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Baltic Sea wave conditions under climate change scenarios

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Anthropogenic climate change can alter the wind- and sea-ice climate and thus the wave conditions in the Baltic Sea. Here, transient simulations with the 3rd generation wave model WAM under two IPCC AR4 emission scenarios (A1B and B1) and two initial conditions of the forcing atmospheric fields are analyzed for the period 1961–2100. Future changes in the wave climate comprise higher significant wave height for most regions and simulations. Median waves show temporal and spatial consistent changes, whereas extreme waves (99th percentile and maximum) show much more variability in space and among the simulations. These changes in the wave fields result from not only higher wind speeds but also from a shift to more westerly winds, which leads to different fetch and thus to different significant wave height and direction. The multi-decadal and the inter-simulation variability illustrate the uncertainty in the estimation of the climate change signal.

Introduction

The Baltic Sea is an economically intensively used semi-enclosed sea, characterized by a complex coastline and bathymetry, by the presence of seasonal sea ice cover and by high variability of wind fields in its several sub-basins. These factors strongly affect the wave conditions in the Baltic Sea. The knowledge of the wave climate in the Baltic Sea is important, as waves have a large impact on coastal and offshore activities, like coastal infrastructure, harbor operations, shipping, offshore platforms and human safety. Changes in the long-term wind and sea-ice conditions caused by anthropogenic climate change may alter the wave climate and may strongly affect the public and economic sectors.

Past and present wave conditions were well investigated in the last decades by analyzing observations and numerical simulations: e.g. Hünicke *et al*. 2015 give an overview on the current knowledge on ocean waves in the Baltic Sea, and Soomere *et al*. (2008) present a detailed review for the Gulf of Finland. Only a few observational sites have records long enough to study wave climate variability (Hünicke *et al*. 2015). Among several other studies, Soomere *et al*. (2012) analyzed the wave climate at the Darss Sill in the southwestern Baltic and Kahma *et al*. (2003) and Broman *et al*. (2006) in the northern Baltic Proper. All investigations point to the high temporal variability (seasonal and inter-annual) due to sea ice and wind variability. In these studies, observed median significant wave heights range between 0.65 m in the southwestern Baltic (Soomere *et al*. 2012) and 0.75 m in the northern Baltic Proper (Broman *et al*. 2006). Maximum observed significant wave heights differ

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between 4.46 m in the southwestern Baltic Sea (Soomere *et al*. 2012) and 7.7 m in the northern Baltic Proper (Kahma *et al*. 2003). Long numerical simulations for past conditions performed by Augustin (2005), Cieślikiewicz and Paplińska-Swerpel (2008), Räämet and Soomere (2010) and Soomere and Räämet (2011) showed generally higher values as compared with observations (Soomere *et al*. 2012), and discussed the high spatiotemporal variability in the Baltic Sea wave climate. Whereas e.g. Zaitseva-Pärnaste and Soomere (2013) discussed the relation between sea ice and wave energy and mean wave height, and Tuomi *et al*. (2011) showed not only the importance of sea ice for the wave climate but also the sensitivity of the simulated waves to the treatment of sea ice in the estimation of wave statistics.

Whereas for the North Sea area several published studies discussed possible future changes (e.g. Debernard and Røed 2008, de Winter *et al*. 2012, Groll *et al*. 2014, Grabemann *et al*. 2015), only a few (unpublished) simulations for future Baltic Sea wave climate exist so far (Meier *et al*. 2015). Scenario simulations with more simplified wave models were introduced by Meier *et al*. (2006). Projections of the future Baltic Sea wave climate were made with more advanced wave models by Kriezi and Broman (2008). However, these studies are either limited to simulations for short periods or for specific regions. Kriezi and Broman (2008) analyzed a one-year simulation for the 4th IPPC Assessment Report (AR4) A2 scenario. A recent publication by Suursaar *et al*. (2016) focused on the Estonian coastal sea using the SWAN wave model with AR5 RCP4.5 scenarios. Dreier *et al*. (2011) introduced a statistical model based on wind-wave correlations for locations in the southwestern Baltic Sea (based on the same wind forcing as used in our study). They found a small increase in the significant wave height in a future climate (AR4 A1B and B1) and discussed changes in wind and wave directions.

Here, we present four transient simulations for the 21st century for the entire Baltic Sea. Changes in 30-year means of annual median and extreme (99th percentile and maximum) significant wave height are discussed based on hourly values. Additionally, changes in the driving wind-fields and the sea-ice conditions in the four simulations are presented. Moreover, a multi-decadal variability of significant wave height and wave direction in the 21st century is given for selected locations. In the statistical analysis of the annual wave climate, sea ice is taken into account by considering only time steps when the grid point is ice-free (ice-free-time-statistics, type F, according to Tuomi *et al*. 2011).

