Wave heights in the 21st century Arctic Ocean simulated with a regional climate model

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Abstract While wave heights globally have been growing over recent decades, observations of their regional trends vary. Simulations of future wave climate can be achieved by coupling wave and climate models. At present, wave heights and their future trends in the Arctic Ocean remain unknown. We use the third-generation wave forecast model WAVEWATCH-III forced by winds and sea ice concentration produced within the regional model HIRHAM, under the anthropogenic scenario SRES-A1B. We find that significant wave height and its extremes will increase over different inner Arctic areas due to reduction of sea ice cover and regional wind intensification in the 21st century. The opposite tendency, with a slight reduction in wave height appears for the Atlantic sector and the Barents Sea. Our results demonstrate the complex wave response in the Arctic Ocean to a combined effect of wind and sea ice forcings in a climate-change scenario during the 21st century.

1. Introduction

Climate studies typically consider temperature, precipitation, and other atmospheric indicators in order to understand past trends and predict future developments. It has been shown, however, that ocean waves can both serve as a climate proxy [*Young et al.*, 2011] and contribute to air-sea interactions at climatic scales [*Babanin et al.*, 2009; *Qiao et al.*, 2010]. Knowledge of waves, their mean and extreme values, and their trends is also very important in navigation, coastal and offshore engineering, and other practical applications. Analysis of satellite observations have shown that global wave heights have been growing over recent decades [*Young et al.*, 2011], while observations of regional trends vary [*Bouws et al.*, 1996; *Gulev and Hasse*, 1999; *Woolf et al.*, 2002; *Hemer*, 2010; *Francis et al.*, 2011].

Waves in the Arctic Ocean pose a new practical and research problem. Apart from the North Atlantic region, this ocean, until relatively recently, has been ice covered enough to prevent noticeable waves occurring. Over the last 40 years, however, a substantial retreat of sea ice is observed in summer. Based on satellite observations for the 1979–2012 period, ice cover in the month of September has been receding at a rate of some 13% per decade, relative to the 1979–2000 average, according to the National Snow and Ice Data Center (NSIDC, http://nsidc.org). In September 2012, the record minimum was reached [e.g., *Parkinson and Comiso*, 2013]. Total ice cover in the Arctic was reduced to only $3.41 \times 10^6 \, \text{km}^2$, that is half of the mean September ice cover over the last two decades of the 20th century. At such rates the summer Arctic could be nearly sea ice free by the 2030s, like some of the CMIP5 global models predict [*Wang and Overland*, 2012].

In practical terms, the newly open seas and extended marginal ice zones provide new opportunities and new problems. Navigation and other offshore and shelf activities become possible or less difficult [*Khon et al.*, 2010; *Stephenson et al.*, 2013], but risks due to waves and associated storm surges and coastal erosion are likely to increase [*Overeem et al.*, 2011; *Dobrynin et al.*, 2012; *Hemer et al.*, 2013]. Air-sea interactions enter a completely new state, with momentum, energy, heat, gas, and moisture fluxes being moderated or produced by waves, and impacting on upper-ocean mixing. Apart from altering air-sea fluxes, winds and waves actively contribute to further retreat of the Arctic ice cover [*Parkinson and Comiso*, 2013]. This new state has important implications for climate modeling, both regionally and globally.

All these issues require knowledge of the Arctic wave climate, but research into this topic requires specific approaches. The past wave climate was non-existent; observations of the present climate are marginal and cannot be extrapolated into the future. This is due both to the short duration of such observations and the

changing dynamic conditions for wave generation. Apart from increased wind fetches because of seasonal ice retreat, wind patterns at high latitudes in both the Northern and Southern Hemisphere also appear to be shifting [*Bosserelle et al.*, 2012; *Dobrynin et al.*, 2012; *Weimerskirch et al.*, 2012].

