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Climate Change and Corresponding Changes of Wave Conditions at the German Baltic Sea Coast

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ABSTRACT: In this study dynamically downscaled wind data from a regional climate model is used as input data for the calculation of four long-term time series of wave parameters for two of the global emission scenarios A1B, B1 (as compiled from Special Report On Emission Scenarios, IPCC - Intergovernmental Panel on Climate Change) with two realisations each. The long-term time series are calculated for a time period from 1960 to 2100 with the help of wind-wave-correlations and a spectral wave model. To assess the changes of the average wave conditions, we compared the frequency of occurrence and average values of the significant wave heights and mean wave directions for time periods of 30 years. The changes of the future wave conditions (2001 to 2100) are compared to actual conditions (1971 to 2000) and the statistical significance of the changes is shown. Moreover significant wave heights with a return period of 200 years are calculated with the help of extreme value statistics for time periods of 40 years and compared between future (2001 to 2100) and actual conditions (1961-2000). Some of the key findings in this study are, that changes of the future wind conditions, with more westerly winds and increasing average wind velocities (up to 4%) to the end of the 21st century, can be linked to significant changes of the frequency of occurrence with increasing average significant wave heights (up to 8%) and more waves coming from westerly directions. Moreover we found a spatial pattern for the changes of the average wave conditions. At westerly wind exposed locations, the average wave heights increase and at easterly wind exposed locations the average wave heights decrease and fewer waves come from northerly to easterly directions. In contrast, we found no significant trend or spatial pattern regarding the changes of the extreme wave heights. Causes of future changes of the extreme wave heights are more complex and cannot directly be linked to the local changes of the average wind conditions. Extreme wave heights with a return period of 200 years can increase/decrease up to/down to 14% depending on the location and the realisation of the future climate.

KEY WORDS: Baltic Sea, Climate Change, Cosmo-CLM, Average and Extreme Wave Conditions.

1 INTRODUCTION

To keep today's high protection level and effectiveness of coastal and flood protection structures for the future, both from a constructional and functional point of view, the changes of the hydrodynamic conditions induced by climate change have to be analysed. Moreover, the recently used structures have to be assessed on the basis of scenarios for the future changes of the near-shore hydrodynamics and if necessary, new ideas should be developed for a long lasting adaptation of the structures.

There are three main influence factors of regional climate change on the local wave climate at the Baltic Sea Coast, namely changes of the regional sea-levels, wind conditions and currents (during storm conditions). In this study we focus on the one hand side on the changes of the wind conditions as derived from runs of the regional circulation model Cosmo-CLM and on the other hand side on the corresponding changes of the local wave climate for average conditions but also for extreme events.

In the absence of strong tides, the local wave climate is mainly generated by the wind field over the Baltic Sea. The connection between changes of the local wind conditions and the local wave climate, but also other coastal processes like coastal erosion and accumulation has been shown in different studies in the past (e.g. Suursaar & Kullas, 2008; Kelpsaite & Dailidiene, 2011).

Another important characteristic of the hydrodynamic and meteorological conditions in the area of the Baltic Sea is the fact that the wave and wind climate are highly inhomogeneous, both in space and time (Räämet & Soomere, 2011).

Analyses on future changes of the wave climate in the Baltic Sea on the basis of projections for different green-house-gas emission scenarios are limited to a few numbers of studies and the results are different. State-of-the-art modelling of future projections of the wave climate depends e.g. on: (i) the atmospheric forcing factors, like e.g. the used driving model (global circulation model) but also the global emission scenarios, (ii) the downscaling approach (statistical or dynamical), (iii) the coupling between a global or regional circulation model and an ocean/sea-ice model and finally (iv) the applied impact model (e.g. a wave model).

The BACC (2009) report compiles results of studies on future projections of wind waves in the Baltic Sea. On the basis of a statistical downscaling approach of the ECHAM3 global circulation model, Miętus et al. (1999) found no significant changes in mean wave height but changes in wave height variability.