Model and ensemble set-up

Model set-up

Ocean waves for the Baltic Sea were simulated with the third generation wave model WAM (WAMDI1988 ver. 4.5.3) with a horizontal resolution of 0.1° × 0.05° (long. × lat.) which corresponds approximately to 3 × 3 nautical miles. The model domain covers the area from 9°–31°E and 53.5°–66°N (Fig. 1). The model was run in shallow-water mode; depth-induced wave breaking was not included. The integration time step was 2 min and the wave spectra were calculated with 24 directions and 35 frequencies (approx. 0.04–1.07 Hz). Wave parameters such as the wave height and wave direction were calculated from wave spectra and stored every hour. The derived wave height was defined after Holthuisen (2007) and it is referred to as significant wave height (SWH). The derived mean wave direction is defined as *going towards*. At the western boundary of the model domain (Skagerrak) wave spectra from a North Sea wave simulation described in Groll *et al*. (2014) (conducted with the same wind forcing as used in this study) were applied as boundary conditions. Here, sea ice was taken into account by setting the wave spectra to missing value when the grid cell is covered by sea ice.

The wave simulations were forced by hourly wind-fields which were taken from existing regional atmospheric simulations (Hollweg *et al*. 2008) performed with the model COSMO-CLM (Rockel *et al*. 2008) with a horizontal resolution of 0.165° × 0.165° on a rotated grid (corresponds to approx. 18 × 18 km over the Baltic Sea area). These regional simulations were driven with data from simulations with the coupled atmosphere–ocean general circulation model ECHAM5/

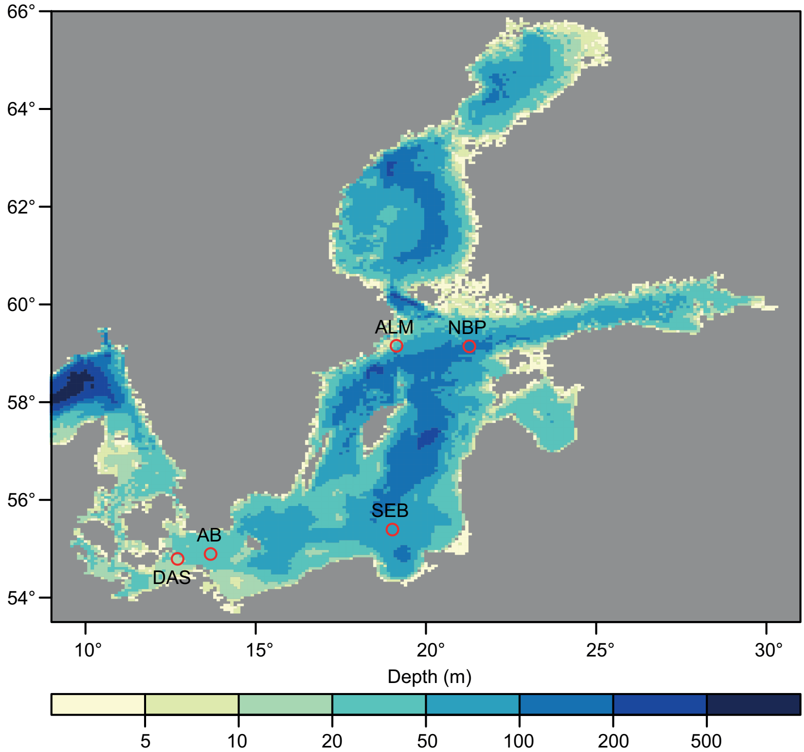

Fig. 1. Model domain and bathymetry. Red circles indicate the locations of Darss Sill (DAS), Arkona Basin (AB), southeastern Baltic (SEB), Almagrundet (ALM) and northern Baltic Proper (NBP).

MPI-OM (Röckner *et al*. 2003, Marsland *et al*. 2003). The bathymetry originated from Seifert *et al*. (2001). Monthly sea ice conditions for the Baltic Sea were implemented from sea-ice thickness by setting the grid cell to ice-covered if the ice thickness > 5 cm. This threshold was chosen after a sensitivity study and resemble realistic sea-ice coverage but was not tested explicitly. The sea-ice data were provided by existing simulations (Neumann 2010), using the same regional atmospheric forcing, with a 3D ecosystem model which consists of a regional ocean circulation model and a thermodynamic sea-ice module.

Ensemble set-up

The ensemble set-up consists of four simulations with two initial conditions of the global model to address the internal variability and two emission scenarios to account for possible future economic developments. For the two initial conditions two randomly chosen years from a 550-year-long simulation with fixed preindustrial greenhouse gas concentration for the year 1860 were used. Using these initial conditions, two global simulations were forced by measured greenhouse gas concentrations from 1860 to 2000 and were then branched off from 2001 to 2100 with the two emission scenarios A1B and B1 (Houghton *et al*. 2001, Nakicenovic and Swart 2000). The A1B emission scenario describes a growing global economy using well-balanced energy sources, whereas the B1 scenario reflects a shift to a more global eco-friendly economy. The regional atmospheric simulations (Hollweg *et al*. 2008) and subsequently the presented wave simulations were started at 1960 and were run till 2100 separately. Hereafter the two wave simulations for the 20th century (1961–2000) are referred to as reference simulations (C20_1 and C20_2) and the four wave simulations for the 21st century (2001–2100) are referred to as future realizations (A1B_1, A1B_2, B1_1 and B1_2).