Here we report modeling of 21st century waves in the Arctic by means of the third-generation wave forecast/ hindcast model WAVEWATCH-III [*Tolman*, 2009] forced by winds and sea ice concentration produced within the regional atmospheric model HIRHAM [*Dethloff et al.*, 1996; *Rinke and Dethloff*, 2008], under the anthropogenic scenario SRES-A1B. The model has been forced at its boundaries by the ECHAM5/MPI-OM [*Jungclaus et al.*, 2006] global model data

2. Model Experiments and Methods of Analysis

Version 3.14 of the third-generation wave model WAVEWATCH-III was employed with 1 degree grid resolution in longitude and 0.25 degree in latitude, applied from 67° through 87° North. Default parameterizations of physics were used for input/dissipation [*Tolman and Chalikov*, 1996] and nonlinear-interaction [*Hasselmann and Hasselmann*, 1985] terms (Auxiliary Material). Outputs of the regional climate model HIRHAM were used as input wind and ice fields for the wave model (Table S1). Significant wave height H_s is the output by WAVEWATCH-III based on the modeled wave spectrum and, for quasi-linear waves, corresponds to 4 standard deviations of surface elevations or mean height of one third of the highest waves [*Young*, 1999].

In WAVEWATCH-III, sea area covered with ice is treated as land. Treatment of grid cells partially covered with ice is detailed by *Tolman* [2003]. In short, if ice cover is less than 25%, the cell is regarded as ice free, if greater than 75% the cell is regarded as land, and otherwise wind input to waves is reduced proportionally to percentage cover (see also Auxiliary Material).

Simulations with the regional model HIRHAM were conducted for the region north of 60°N. Horizontal resolution of the model is 0.25 degrees (approximately 25 km). Recent studies demonstrated the model's skills at capturing the present-day climate and its variability [*Rinke et al.*, 2010].

For estimates of changes in wave climate in the 21st century, the ECHAM5/MPI-OM simulations using the anthropogenic climate-change scenario SRES-A1B for 2046–2065 were downscaled with HIRHAM (Table S1). The SRES-A1B scenario is a moderate scenario of the 4th Assessment Report of the Intergovernmental Panel on Climate Change [*IPCC*, 2007] and characterized by rapid economic growth, growth of global population up to nine billion in 2050, and balanced emphasis on all energy sources. For reference, the results covering 1980–1999 from the downscaled ECHAM5/MPI-OM 20th century simulation with anthropogenic forcing are used. Additionally, a sensitivity experiment was conducted to isolate effect of ice retreat and wind-pattern change. In this experiment, the WAVEWATCH-III was forced by sea ice concentration corresponding to the 2046–2065 period while wind was kept at the 1980–1999 level (Table S1). The wind contribution term to H_s change (δH_{WIND}) is calculated as follows:

$$\delta H_{WIND} = \frac{\delta H - \delta H_{ICE}}{\delta H} \times 100\%,$$

where: δH—significant wave height changes (relative to 1980–1999) simulated by WAVEWATCH-III forced both with surface wind and sea ice concentration corresponding to period 2046–2065; δH_{ICE}—significant wave height changes (relative to 1980–1999) obtained from the sensitivity experiment W21$_{ICE}$ (Table S1) with sea ice corresponding to the 2046–2065 period while wind forcing is kept at the 1980–1999 level.