Contrary changes of the wave climate, with increases of the annual mean significant wave heights and the 90th percentile up to 0.4m resp. 0.5m, were found by Meier et al. (2006). Their investigations are based on dynamical downscaled wind data (regional circulation model RCAO) for two of the SRES scenarios A2 and B2 from the global climate models ECHAM4/OPYC3. Finally a simple wave model was applied to calculate the wave climate from the wind data.

A recent study on the changes of the wave climate in the Baltic Sea was carried out by Groll et al., 2012. In their study dynamical downscaled wind data (regional circulation model Cosmo-CLM) for two of the SRES scenarios A1B and B1 from the coupled atmosphere-ocean global circulation model ECHAM5/MPI-OM are used to calculate the wave climate with the help of the spectral wave model WAM (Hasselmann et al., 1988). The results show increases of the 99th percentile of significant wave heights up to 0.5m for the south-eastern part of the Baltic Sea.

The study presented here uses the same atmospheric forcing and SRES scenarios but a different impact model to calculate the wave climate. The used statistical correlation method between local wind and waves has been already described e.g. by Dreier et al. (2011). For the investigations presented in this paper, the statistical approach was extended to a combined statistical/numerical approach (hybrid approach) for the analysis of changes of extreme wave events. A more detailed description of the hybrid approach follows in the next section of the paper.

Since the wave conditions were derived for locations in the Baltic Sea near the 10m depth contour line ca. 1km off the coast (at quasi deep water conditions) the future sea level rise was neglected within the calculations of the wave climate.

2 STUDY METHODS

2.1 Climate models

For the investigations on the changes of the local wave climate, we use dynamical downscaled wind data of the regional circulation model Cosmo-CLM (Rockel et al., 2008) which was forced by the global atmosphere-/ocean-ice-model ECHAM5/MPI-OM.

Climate data from different Cosmo-CLM model runs (Lautenschlager et al., 2009) are available from the CERA climate data archive. The climate variability of the 20th century (1960-2000) is represented through 3 independent realisations (C20_1, C20_2 and C20_3).

For the projections of the future climate, two of the climate model runs for the 20th century were continued and forced by the SRES (Nakićenović et al., 2000) scenarios A1B (global economic) and B1 (global environmental), resulting in 4 independent realisations (A1B_1, A1B_2, B1_1 and B1_2).

The realisations for the past and the future have been combined to 4 transient time series (C20_1+A1B_1, C20_1+B1_1, C20_2+A1B_2 and C20_2+B1_2) of near surface wind conditions (10m above surface) covering a period from 1960-2100.

2.2 Hybrid Approach

For the statistical assessment of the changes of the wave climate, induced from changes of future wind conditions, we use wind-wave-correlations that have been derived at different locations at the German Baltic Sea Coast (Fröhle & Fittschen, 1999; Fröhle, 2000). The locations that have been used in this study can be seen in Figure 1: Warnemünde (cp. Figure 1 right), Travemünde (Bay of Lübeck, cp. Figure 1 bottom) and Westermarkelsdorf (West coast of the Island of Fehmarn/Bay of Kiel, cp. Figure 1 top).