Evaluation of the reference wave climate

The reference simulations incorporate the green-

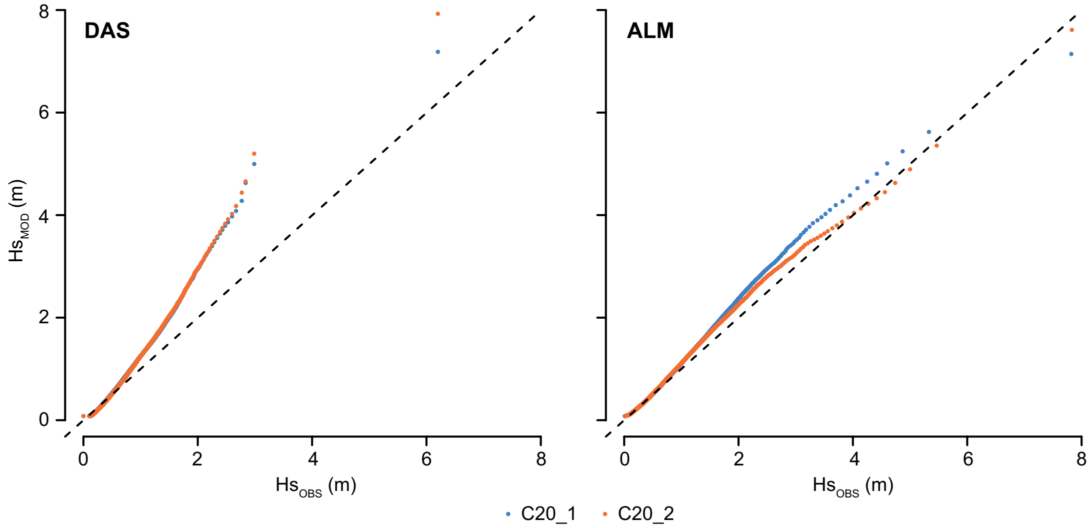

Fig. 2. Quantile-quantile plot of the observed significant wave height (Hs_{OBS}) *versus* the simulated wave height (Hs_{MOD}) for both reference climates (C20_1 and C20_2) at the Darss Sill (DAS, 12.7°E, 54.7°N) for the period 1991–2000 (left) and at Almagrundet (ALM, 19.13°E, 59.15°N) for the period 1978–2000 (right).

house gas concentrations measured from 1960 to 2000, but not the actual weather information. Therefore, only climate statistics from the simulations can be compared with observations. To get reasonably robust statistics, long time series of wave conditions are necessary, which are rare. The two reference simulations (C20_1 and C20_2) were compared with observations at the Darss Sill (12.7°E, 54.7°N) in the southwestern Baltic for the period 1991–2000 and Almagrundet (19.13°E, 59.15°N) in the northern Baltic Proper for the period 1978–2000. These records were intensively used in a variety of studies, e.g. Soomere *et al*. (2012) used the observation site Darss Sill for comparison with two wave hindcast simulations and e.g. Broman *et al*. (2006) analyzed trend and extremes at Almagrundet.

To compare the distributions of the SWH of the observations (Hs_{OBS}) and of the reference simulations (Hs_{MOD}) at the Darss Sill and Almagrundet a quantile-quantile plot was used (Fig. 2). At the Darss Sill, waves up to 0.5 m show a good agreement. For waves > 0.5 m the reference simulations indicated a clear overestimation. Such overestimation of the observed wave height can also be found in Soomere *et al*. (2012) for both hindcast simulations, although the overestimation of the simulated SWH was smaller than that in the present study. At Almagrundet, the comparison showed an overall good agreement between the observations and the reference simulations. However, to account for the general deviation between the observations and the reference simulations the focus was on the relative changes.

Climate change in future realizations

Spatial variability at the end of the 21st century

Thirty-year means of annual median, 99th percentile and maximum hourly wind speed and SWH were calculated for all four realizations for the period 2071–2100, and were compared with the corresponding reference climate (1961–1990) to analyze future changes in wind and wave conditions. The difference between 30-yr means within 2001 and 2100 (e.g. 2071–2100) and the mean for 1961–1990 is referred to as climate change signal.

Wind climate

As the wind is the major forcing factor for the sea state, changes in the wind climate consider-

