Impact of a Warmer Climate on the Global Wave Field

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ABSTRACT

Changes in global wave climate and its impacts received only minimal attention in the IPCC Fourth Assessment Report (AR4). Discussions provided are mostly restricted to the long-term variability of the significant wave height based on visual estimates from voluntary observing ships while other components of the wave climate are mostly ignored. Despite some attempts in studying the impact of a warmer climate on the global wave field based on statistical projections, and some recent regional dynamical projections using regional climate models to force wave models, a coherent global modelling study of the future changes in the global wave climate is still lacking.

Tropical and extra-tropical cyclones are the main generating forces behind the global wave field. Recent studies, based on runs with the high resolution (T213; 63 km) version of the ECHAM5 global climate model revealed that in a warmer climate extra-tropical storms will not necessarily get more intense. On the other hand a poleward shift of the extra-tropical storm tracks is expected in both hemispheres. The effects of these changes on the future global wave climate are investigated in the present study. The high-resolution ECHAM5 near-surface wind fields are used to force the wave model WAM and to simulate the global wave climate of two 32-yr periods that are representative for the end of the twentieth (1959-1990) and twenty-first (2069-2100) centuries. The twentieth century period is referred to as the control period. Comparison of control period wave climate with that obtained from the corrected ECMWF reanalysis shows a good agreement and comparison of climate change signals (future-present) reveals changes consistent with poleward shift of extra-tropical storm tracks. Further studies using different model/emission scenario combinations are needed to fully assess robustness and uncertainty of these changes.

1. INTRODUCTION

Long-term changes in ocean wave climate may be caused by changes in the large scale atmospheric circulation, changes in the statistics of tropical and extra-tropical cyclones, or changes in mean sea ice conditions that may result in modified fetch conditions. Locally and in particular near the coasts, also changes in water depth resulting from erosion, water works such as dredging, etc. may play a role.

In the future, changes in ocean wave climate caused by corresponding changes in the atmospheric circulation and extremes may become important. On a regional scale, there are a number of studies using both statistical (e.g. WASA 1998) or dynamical downscaling techniques (e.g. Grabemann and Weisse 2008; Debernhard et al. 2008) to make inferences about possible future changes in ocean wave climate. While the latter are particularly useful for local decision makers because of their high spatial and temporal resolution, they provide only a scattered view about possible changes on the global scale and usually may not fully account for the effects of potential changes in the swell climate.

Studies on a global scale are therefore needed to complement the results from such high-resolution but regional analyses. However, on a global scale, studies about such changes are still limited. The majority of existing studies are based on statistical downscaling approaches that link changes in the large scale atmospheric circulation to changes in the statistics of significant wave heights (e.g., Wang et al. 2004, Caires et al. 2006). Usually atmospheric reanalysis data and related wave hindcasts are used first to train a statistical model which is subsequently applied to the output of climate models simulating future climate conditions. This way, inferences about large-scale changes in ocean wave climate are obtained. Such approaches are mostly limited to significant wave height only while other parameters such as wave period, direction or spectral properties have received less attention. To fully account for the latter, dynamical simulations using global wave models driven by present day and future atmospheric conditions are needed. To our knowledge, the only study published so far is the one by Mori et al. (2009) in which the wave model SWAN (Booij et al. 1999) driven by atmospheric wind fields from a high-resolution (about 20 km) atmospheric GCM (MRI-JMA, Kitoh et al. 2009) under the A1B emission scenario was used to simulate three time slices for present and future climate conditions. More studies using different model combinations and/or emission scenarios are, however, urgently needed to provide a comprehensive assessment of potential future changes in ocean wave climate and its uncertainty. Here we describe initial results from a simulation in which the ocean wave model WAM was driven by atmospheric wind fields from the ECHAM5 global climate model (Roeckner et al. 2003) at about 63 km spatial resolution under the A1B emission scenario. In section 2 model set-up and experiments are briefly described. Results for present wave climate are compared with those from the corrected ERA-40 reanalyses (Caires and Sterl 2005) and possible long-term changes in ocean wave climate are analyzed in section 3. Eventually in section 4, these results are discussed and compared to those from existing studies such as (Mori et al. 2009) or (Wang and Swail 2006).