3. Results

Simulated changes in significant wave height H_s together with the changes in duration of ice-free (ice concentration less than 25%) season and 10 m wind speed U_{10} for the Arctic Ocean are shown in Figure 1. These changes are for the 20 year period 2046–2065 with respect to the reference period 1980–1999 at the turn of the 20th century, for September (Figures 1a, 1b, and 1c) and October (Figures 1d, 1e, and 1f). As seen in Figures 1c and 1f, the modeled significant wave heights tend to grow towards the mid-21st century (see also Supplementary Figures S1–S5). This growth apparently relates to the increase in open-water area that should lead to longer wave-development fetches. Additionally, the
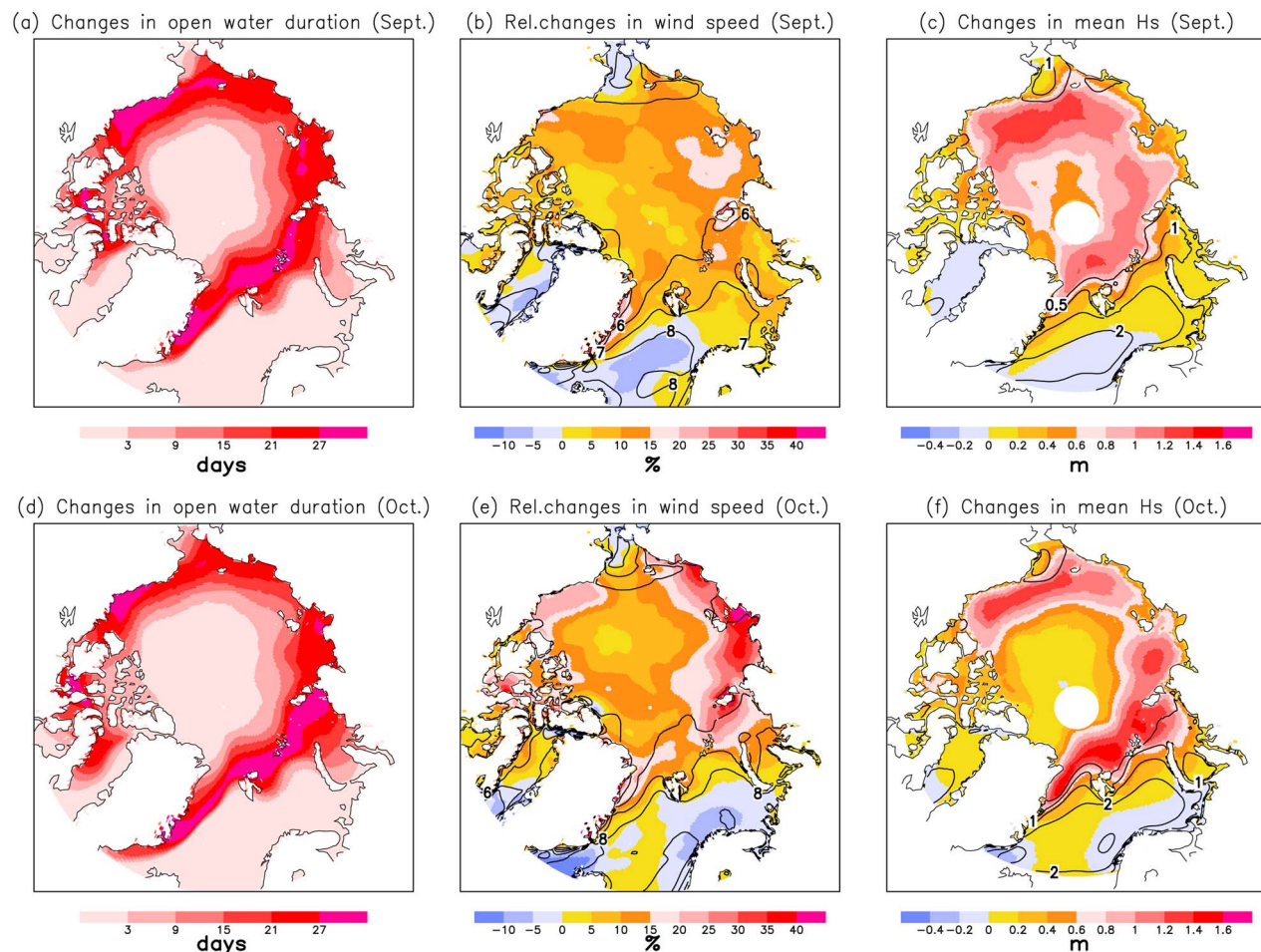
Figure 1. (a,d) Simulated changes in open water duration (ice concentration less than 25%), (b,e) mean wind speed at 10 m height U_{10} (normalized to mean U_{10} for reference period 1980–1999), and (c,f) significant wave height H_s for the period 2046–2065 relative to 1980–1999, for September and October. Contours indicate mean climatological U_{10} and H_s for 1980–1999.

model exhibits a general rise in surface winds (Figures 1b and 1e) in the Arctic, particularly in the Kara, Laptev, and East Siberian Seas that further stimulates overall wave growth. An opposite trend of declining wave height is seen in the Barents Sea (Figures 1c and 1f) due to a regional decrease in wind speed (see also Supplementary Figures S--S5).