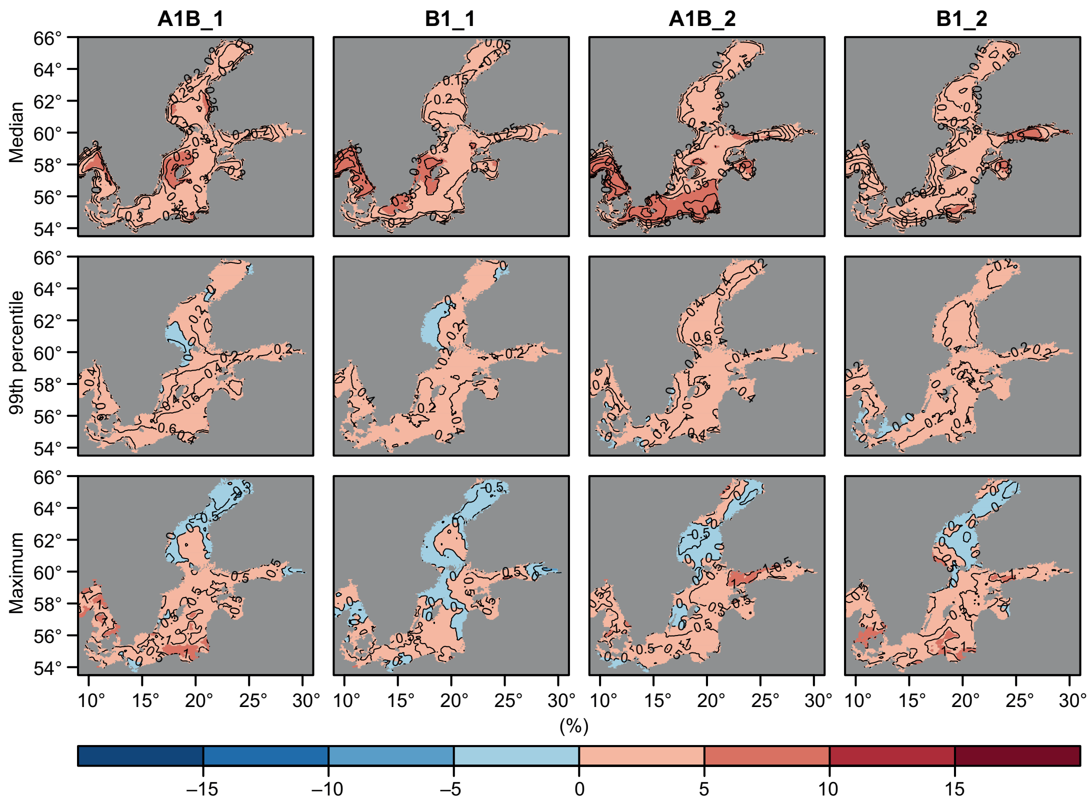

Fig. 3. Differences in 30-year means of annual median, 99th percentile and maximum wind speeds between 2071–2100 and 1961–1990 for four realizations (A1B_1, B1_1, A1B_2, B1_2). Relative changes in colors, absolute changes as contour lines.

ably affect the changes in the wave climate. For the end of the 21st century all four realizations indicated an increase in the median wind speed in the whole Baltic Sea (Fig. 3). Changes of more than +5% were limited to some regions, which were heterogeneously distributed in the four realizations. For most regions the climate change signals of the 99th percentile wind speed (Fig. 3) showed an increase in all four realizations, but these changes were less than +5%. A decrease was found for some regions, but they were not spatially equally distributed in the four realizations. Two realizations showed a decrease in parts of the northern Baltic Sea and two realizations in parts of the southwestern Baltic Sea. Changes in the 30-year mean of the annual wind speed maximum (Fig. 3) showed a decrease in all realizations in parts of the northern Baltic Sea and an increase for most parts in the southern Baltic Sea. Only in some, heterogeneously-distributed regions an increase of more than +5% was indicated by all four realizations. Climate change signals towards the middle of the 21st century (2021–2050) showed the same sign but are generally smaller (not shown).

Sea Ice climate

Besides changes in the wind climate, changes in the sea ice coverage affect the wave climate, especially in the northern parts of the Baltic Sea (Bothnian Sea, Bothnian Bay and the Gulf of Finland). To show the changes in future sea-ice conditions, the 30-yr mean of the number of months per year which are free of ice was calculated for the period 2071–2100 (Fig. 4). Sea ice coverage almost completely vanished in the Bothnian Sea in all four realizations and was dramatically reduced in the Bothnian Bay and

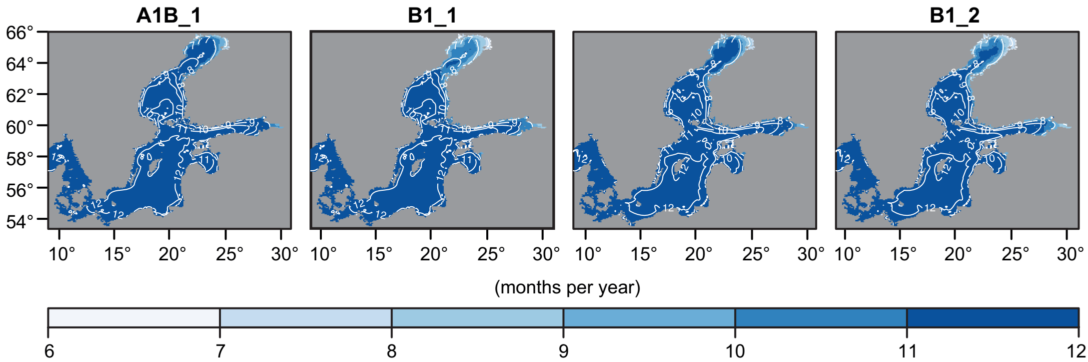

Fig. 4. 30-year means of the months per year which are free of sea ice in the period 2071–2100 (1961–1990) for the four realizations (A1B_1, B1_1, A1B_2, B1_2) in color (as contour lines).

the Gulf of Finland. Only the B1 realizations still showed some months of ice coverage in open waters in the Bothnian Bay. This considerable reduction will further influence the wave climate in the Baltic Sea.