2. WAVE MODEL SETUP AND FORCING DATA

The WAM Cy 4.5.3 wave model is applied in this study. WAM Cy 4.5.3 is an update of the WAM Cy 4 wave model, which is described in Komen et al. (1994) and Günther et al. (1992). Compared to WAM Cy 4, the basic physics and numerics are retained but the source function integration scheme developed by Hersbach and Janssen (1999) and the model up-dates described in Bidlot et al. (2005) are incorporated. Other major changes introduced in the model are technical improvements and up-dates.

The wave model runs are performed on a regular longitude/latitude global grid with a fixed resolution of 0.5^0, extending from 78^0 South up to 80^0 North. The spectral domain is discretized in 25 frequency bins from 0.041 Hz to 0.411 Hz, and in the direction-space a full circle is used with a resolution of 15^0. The model is run in shallow water mode, taken into account, shoaling and wave energy dissipation at the sea floor.

The model is forced every 6 hours with wind fields in 10m height above the sea surface from a ECHAM5 global climate model (Roeckner et al. 2003 and Bengtsson et al., 2006, 2009) simulation at about 63 km spatial resolution under the A1B emission scenario. Wind fields are kept constant over 6 hours and are bi-linearly interpolated to the model grid. Sea ice fields are updated every 24 hours.

The wave runs are done using integration time steps of 5 minutes for advection and 10 minutes for the source functions. Wave output at each grid point is saved every 6 hours, including the 29 integrated wave parameters listed in Table 1 and the wave spectra. Whereas the integrated parameter data set is used for standard analysis, the wave spectra data-set will be used for more detailed long wave (swell) investigations and to force higher resolution regional wave models.

Table 1: Integrated output parameter

Parameter No.	Parameter	Dimension
1	Wind speed U10	m/s
2	Wind direction	Degree from North (towards)
3	Friction velocity	m/s
4	Drag coefficient	
5	Water depth	M
6	Current speed	m/s
7	Current direction	Degree from North (towards)
8	Significant wave height	M
9	Wave peak period	S
10	Wave mean period	S
11	Wave Tm1 period	S
12	Wave Tm2 period	S
13	Wave direction	Degree from North (towards)
14	Directional spread	Degree
15	Normalized wave stress	%
16	Sea significant wave height	M
17	Sea peak period	S
18	Sea mean period	S
19	Sea Tm1 period	S
20	Sea Tm2 period	S
21	Sea direction	Degree from North (towards)
22	Sea directional spread	Degree
23	Swell significant wave height	M
24	Swell peak period	S
25	Swell mean period	S
26	Swell Tm1 period	S
27	Swell Tm2 period	s
28	Swell direction	Degree from North (towards)
29	Swell directional spread	Degree

Figure 1 gives an overview of the time slice experiments. To investigate the impact of a warmer climate on the global wave field two model simulations are performed. For the control run, representing the present climate, the period 1959 to 1990 is computed and for the future climate the years 2069- 2100 are simulated.