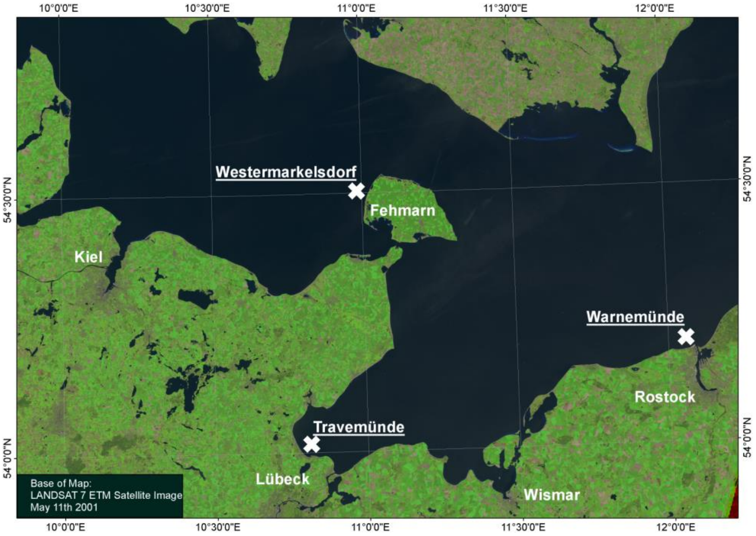

Figure 1 Locations of the study area at the German Baltic Sea Coast.

For an assessment of the correlations we calculated mean absolute deviations between calculated and observed wave heights, periods and directions and found a good agreement between calculated and observed values. The average deviations between calculated and observed wave parameters are below 10cm for the significant wave heights (H_{m0}), 0.5s for the mean wave periods (T_{m02}) and 8° for the mean wave directions (Θ_m) (Dreier et al., 2012).

The correlations between the measured wind velocities and the wave heights in each directional class are only valid to a certain error margin. Therefore a cut off criteria for maximum wind velocities, derived from a sensitivity analysis from Fröhle & Fittschen (1999), has been applied for a 5% error margin (Equation 1).

$$U_{cut} = 1.16 \times U_{\max,correlation} \tag{1}$$

If the wind data of the regional circulation model exceed the maximum wind velocities used for the correlation (cp. Equation 1, $U_{max,correlation}$) between the observed wind and wave data, the calculated wave heights become unreliable. The latter occurs approximately in 2% of the hourly simulated wind data and for a time period of 30 years. In this case we calculate the wave parameter with the help of stationary numerical simulations of the wave model SWAN (Booij et al., 1999) instead of calculating them from wind-wave-correlations.

The numerical wave model has been set up for the area of the Western Baltic Sea (Figure 2 left, red box resp. Figure 2 right) at a mean sea level.

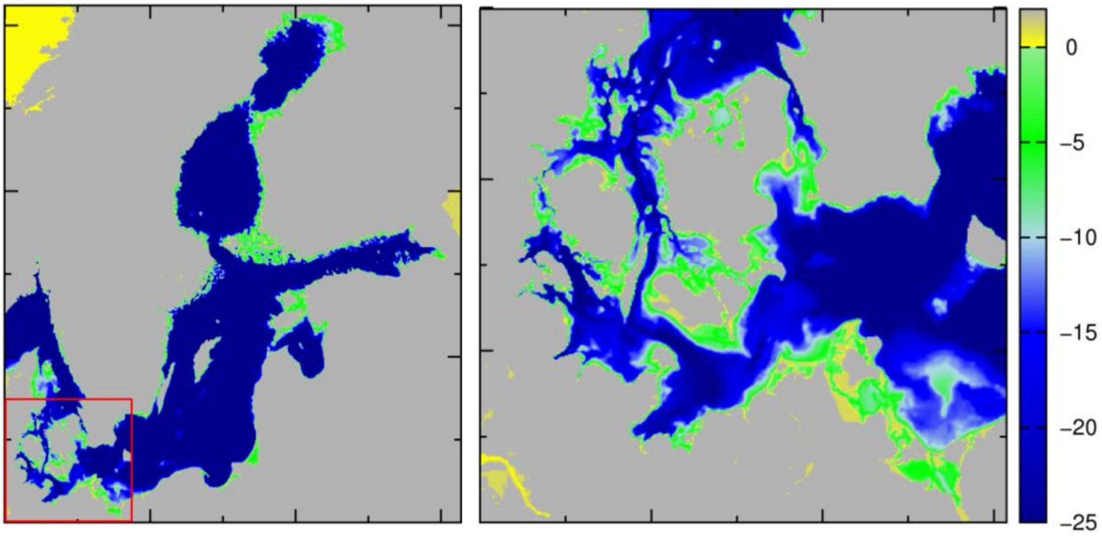

Figure 2 Bathymetry [m over Mean Sea Level] Baltic Sea (left) and Western Baltic Sea (right).

