cm is evident. However, statistically significant changes are limited, if any, to the Skagerrak and along the British Coast in most time periods and realizations and corresponds to a change from 5% to 8% relative to the reference period.

The climate change signals for extreme wave heights (99 percentile) are shown in Figure 6. In the early 21st century period changes in the extreme wave height are spatially heterogeneous between the four realizations. The changes for the period 2041–2070 show large areas with a

Figure 5: Differences of the 30-year mean of annual median significant wave height in [cm] for the periods 2011–2040, 2041–2070 and 2071–2100 (rows) relative to 1961–1990 for the four realizations A1B_1, B1_1, A1B_2 and B1_2 (columns). Dotted areas show differences which are not statistically significant on the 95%-level based on a Students t test with Welch correction.

decrease of the extreme wave height in the western parts in all realizations (below -40 cm) and in the central parts of the North Sea in two realizations (A1B_2 and B1_2). The strongest increase of extreme wave height is evident in the Skagerrak (up to $+40$ cm). In the period 2071–2100 larger areas show an increase in extreme wave height, specially A1B_1 with statistically significant changes of more than $+30$ cm in the eastern parts of the North Sea (German Bight and Skagerrak). B1_1 displays a similar pattern, but with a smaller increase ($+10$ cm to $+20$ cm) in the east and larger decrease (below -40 cm) in the west. A1B_2 and B1_2 show changes with an increase around $+10$ cm along the German and $+20$ to $+30$ cm along the Danish coasts and more than $+30$ cm in the Skagerrak. In the northwestern parts both realizations show a decrease in extreme wave height below -40 cm (-20 cm) in A1B_2 (B1_2). Statistically significant changes are again limited to the Skagerrak and small areas off the British coast and correspond to a change from 5 % to 10 % relative to the reference period.

The accordant climate change signal indicates the areas where all four future climate realizations show at least the same change in significant wave height and thus give more confidence in the resulting changes as those derived from a single realization. Figure 7 shows accordant signals for median wave heights and Figure 8 for extreme wave heights for the three time periods. In the period 2011–2040 the accordant signal for median and extreme wave height is zero for most regions. In the period 2041–2070 the four realizations agree on the sign of climate change

Figure 6: As Figure 6, but for the 30-year mean of annual 99 percentile significant wave height.

over larger areas. For the Skagerrak all four realizations show an increase of more than +2 cm (+10 cm) in median (extreme) wave height. For the north western parts they show a decrease of below -4 cm (-20 cm) in median (extreme) wave height. In the last period (2071-2100) all four realizations show the same sign of change in median wave height over larger areas. Changes with a positive sign are concentrated over the eastern North Sea (greater than +4 cm in the Skagerrak). Areas with a decrease of the significant wave height are extended from the western North Sea to large parts of the southern and central North Sea (below -4 cm in the northwestern parts). The accordant climate change signal for extreme wave heights covers smaller areas as the signal for the median wave height and shows an increase in the southern and eastern parts of the North Sea with a maximum of agreement in the Skagerrak of more than 20 cm. A decrease of below -20 cm is located at the northwestern parts of the model domain.

3.2.2 Multi-decadal variability at three locations

Figure 9 shows time series of the 30-year running mean of the annual median and 99 percentile significant wave heights for three locations for all realizations. The 95%-confidence intervals of the reference period (1961-1990), determined by bootstrapping, are marked as grey areas in the figures.

The time series for median wave height (upper panels in Figure 9) at CNS show a slight decrease (-3 cm to -5 cm) towards the end of the century in all realizations. The more coastal locations NOR and SYL show a small increase. However most of the changes are within the 95%-confidence interval of the reference period and the largest changes do not always occur at

Figure 7: Accordant differences in all four realizations with at least the same change of the median significant wave height in [cm] for the periods 2011–2040 (left), 2041–2070 (middle) and 2071–2100 (right) relative to 1961–1990. White areas indicate regions where the four realizations do not show the same sign of difference.

Figure 8: As Figure 7, but for 99 percentile of significant wave height.

the end of the simulations (e.g. increase at NOR during the first half of the 21st century in A1B.2).

The time series of extreme wave height (lower panel in Figure 9) show strong multi-decadal variations and an increase towards the end of the 21st century at NOR and SYL (up to 25 cm) that varies between the realizations. At CNS the extreme wave height shows large variations throughout the 21st century within one and between all four realizations. Again, most changes are within the 95%–confidence interval and the wave height exceeds the confidence interval not necessarily towards the end of the 21st century.