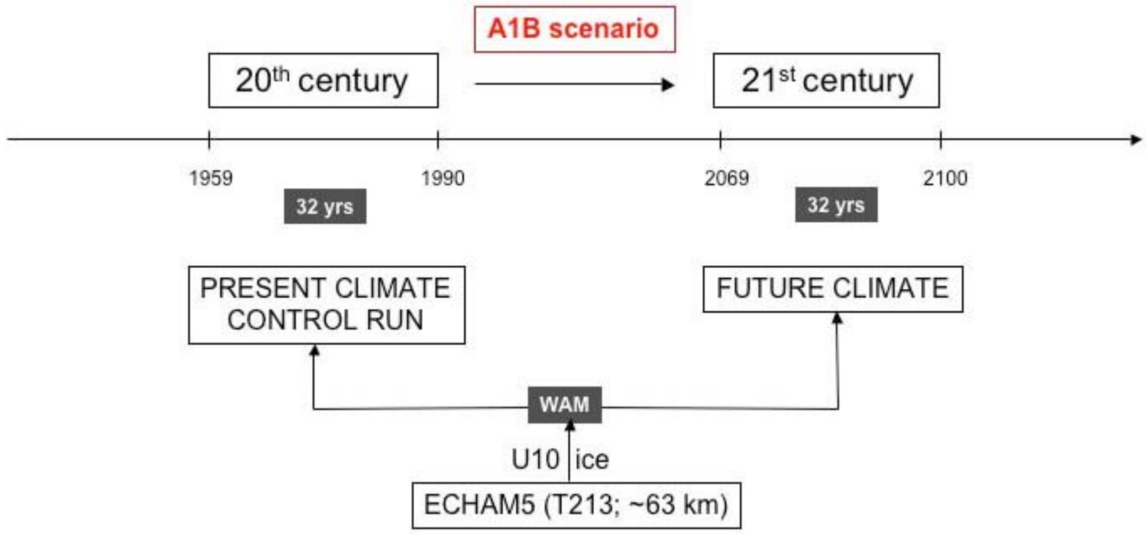

Fig. 1: Set-up of the wave model runs.

3. CONTROL RUN VALIDATION

The significant wave heights from the control period are compared with the ECMWF reanalysis ERA-40 for validation, and, for the short overlapping period (1979-1990), also with ERA-Interim. In the following only comparisons with the corrected ERA-40 (C-ERA40) data (Caires and Sterl, 2005) are presented.

Figure 2 shows the annual mean significant wave heights and wind speeds for the control run (1959-1990). Clearly pronounced are the Southern and Northern Hemisphere extra-tropical storm track tracks. Here annual mean significant wave heights reach values of up to 5 m in the Southern Indian Ocean and up to 4 m in the Northern Hemisphere. Caused by the wave propagation effects, the area of high waves is broader in the north-south direction and more extended to the east when compared to the patterns obtained for near-surface marine wind speed (Figure 2)

Figure 3 presents the differences in annual mean significant wave heights (WAMECHAM5 minus C-ERA40) and wind speeds (ECHAM5 minus ERA40) between ERA and our control run. The wave heights from the WAMECHAM5 run are higher everywhere when compared to C-ERA40. The differences in the North Atlantic are less than about 0.4 m. In the tropical Pacific the mean wave heights are up-to about 1.0 m higher in the WAMECHAM5 run than in the C-ERA40. There are no systematic differences between the results in the northern and southern storm belts. The wind differences (ECHAM5 minus ERA40) however show significant differences. This is as expected because these were the main reason to correct ERA40 wave data set (Caires and Sterl, 2005). The somewhat higher wave heights in the tropical Pacific in the WAMÈCHAM5 runs are probably caused by the incorporation of the small (subgrid) islands in the ECMWF wave model set-up, which leads to an additional swell dissipation. In the Atlantic this effect is not present. Another reason may be the under-forecasting of tall waves by the ERA-40 winds in the Southern storm belts, which leads to less swell generation. It remains to be seen how WAMECHAM5 compares with global altimetry Hs data and with the ERA-Interim. The largest differences are observed at the Antarctic coast and are probably due to the differences in the sea ice data used in the model runs.