The boundary conditions are resolved with a resolution of ΔU_{10}=1m/s for the wind velocities and $\Delta \Theta_w$=10° for the wind directions.

Finally we use either wind-wave-correlations or the numerical wave model to calculate 4 transient time series of wave parameters on the basis of the 4 transient time series of wind conditions. The advantage of the combined approach is the fast compilation of reliable long-term time series of wave parameters for the area of the Baltic Sea which can be analysed with the help of extreme value statistics, as shown in the next sections of the paper.

3 RESULTS AND DISCUSSION

3.1 Changes of Future Average Wind Conditions

To assess future changes in wind, we extracted time series of near-surface wind velocity and direction from the Cosmo-CLM model at grid points close to the locations of the study area (cp. Figure 1). From the time series of wind data, we calculated the frequency of occurrence and the average value of the wind velocity and direction for time periods of 30years and compared the values for e.g. the scenarios 2050 (2021-2050) and 2100 (2071 2100) to the values of the control period 1971-2000.

Examples for the changes of the average wind conditions at the location Warnemünde are shown in Figure 3.The changes of the frequency of occurrence for the wind velocity and direction are shown in Figure 3 top left resp. right, for the two scenarios 2050 (dashed line) and 2100 (solid line) compared to the control period (1971-2000).

Regarding the changes of the wind velocity (cp. Figure 3 top left) it is concluded that the frequency of occurrence of lower wind velocities decreases while the frequency of medium and higher wind velocities increases. This change is more explicit for the scenario 2100 than for the scenario 2050. In consequence, the average wind velocity increases up to 4% to the end of the 21st century at this location (cp. Figure 3 bottom left).

Regarding the changes of the wind direction (cp. Figure 3 top right) it is noted that the frequency of occurrence of easterly wind directions decreases while the frequency of westerly wind directions increases up to 2% to the end of the 21st century. In consequence, the average wind direction is changing up to 9° towards westerly directions at this location (Figure 3 bottom right).

The changes of the frequency of occurrence of the wind velocity and direction near the locations of Travemünde and Westermarkelsdorf show in general the same tendency, except for a few velocities resp. directions. The changes of the average wind conditions also have effects on the local wave climate, as shown in the next section of the paper.