Transient changes in the frequency distribution of the wave height are presented in Figure 10. These changes are displayed as 30-year means relative to the reference period 1961–1990 and grey areas indicate that changes are within the 95%–confidence interval of the distribution for the reference period. At CNS this distribution shows generally more (less) frequent smaller (higher) waves towards the end of the century with some differences between the realizations. At the location near the southern coastline of the German Bight, NOR, the changes in the distribution are dominated by the initial conditions. The distributions for the realizations with the first initial conditions (A1B.1 and B1.1) show more frequent mean waves (between the 25

Figure 9: 30-year running means of the annual median (top) and 99 percentile (bottom) significant wave height in [cm] for the three locations CNS (left), NOR (middle) and SYL (right) relative to the corresponding mean for the period 1961–1990 (A1B.1 - red; A1B.2 - orange; B1.1 - blue; B1.2 - cyan). Grey shaded areas show the 95%–confidence interval of the 30-year mean for the corresponding reference period 1961–1990, determined by bootstrapping.

and 75 percentile) and a reduction of smaller waves and partly of higher waves. The other two realizations show opposite characteristics - reduction of the mean wave heights and an increase of higher and lower waves. For the more easterly location, SYL, all four realizations show less (more) frequent smaller (higher) waves towards the end of the 21st century, whereas changes in the mean conditions are more heterogeneous between the realizations. However, over large parts of the distribution the changes are within in the 95%–confidence interval.

Besides the significant wave height also the wave direction is altered by the changes of the forcing conditions in the future climate realizations. Only changes which exceed the 95%–confidence interval of the reference period are discussed and shown in Figure 11.

The wave directions in the North Sea are effected by the wind field but they are also influenced by the surrounding landmasses. For the location in the central North Sea (CNS) about 38% of the waves propagate toward S and SE, whereas the main wind direction (about 37%) is W to SW (not shown). The fetch from W to SW is limited by the coast of Great Britain, but wind from the NW to N may result in a larger fetch. In the course of the 21st century the frequency of southernly waves decreases and becomes equal to those of easterly waves which increase in frequency. SE with about 20% remains to be the main wave direction showing also a small increase. Waves propagating to westerly directions are already less frequent in the reference period and become less often in the future climate realizations. The overall changes in the frequency distributions of wave directions are comparable in all four realizations.

The dominant wave directions for the locations near the German coast (SYL and NOR) are SE and E (frequency up to 60% for the reference period). There is an increase in frequency of waves to the east towards 2100. Furthermore, there is an increase of waves propagating SE and NE but these changes show a larger variability within the climate projections. A decrease in

Figure 10: Differences of the 30-year running mean of the annual distributions of the significant wave height relative to the period 1961–1990 for the four realizations (columns) and the three locations (rows). H_s^* gives the 25, 50, 75 and 99 percentile of the significant wave height of the corresponding reference period in [m]. Colors show differences (ΔN) of the frequency (N) for every percentile based on the reference period in [%] which are beyond the 95%–confidence interval of the reference period, determined by bootstrapping. Grey displays where differences are within the 95%–confidence interval

frequency towards 2100 covers the sectors S, SW, W, NW which are all sectors of less frequent waves.

4 Discussion

The wind conditions which are the most important driving factor for generating ocean waves have changed in the four presented future climate projections. Not only changes in wind speed are important for changes in wave height but also changes in wind direction by means of the possible fetch. Gaslikova et al (2013) figure out that high wind speed (99 percentile) tends to increase towards 2100 in the four climate realizations. Furthermore, the directional distribution of high wind shows an increase of westerly winds. Generally, this shift to more frequent westerly directions is consistent with results from Pinto et al (2007). For the same global realizations used here as driving data, they show a shift towards more positive North Atlantic Oscillation (NAO) phases and, thus, to a more westerly flow toward the end of the century. Other GCM simulations show also a poleward shift of the Northern Hemisphere storm tracks and thus an

Figure 11: As Figure 10 but for the eight main wave directions. N* gives the frequency of waves for each sector relative to all waves of the corresponding reference period in [%]

intensification of the west wind zone over Europe under AR4 emission scenarios (e.g. Yin, 2005). Also newer GCM simulations under AR5 emission scenarios show a similar intensification of the westerly winds in the North Sea region (e.g. de Winter et al, 2013).