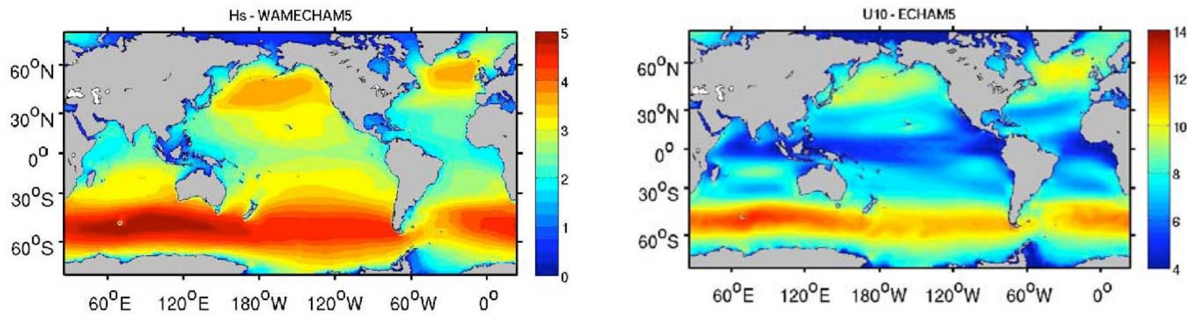

Fig. 2: Annual mean sig. wave heights (m; left) and wind speeds (m/s; right) for the control run (1959-1990)

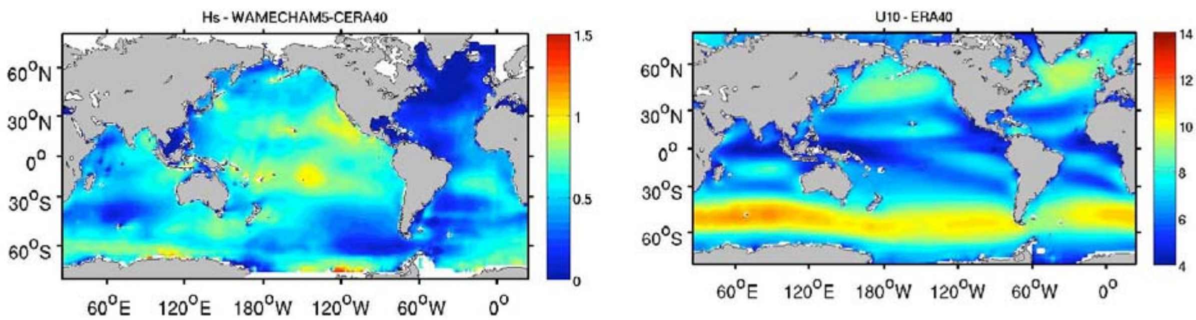

Fig. 3: Difference of annual mean sig. wave heights (m; left) WAMÈCHAM5 minus C-ERA40 and wind speeds (m/s; right) ÈCHAM5 minus ERA40 for the control run (1959-1990).

The comparisons for the summer and winter seasons (Fig.4) basically show the same differences as the annual comparison. But the differences are more pronounced in the Northern Hemisphere winter season. The strong difference close to Japan needs further analysis.

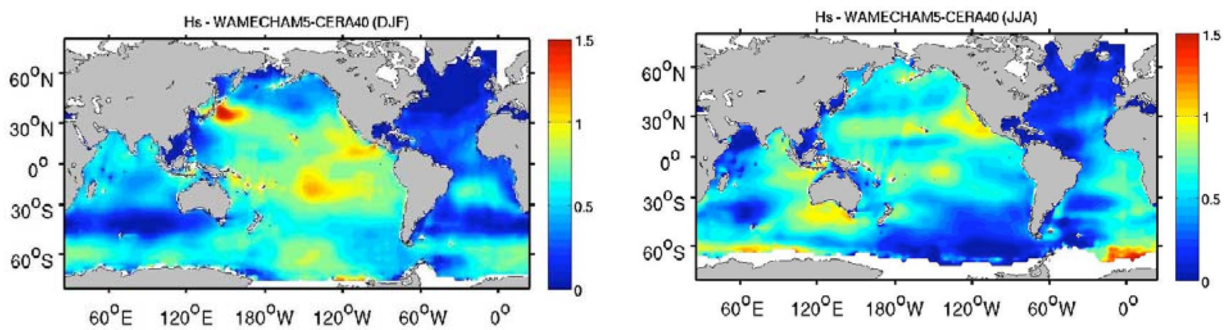

Fig. 4: Difference of seasonal mean sig. wave heights (m) between the WAMÈCHAM5 minus C-ERA40 runs. Left panel for DJF and right for JJA.