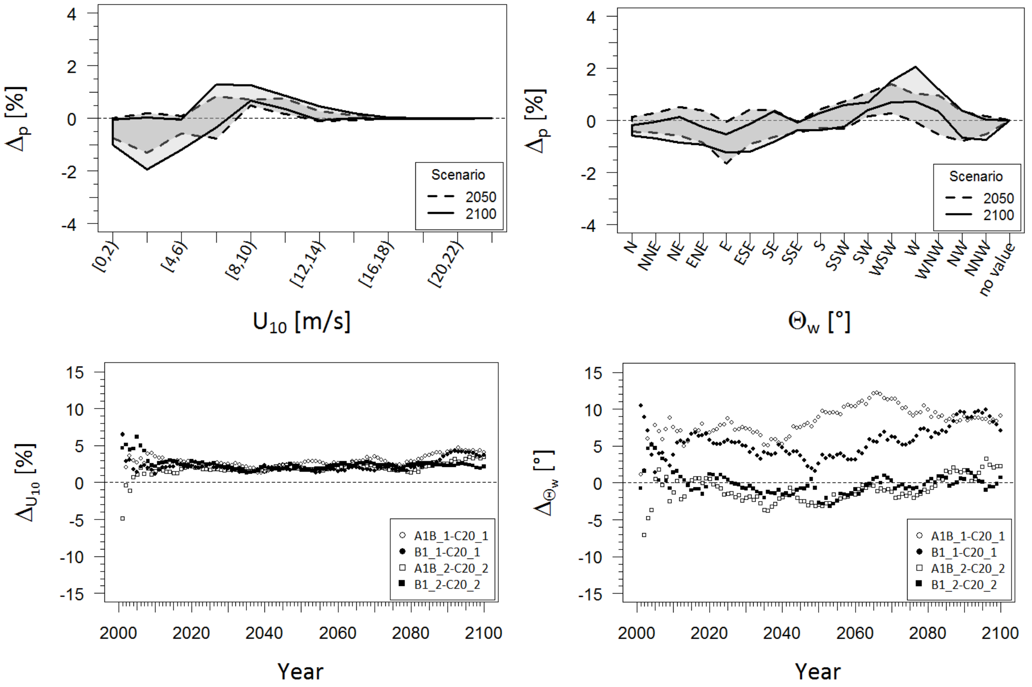

Figure 3 Changes of the frequency of occurrence of the wind velocity U_{10} (top left) and wind direction Θ_w (top right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) and corresponding changes of the 30 years average wind velocity U_{10} (bottom left) and wind direction Θ_w (bottom right) for the climate change scenarios A1B and B1 compared to the control period 1971-2000, near Warnemünde.

The results for the changes of the future wind conditions are in agreement with analysis from the North German Climate Bureau (Meinke et al., 2010). Their analyses were carried out on the basis of data from multi-ensemble climate simulations (e.g. from the PRUDENCE and CERA climate data archive) using different global (e.g. ECHAM5/MPI-OM, ECHAM4/OPYC3 and HadAM3H) and regional circulation models (Cosmo-CLM, REMO, RCAO) and SRES scenarios (A1B, B1, B2 and A2).

The results for the changes of the average wind velocity between the control period (1961-1990) and the end of the 21st century (2071 2100) are spreading between +1% and +4% due to the uncertainty of the ENSEMBLE approach. Regarding the changes of the wind velocity 97% of all ENSEMBLE members agree with the increasing trend of change. Another outcome of their analyses is that in the future more westerly winds can occur (increases between 7% and 13%).

3.2 Changes of Future Average Wave Conditions

From the derived time series of wave parameters (see section 2.2 Hybrid Approach), we calculated the frequency of occurrence and the average value of the significant wave height (H_{m0}) and mean wave direction (Θ_m) for time periods of 30years and compared the values for e.g. the scenarios 2050 (2021-2050) and 2100 (2071 2100) to the values of the control period 1971-2000.

Example results for the changes of the frequency of occurrence of the significant wave height and mean wave direction at the location of Warnemünde and Travemünde are given in Figure 4 resp. Figure 5.

At locations exposed to westerly winds (e.g. Warnemünde and Westermarkelsdorf) it can be concluded that the frequency of occurrence of medium and higher wave heights increases while the frequency of lower wave heights decreases (cp. Figure 4 top left).