Wave climate

The relative changes of the median SWH at the end of the 21st century (2071–2100) showed an increase for the entire Baltic Sea in all four realizations (Fig. 5). The largest increase of more than +15% could be seen in parts of the Bothnian Sea and Bothnian Bay in A1B_1. In general, the largest changes in the median SWH occurred along the coasts of Lithuania, Latvia and Estonia, in the eastern Kattegat and in the Gulf of Finland and exceed +10% as compared with the SWH of the corresponding reference period. The smallest increases could be found in the entire southwestern Baltic Sea and eastward of coastlines. The 99th percentile SWH also showed an increase in most parts of the Baltic Sea, except for some regions in the southwestern Baltic Sea. The largest increases ranged between +5% and +10% and occurred in single realizations and some regions. Again, all realizations showed the largest changes westward of coastlines with a consistent increase of more than +10% in small areas along the Lithuanian and Latvian coasts. Small areas in the southwestern Baltic Sea showed a decrease of more than 5%, these areas occurred predominantly eastward of coastlines. Generally, the climate change signals of the annual maximum SWH were comparable with those of the 99th percentile SWH, but in some realizations they showed larger spatial variability and an increase in +10% to +15% in the southeastern Baltic Proper, along the coast of Lithuania, Latvia and Estonia and in the Gulf of Finland. They displayed also a larger decrease (–10%) in some regions, which occurred mostly in the southwestern Baltic Sea.

All four realizations mostly showed an increase in the median and severe SWH for large parts of the Baltic Sea. However, the changes differed in magnitude and space between the four realizations. A more robust conclusion for changes in wave climate was given by the common change (Fig. 6), i.e. when for a specific region all four realizations showed at least the same amount of change. For the period towards the middle of the 21st century (2021–2050), a common increase in the median SWH for almost the entire Baltic Sea was evident but generally changes did not exceed +5% of the reference period. The 99th percentile and the maximum SWH also showed large areas with a common increase, but only in the case of the maximum SWH the increase was greater than 5% in some areas. There were also some common decreases in very small areas in the southwestern Baltic Sea. The common change towards the end of the 21st century (2071–2100) showed a similar pattern. For the median SWH, most of the areas with an increase of more than +5% were larger and there were some areas with an increase of more than +10%. As compared with the respective values for the reference period 1961–1990,

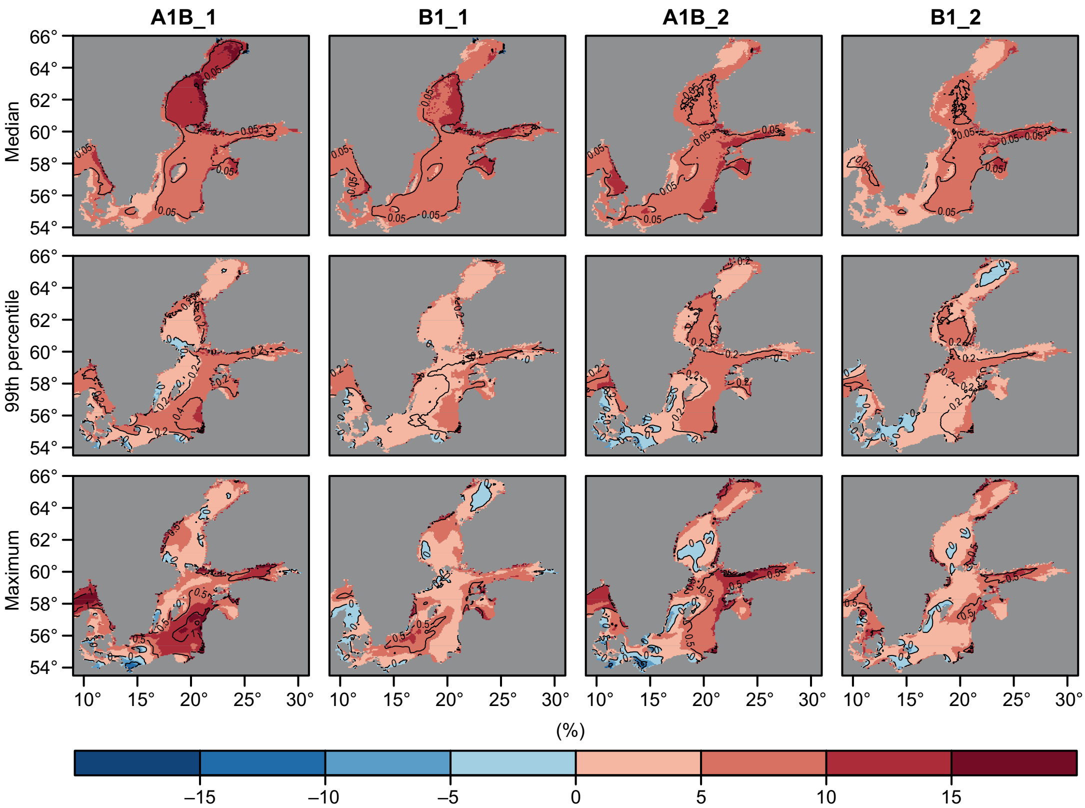

Fig. 5. Differences in 30-year means of annual median, 99th percentile and maximum significant wave heights between 2071–2100 and 1961–1990 for four realizations (A1B_1, B1_1, A1B_2, B1_2). Relative changes in colors, absolute changes as contour lines.

the 99th percentile and maximum SWH also showed a common increase of more than +5% in large areas, especially along the coast of Lithuania, Latvia and Estonia and areas in the Gulf of Finland. Some limited areas in the southwestern Baltic Sea showed a common decrease, but always within –5% of the reference period.