4. FUTURE WAVE CLIMATE CHANGES

Figure 5 (right panel) shows the expected changes in mean near-surface (at 10 m height) marine wind speed towards the end of the 21st century. Most pronounced is an increase in near-surface wind speed in the Southern Ocean around 60 degrees latitude and a corresponding decrease around 40 degrees latitude. These changes appear to be associated with a poleward shift of the Southern Hemisphere extra-tropical storm track (Bengtsson et al. 2009), a result which appears to be consistent among most existing atmospheric climate change simulations (Meehl et al. 2007). Moreover, a reduction in near-surface marine wind speeds in low latitudes as well as in the mid-latitudes of the Northern Hemisphere can be inferred. At high latitudes some increase is obtained, possibly associated with a reduction in sea ice and corresponding changes in surface roughness.

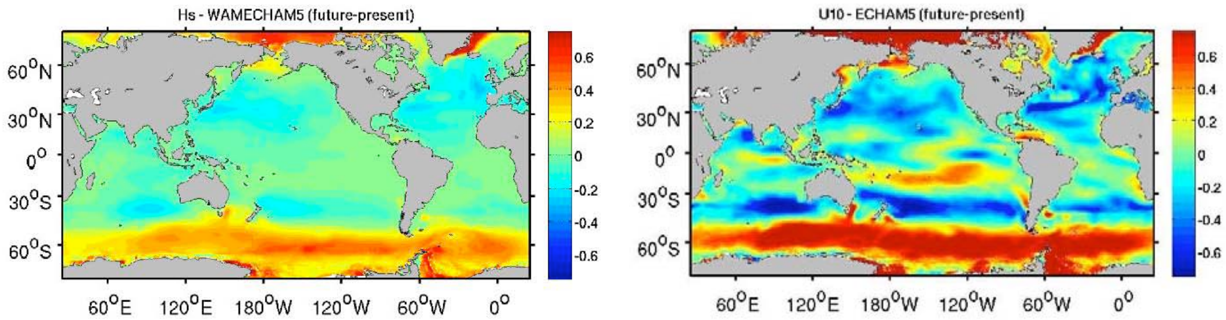

Fig. 5: Difference of annual mean sig. wave heights (m; left) and wind speeds (m/s; right) between the future minus present climate (control run).