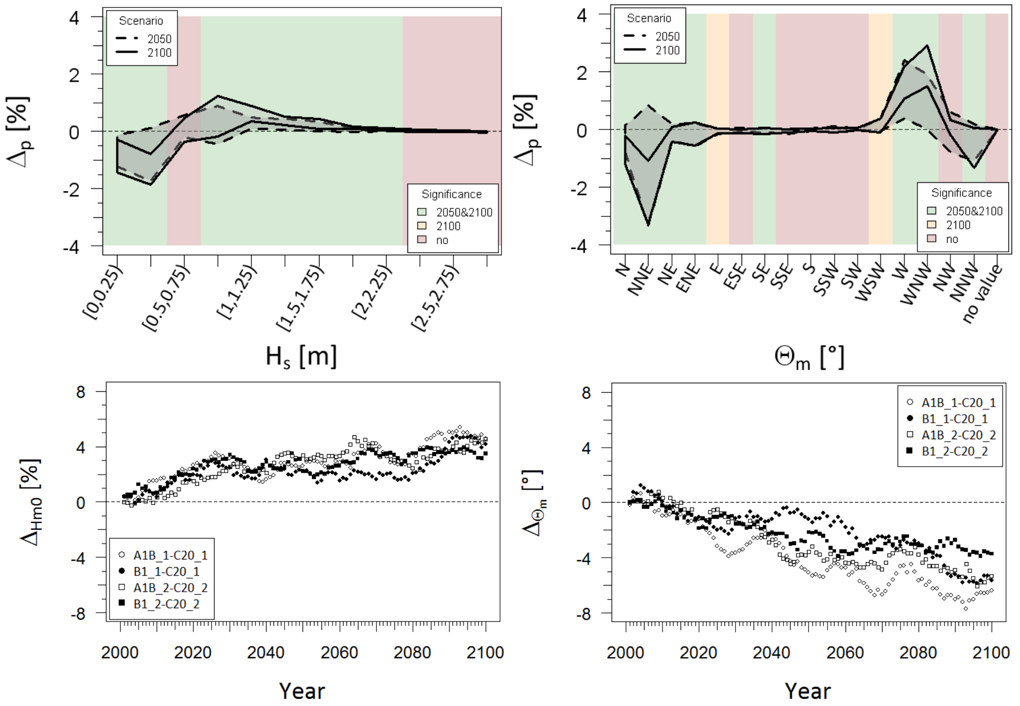

Figure 4 Changes of the frequency of occurrence of the significant wave height H_S (top left) and wave direction Θ_m (top right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) and corresponding changes of the 30 years average significant wave height H_S (bottom left) and wave direction Θ_w (bottom right) for the climate change scenarios A1B and B1 compared to the control period 1971-2000, near Warnemünde.

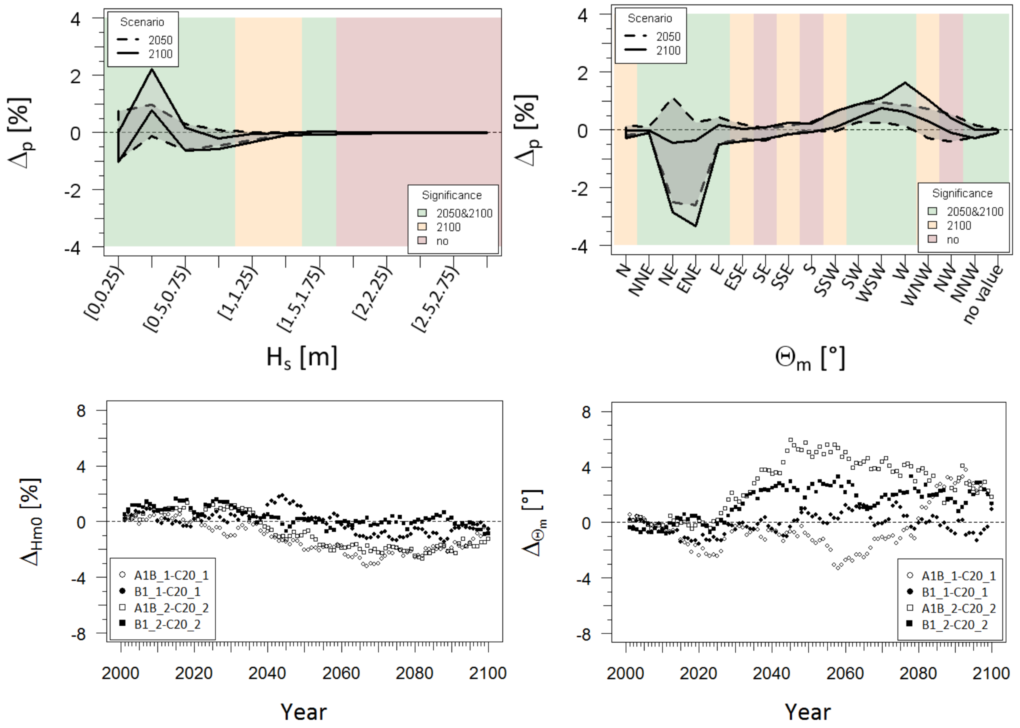

Figure 5 Changes of the frequency of occurrence of the significant wave height H_S (top left) and wave direction Θ_m (top right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) and corresponding changes of the 30 years average significant wave height H_S (bottom left) and wave direction Θ_w (bottom right) for the climate change scenarios A1B and B1 compared to the control period 1971-2000, near Travemünde.