The changes in significant wave height and wave direction as described in the previous sections are consistent with the above mentioned changes in the wind field. Toward the end of the 21st century (2071–2100) the slight increase in wind speed in most parts of the North Sea together with a general shift towards more westerly to southwesterly flow lead to a small increase of the median and 99 percentile wave heights in the eastern areas of the North Sea in all realizations. They differ in detail but all show a maximum in the Skagerrak (Figure 7 and 8). The more frequent winds from westerly directions lead consistently to a reduction of the significant wave height in the western areas of the North Sea toward 2100. The changes range between 5% and 10% and vary in magnitude as well as in their spatial distribution between the realizations. However, the increase in wave height in the eastern North Sea and the corresponding decrease in the western parts for 2071–2100 is valid for all realizations.

These climate change signals for the end of the 21st century are comparable to those from earlier studies by e.g. Debernard and Røed (2008), Grabemann and Weisse (2008), Lowe et al (2009) and de Winter et al (2012) using different models and scenarios. In most of the earlier studies time slices toward the end of the 20th and the 21st century are compared. Such studies address the uncertainties due to different model combinations and scenarios. The transient sim-

ulations investigated here give the opportunity to analyze the temporal variability throughout the 21st century. This variability points to the internal climate system variability.

Temporal variations of the 30-year running climate change signals in the four realizations show that the change of significant wave height toward the end of the 21st century does not occur steadily. Superimposed there are strong multi-decadal fluctuations within each and between the realizations. These fluctuations imply that the climate change signal can already temporally exceed the 95%-confidence interval of the reference period before the end of the 21st century and point to the uncertainty of the climate change signal. Thus, the strongest increase in wave height must not necessarily occur toward 2100.

For the two coastal locations (NOR and SYL) changes in the distribution of the wave height do not show a general shift towards higher values, but from lower to higher values. For the central North Sea (CNS) a general shift towards smaller waves is evident and in agreement with the decrease of the median wave height.

The main wave directions are affected by the geographical setting of the North Sea and the surrounding landmasses within the west wind zone of the mid latitudes. For the location in the central North Sea (CNS) there is a shift between the main wind and main wave directions which is owed to the possible larger fetch from northwestern areas and thus from the North Atlantic, whereas the fetch from the main wind direction (W to SW) is limited by the coast of Great Britain. Changes in wind direction towards a more westerly flow lead to an increase in frequency of easterly wave directions (SE to NE) and a corresponding decrease of westerly wave directions. The decrease of the amount of waves propagating to the west corresponds to the decrease in frequency of easterly winds and results in a reduction of the wave height along the coast of Great Britain. The locations near the German coast (SYL and NOR) are even more influenced by their geographical settings. The increase in frequency of westerly winds in the four climate realizations which results in an increase in frequency of waves to the east towards 2100 is more important for SYL at the eastern coast of the German Bight than for NOR at the southern coast. These more frequent westerly winds result in a stronger increase of the wave height along the eastern coast of the North Sea than at the southern coast of the German Bight. The overall changes in the frequency distribution of wave directions are comparable in all four realizations.

5 Conclusions

Four future climate realizations, including two emission scenarios (A1B and B1) and two initial conditions, are used to investigate possible changes in future wave climate in the North Sea relative to corresponding reference climate. All four realizations show, not always statistically significant in a single realization, an increase (SE to NE North Sea) or decrease (W to NW North Sea) of the significant wave height toward the end of the 21st century. However, temporal variations throughout the simulation period are in the same order of magnitude as the afore mentioned changes and point to the large uncertainty in the climate change signal.

Besides the changes in wave height, changes of the wave direction are important for the wave climate. It is found that changes in the wave direction are more robust throughout the realizations than changes in the significant wave height. A steady increase of the frequency of the dominant eastern directions leads to higher (lower) wave heights in the eastern (western) parts of the North Sea due to the possible fetch length. This change of the directional distribution seems to result in more frequent extreme waves along the south-to-north oriented coast of the North Sea from the German Bight to the Skagerrak. The results show that not only an increase in wind speed and the corresponding wave height could change the wave climate, but changes of the wind and wave direction specially in areas with complex land sea distribution like the North Sea are equally important.

The discussed changes of the wave climate in the North Sea under the four future climate

change scenarios are comparable to those presented in e.g. Debernard and Røed (2008) and Grabemann and Weisse (2008) which also show an increase in extreme winds and significant wave heights in the German Bight and along the eastern North Sea coasts for 2071–2100 in comparison to 1961–1990. This agreement enlarges the probability for an increase in future wave heights in these areas, the magnitude of a possible increase is much more uncertain.

Beside the chosen scenarios, the used GCM is important for the projected future wave climate. Further the discussed results show the importance of the internal variability within and between the realizations. However, a larger ensemble of future climate realizations is needed to address the uncertainties due to initial conditions in addition to the scenario and model induced uncertainties in detail.

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