Multi-decadal variability

The transient simulations provide the opportunity to analyze continuous climate change signals within the 21st century and not only changes towards its end or for other specific periods. To analyze the intra-century temporal variability of the Baltic Sea, wave climate 30-year running means of the SWH and wave direction were compared with the corresponding reference period (1961–1990) for three selected locations: Arkona Basin (AB), southeastern Baltic (SEB) and northern Baltic Proper (NPB) (*see* Fig. 1).

Significant wave height

The 30-year running means of annual median, 99th percentile and maximum SWH for the selected three locations were compared with the values for the reference period. The median SWH showed an almost steady increase towards the end of the 21st century at all locations (Fig. 7). Most of the single realizations exceed the 95% confidence interval of the reference period in the first half of the 21st century and all realizations were beyond this threshold by the end of the century. The increase ranged between +5% and +10% of the reference median SWH (Fig. 7). Generally, the variability for the running means of the annual 99th percentile SWH

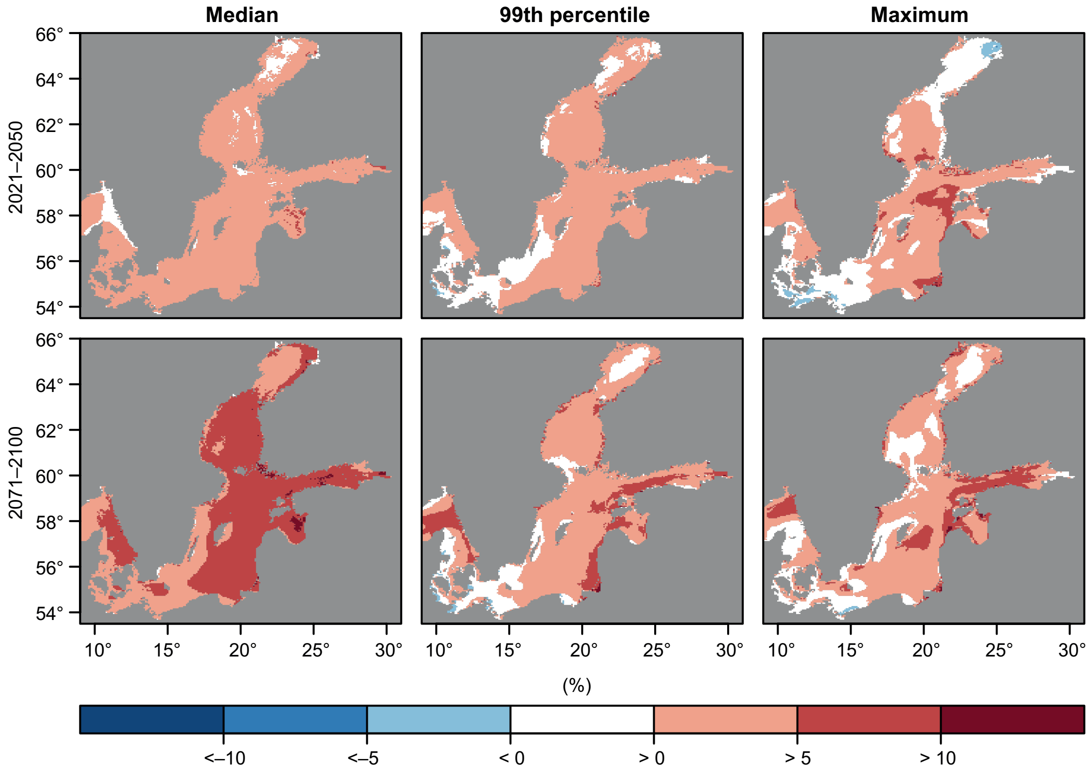

Fig. 6. Common changes in the four realizations for 30-year means of annual median, 99th percentile and maximum significant wave height for the periods 2021–2050 and 2071–2100 relative to the period 1961–1990. Colored areas indicate regions where all four realizations showed at least the same amount of relative change. White areas indicate regions where the four realizations did not show the same sign of change.

was higher as compared with the variability for the median. For SEB and NBP, the running means of the 99th percentile SWH exceed the confidence interval for some realizations in the first half of the 21st century and for all realizations towards the end of the 21st century. Their increases ranged between about +5% and +8% of the reference value (Fig. 7). For AB, the respective changes were almost within the confidence interval for the entire simulation and point to the high uncertainty of a possible change in the extreme wave climate for this region (Fig. 7). The multi-decadal variability of the running means of the annual maximum SWH within each and among all realizations was greater than the variability for the 99th percentile SWH. The high variability of the annual maximum SWH was also confirmed by the 95% confidence interval which was about two times greater and which was only exceeded by single realizations for SEB and NBP. For AB, the 30-year running means of the annual maximum SWH were almost entirely within the confidence interval in all four realizations (Fig. 7).