Figure 2 demonstrates projected future changes in the occurrence of strong winds ($U_{10} > 8$ m/s), and what we call here large waves ($H_s > 2$ m) and extreme waves ($H_s > 3$ m). Due to the observed growth in wind speeds and wave heights in the Arctic Ocean we can expect an increase in the proportion of days with strong wind-wave conditions. Indeed, in Figures 2a and 2d one can see such an increase for the number of high-wind days in the Arctic, particularly over the coastal Seas. Waves in excess of 2 m significant height will become more frequent in general, with the spatial pattern of changes following the pattern for the monthly mean H_s in Figures 1c and 1f. Frequency of occurrence of extreme waves, on the contrary, only changes marginally. In northern parts of the Barents, Kara, and Chukchi Seas and near Greenland in October (Figures 2c and 2f) it grows, whereas over the North Atlantic sector and most of the Barents Sea such waves will become less common. Since the latter sector has always been ice free in summer, its future wave trends agree with results of simulations [Dobrynin et al., 2012] where future wave climate trends were studied by presuming a fixed Arctic ice cover.

Estimates of the relative contribution of the two different factors, i.e. changes to wind speed and ice-free area, were performed in % of the H_s changes caused by both factors, between the end of the 20th century and mid
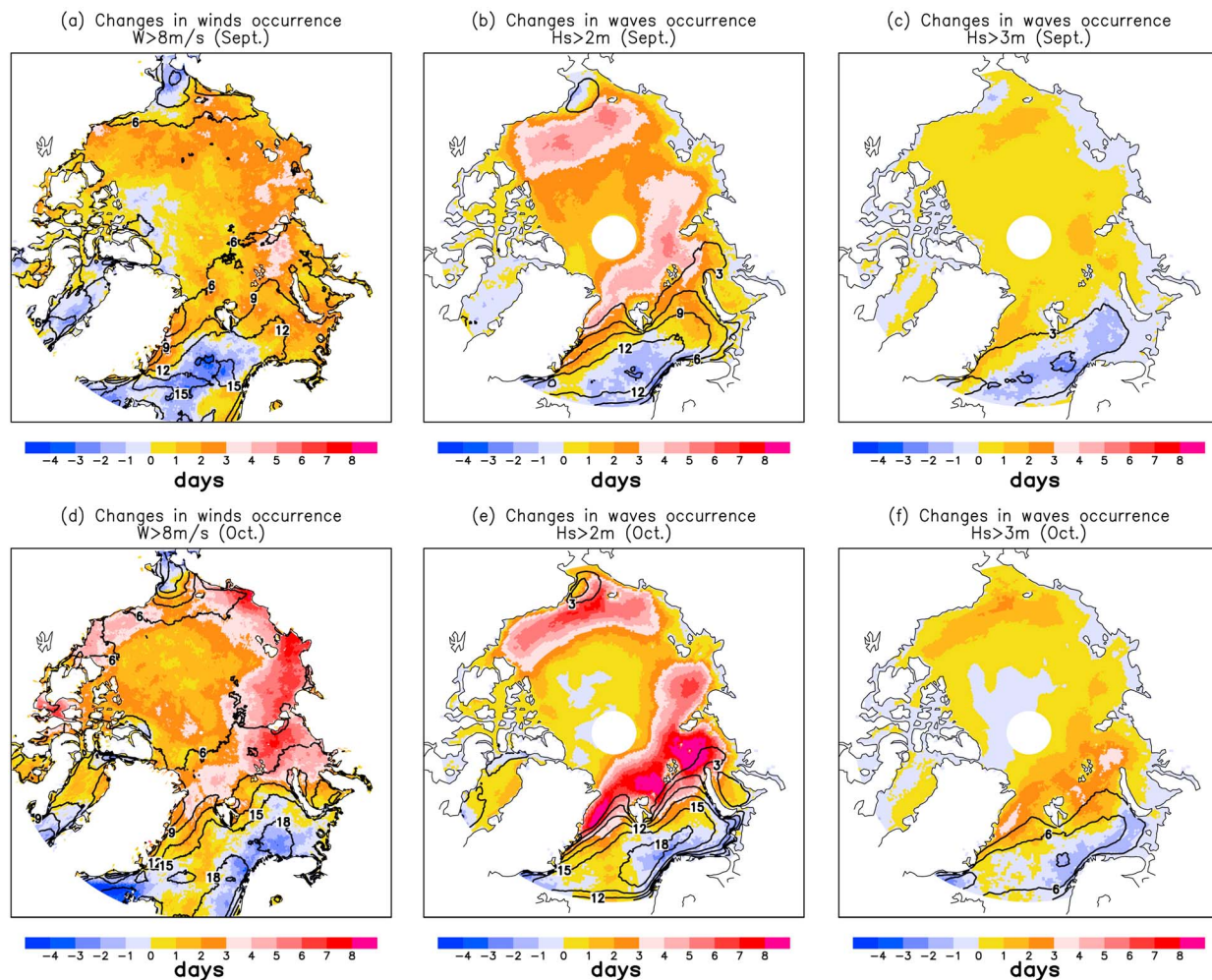
Figure 2. (a,d) Simulated changes in occurrence of winds exceeding 8 m/s, significant wave heights exceeding (b,e) 2 m and (c,f) 3 m for the period 2046–2065 relative to 1980–1999, for September and October. Contours show mean values for the reference period.