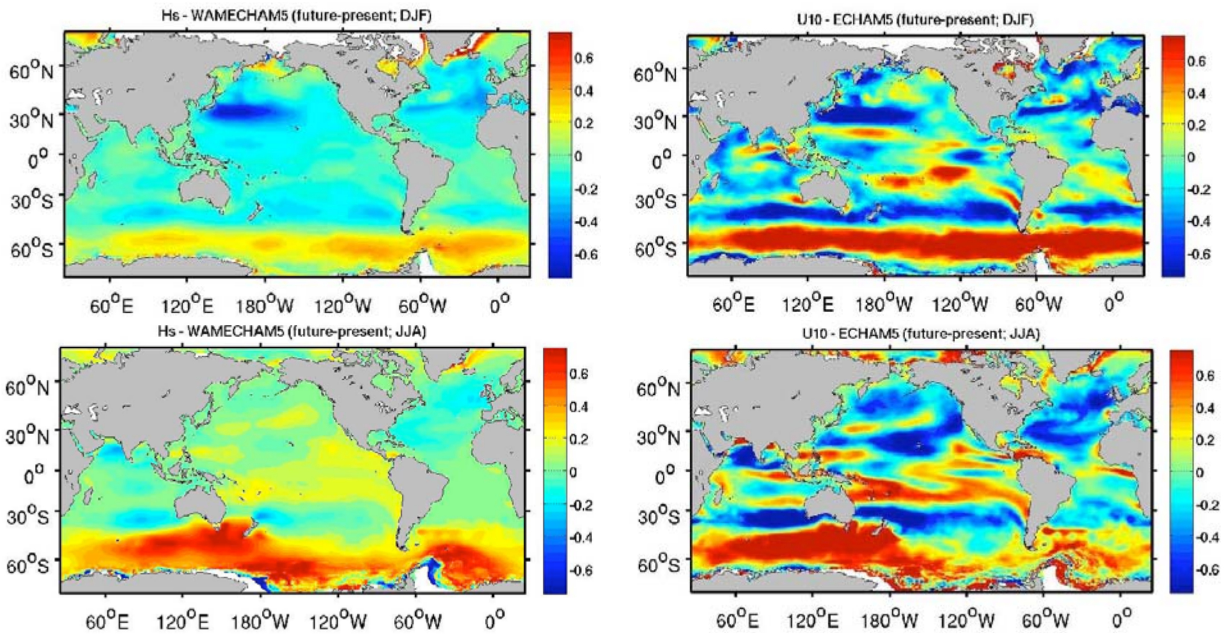

Fig. 6: Difference of seasonal mean sig. wave heights (m; left) and wind speeds (m/s; right) between the future minus present climate (control run). Top panels for DJF and bottom for JJA.

The corresponding changes in mean significant wave height are shown in Figure 5 (left panel). Changes are most pronounced in the Southern Hemisphere storm track where increases of up to about 60 cm (10-15%) are found. Again the reduction in sea ice in the Northern Hemisphere can be inferred from a corresponding increase in mean significant wave height. For all other areas, changes are small and usually less than 20 cm. Generally, changes are more/less pronounced during winter/summer in each Hemisphere (Figure 6 left panels).

Remarkable is the increase of the significant wave height in the Central Pacific during Southern Hemisphere winter, which might be accounted for by increased swell generation in the southern Hemisphere storm track.

5. DISCUSSION

Initial results of our analyses suggest that largest changes in ocean wave climate (in terms of long-term averaged significant wave height) are to be expected at mid- to high latitudes and are associated mainly with changes in sea-ice conditions (mostly at the Northern Hemisphere) and a poleward shift of the mid-latitude storm track (mostly at the Southern Hemisphere). The latter is consistent with changes found in the study by Mori et al. (2009) based on dynamical wave modelling and studies such as those by Wang and Swail (2006) using statistical downscaling approaches. The tendency for a poleward shift in extra-tropical cyclone activity by several degrees latitude in both hemispheres appears to be a consistent result of many studies emerging more recently (Meehl et al. 2007). The shift is associated with increased storm activity at higher and reduced storm activity at mid-latitudes. Possible explanations have been put forward for example by Bengtsson et al. (2006) or Yin (2005) and are related to differential changes of the meridional temperature gradient with height and the resulting regional differences in changes in vertical stability. Generally, the poleward shift in extra-tropical storm activity appears to be more pronounced in the Southern Hemisphere (Bengtsson et al. 2006) which is consistent with the results found in our wave modeling study. Regionally, large differences may occur as secondary changes in storm track location and activity may be associated with regional SST changes (e.g., Yin 2005, Bengtsson et al. 2006). Therefore, additional simulations of future wave climate on a global scale are needed to fully assess the range of potential changes and its uncertainties. A corresponding effort has been suggested by Hemer et al. (2010) and put forward further by the COWCLIP (Coordinated Ocean Wave Climate Projections) initiative with support from the World Climate Research Programme and the Joint Technical Commission for Oceanography and Marine Meteorology of WMO and Intergovernmental Oceanographic Commission (IOC) of UNESCO (Hemer et al. 2011). Moreover, further analysis in terms of variables other than significant wave height is needed and underway to fully assess potential future changes in ocean wave climate.

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