Wave direction

Besides changes in the SWH, changes in wave direction may also have a significant effect on the wave climate under a possible climate change.

The distribution of the wind direction (not shown) with a maximum of west to southwesterly directions was comparable at different locations in the Baltic Proper (Meese 2015). In contrast, the distribution of the wave direction was much more affected by the surrounding coastline and shelter effects and thus by fetch variations. In the reference climate, in AB most waves headed

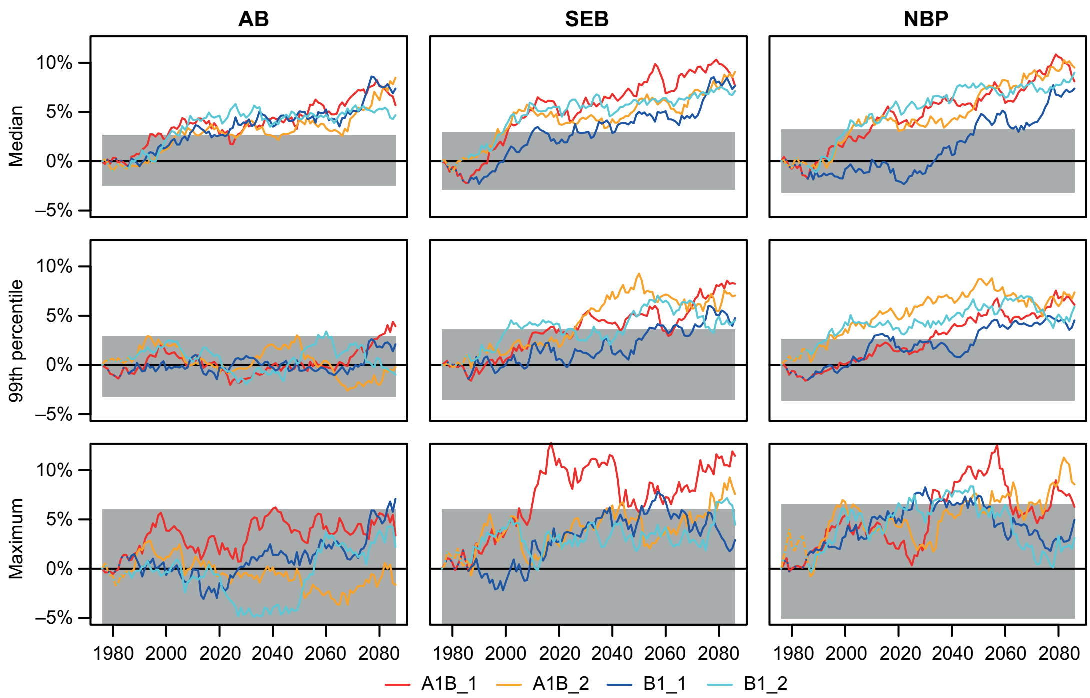

Fig. 7. Thirty-year running means of the annual median (top), 99th percentile (middle) and maximum (bottom) significant wave heights as percentage deviation from the corresponding mean for the period 1961–1990 in Arkona Basin (AB), southeastern Baltic (SEB) and northern Baltic Proper (NBP) for the four projections A1B_1, A1B_2, B1_1 and B1_2. Gray areas show the 95% confidence intervals of the 30-year mean for the corresponding reference period 1961–1990, determined by bootstrapping.

eastward, some showed westerly directions and only a few headed south or north; whereas in SEB located in the center of the southeastern Baltic Sea, waves heading east dominated, with a secondary maximum of waves running south and in NBP most waves headed northeast.

Due to the geographical characteristics of the Baltic Sea region, changes in the wind direction distribution lead to changes in the wave direction distribution and thus affect the SWH. The relative changes in 30-year running means of the annual frequency distribution of eight wave directions (going towards) were calculated for the same three locations as discussed before (Fig. 8). Besides some variability in the direction distribution, an intensification of waves heading in easterly direction is evident for all realizations and all locations throughout the 21st century. Towards the end of the simulation period, waves heading east are up to +15% more often than in the reference period. Waves heading west are less frequent (–15%).

Discussion and conclusion

The four realizations showed a slight increase in the wind speed for most areas towards the end of the 21st century, but this increase was seldom above +5% of the values for the reference period 1961–1990. A priori, changes in wind speed cannot be linearly transferred to changes in the SWH and, thus, in some realizations the increase in SWH is often above +5% and even up to +10%. Additionally, the decrease in the sea ice cover in the northern Baltic Sea further altered the wave climate. Especially, the increase in 30-year the mean annual maximum SWH in the northern Baltic Sea could not be explained by the decrease in 30-year mean annual maximum wind speed, but it was consistent with the large reduction in the sea-ice cover. An analysis of common changes in all realizations emphasized an increase of more than +5% in median wave height for large parts of the Baltic Sea. Common change of extreme wave heights also increased, the increase being greater