21st century periods. In Figure 3, we show the percentage, due to variations in surface wind speed U_{10}, for monthly mean H_s (Figures 3a and 3d) as well as for occurrence of waves with $H_s>2$ m (Figures 3b and 3e) and $H_s>3$ m (Figures 3c and 3f). In the simulations, concurrent variations of ice cover were accounted for (see "Model experiments and methods of analysis" for details). According to Figures 3a and 3d, in open water areas, such as the ice-free North Atlantic and to some extent Barents and Kara Seas, the changes in significant wave heights are mostly (more than 85%) due to variations (increases or decreases) in surface winds in the 21st century. The wind contribution term is expected to be comparable or exceeding the contribution of longer wind fetches for areas showing the most rapid retreat of ice cover, if they were at least partially free of ice in the 20th century (45–75% areas in Figures 3a and 3d). Therefore, for such Arctic areas, accounting for wind variations can more than double the wave-height response to the changing climate. On the contrary, sea ice retreat is a dominant factor causing the wave height growth in the inner Arctic Ocean and the Arctic Shelf Seas covered with ice throughout the year in the 20th century (Figures 3a and 3d). It is worth noting the substantial contribution of wind changes to occurrence of large waves in the Kara, Laptev, Eastern Siberian and Beaufort Seas (Figures 3b and 3e) and for occurrence of extreme waves in the Kara Sea (Figures 3c and 3f).