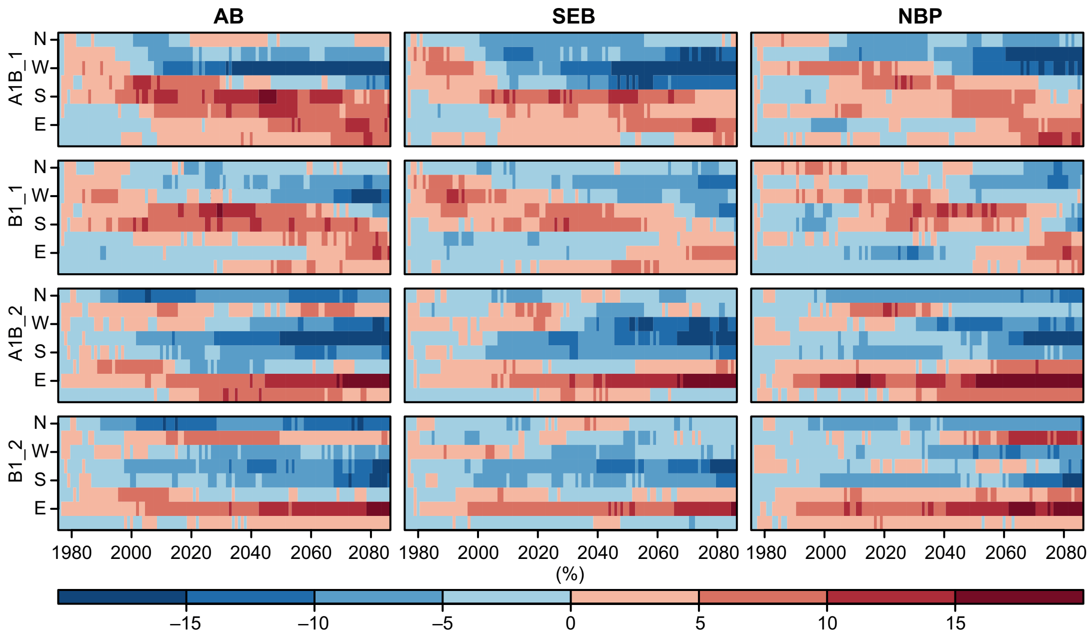

Fig. 8. Relative differences in the 30-year running means of the annual distributions of eight wave directions (going towards) relative to the period 1961–1990 for the four realizations (rows) and the three locations (columns). Reddish (blueish) colors indicate more (less) waves heading in a certain direction.

than +5% only in the eastern Kattegat, along the coasts of Lithuania, Latvia and Estonia and in the Gulf of Finland. For some parts of southwestern Baltic Sea, especially eastwards of coastlines, a common decrease was found which did not exceed –5% as compared with the reference-period values. These results are in agreement with those of Suursaar *et al*. (2016) who discussed changes in the western Estonian coastal sea in a single future realization with RCP 4.5 forcing. For that region, they found an increase between +5% and +20% westward of coastlines and a small decrease eastwards of coastlines.

The analysis of the multi-decadal variability of the wave climate within the 140-year-long simulations revealed different characteristics, which depended on the spatial location and the three location parameters of the distribution. The multi-decadal variability of the mean annual median SWH increased beyond the confidence interval of the reference period for all locations and simulations towards the end of the 21st century. For the mean annual 99th percentile SWH, only in SEB and NBP the values increased beyond the confidence interval towards the end of the 21st century in all simulations, whereas for AB the extreme SWH remained within the confidence interval in almost all simulations during the whole simulation period. For the mean annual maximum SWH, the confidence interval of the reference period was much wider and the simulated changes beyond the confidence interval were greater than +5% of the reference mean, and occurred only in some realizations. This points to the high uncertainty of changes in the extreme SWH, especially in terms of the annual maxima.

The analysis of the multi-decadal variability of the wave direction distribution showed a shift towards an increased frequency of waves heading in easterly directions, which is consistent with the increase in the frequency of strong westerly winds discussed by Groll *et al*. (2014) for the North Sea and a shift to a more positive North Atlantic Oscillation (Pinto *et al*. 2007). Dreier *et al*. (2011) using the same atmospheric data, also showed a shift towards more westerly winds in the southwestern Baltic Sea. Moreover, the shift to more westerly winds was already found in studies of the recent climate (e.g. Bierstedt *et al*. 2015). The aforementioned changes in the wave climate can be important, e.g., for the sediment transport in coastal waters in the Baltic Sea as presented by Dreier *et al*. (2011).

Besides the limitation due to the use of only one general circulation model in the ensemble set-up, the temporal and spatial differences in significant wave height and wave direction point to the uncertainties due to different emission scenarios and initial conditions and, thus, to the internal variability. However, the four realizations of a possible future wave climate gave some evidence of an increase in the significant wave height in the Baltic Sea. Changes in extreme waves were smaller and more uncertain than in median waves. Changes in the wave direction were generally more explicit and pointed to more (less) frequent waves heading east (west). The changes in the wave directions may also explain the discrepancies between small but homogeneous wind speed changes and greater but more heterogeneous wave height changes as different fetch and shelter effects related to the complex bathymetry of the Baltic Sea are also important.

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