4. Summary and Conclusions

Overall it should be stressed that, for a more accurate estimate of possible changes in wave climate in the Arctic Ocean over coming decades, a more detailed analysis of natural climate variability in the
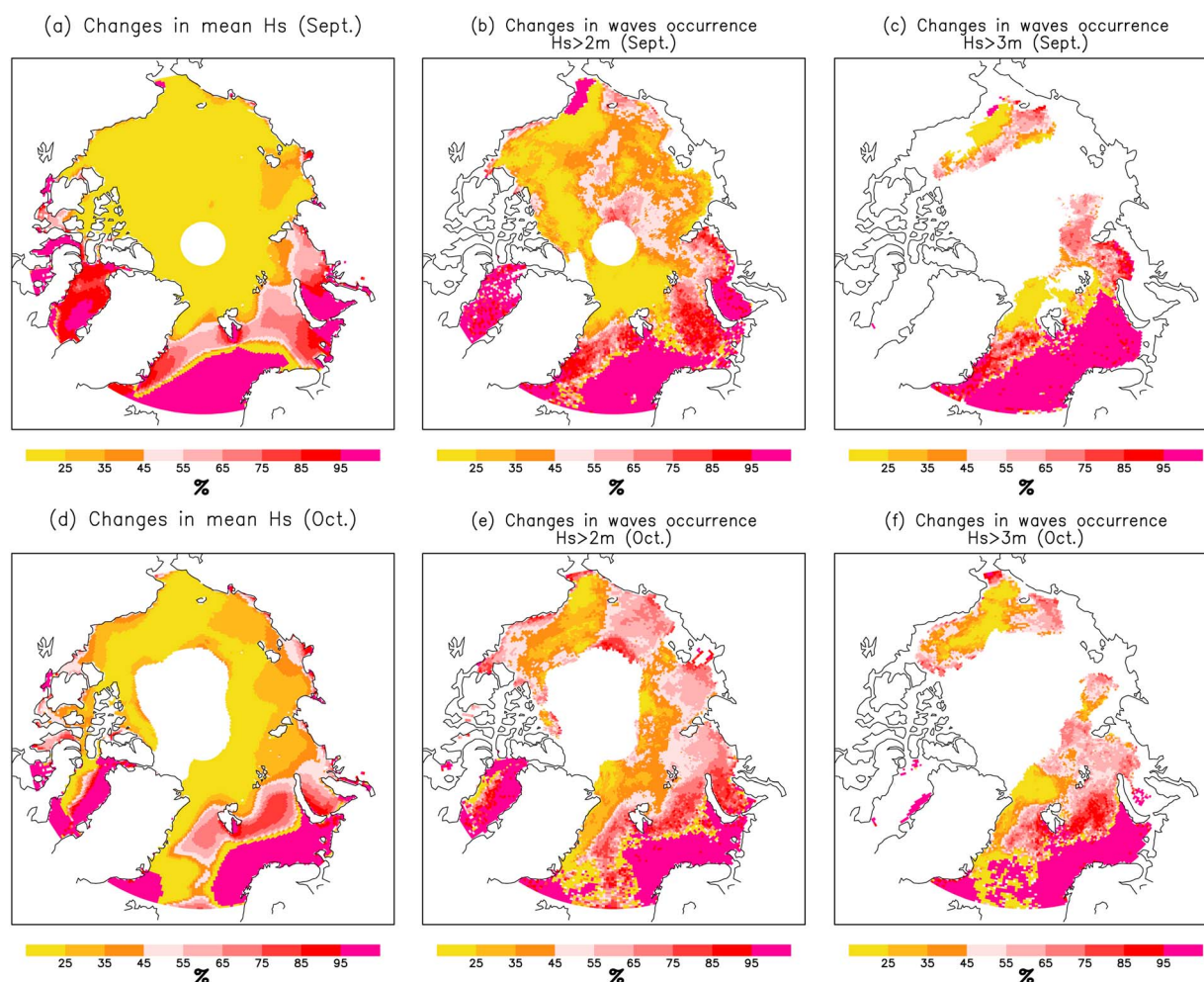
Figure 3. (a,d) Changes in significant wave height and wave occurrence at Hs exceeding (b,e) 2 m and (c,f) 3 m caused by variations of U_{10} alone (2046–2065 relative to 1980–1999), for September and October.

region is necessary. Due to a general underestimation of ice retreat in climate models [*Wang and Overland*, 2012], effects quantified in this paper can be enhanced regionally. Wave activity and an increasing number of storms can further advance such enhancement [*Simmonds and Rudeva*, 2012; *Parkinson and Comiso*, 2013; *Zhang et al.*, 2013]. Natural cycles, such as the Atlantic Multidecadal Oscillation, may have an essential influence on relatively fast (within several decades) climate changes [*Mokhov et al.*, 2012].

In conclusion, we conducted an analysis of possible changes to the wind-wave climate in the Arctic Ocean in the 21st century. This was done by means of a third-generation wave model and climate modeling under an anthropogenic-forcing scenario. The outcomes demonstrate overall growth in wave height in the Arctic. Concurrent with mean wave growth, models predict more frequent extreme waves in different areas of the Ocean.

Changes to wave climate are due to both ice retreat in summer months and a regional increase in surface winds. The relative importance of these two factors is estimated. It is concluded that the role of wind change, both increases and decreases, is very significant. These changes, in addition to changes imposed by ice retreat and longer wave fetches, can more than double the wave-height response. This is most pronounced in areas with the most rapid reduction in ice cover. At the Arctic Shelf, particularly in the Kara, Laptev, East Siberian, and Beaufort Seas, the relative contribution of wind variations is significant for changes in the occurrence of large waves with significant wave height in excess of 2 m.

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