The change of the frequency of occurrence of the significant wave height is more explicit for the scenario 2100 (cp. Figure 4 top left, solid line) than for the scenario 2050 (cp. Figure 4 top left, dashed line).

Due to the shift of the frequency of occurrence towards higher significant wave heights, the average significant wave height increases between 3% to 5% in the case of Warnemünde (cp. Figure 4 bottom left) and 4% to 7% in the case of Westermarkelsdorf (not shown here) to the end of the 21st century (2071-2100) compared to the control period (1971-2000).

The results for the changes of the significant wave heights presented here are in agreement with results from Groll et al. (2013) who used the wave model WAM (Hasselmann et al., 1989) to calculate hourly wave parameters between 1960-2100 for the entire Baltic Sea (cp. Figure 2 left) with a spatial resolution of ca. 5.5km. The wave model was run on the same wind data (runs of the regional circulation model Cosmo-CLM for the SRES scenarios A1B and B1), thus first comparisons between the results of different approaches to model the wave climate (numerical vs. combined statistical/numerical) can be done.

Figure 6 left shows exemplarily the calculated changes of the 50th percentile of significant wave height for the first realisation of the SRES scenario A1B to the end of the 21st century (1971-2100) compared to control period 1961-1990. In agreement with our results, maximum increases up to 7.5% of the 50th percentile of significant wave height were found at westerly exposed locations. Nevertheless it should be noted, that the results can not directly be compared at near-shore locations, due to the coarse spatial resolution of the WAM model (5.5km).

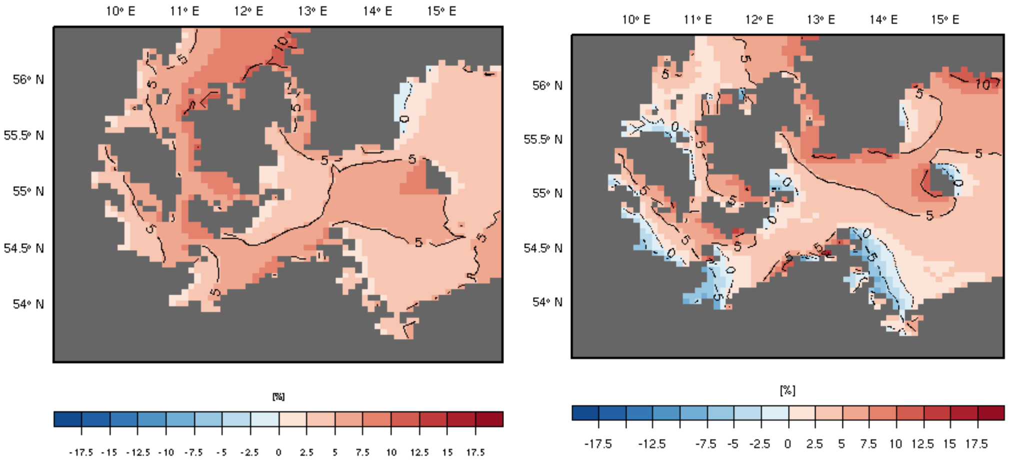

Figure 6 Changes of 50th percentile (left) and 99th percentile (right) of significant wave height H_s to the end of the 21st century (2071-2100) for the first realisation of the climate change scenarios A1B compared to the control period 1961-1990 (Groll et al., 2013)

At locations exposed to easterly winds (e.g. location Travemünde) we found a contrary signal of change for average wave conditions: the frequency of occurrence of medium and higher wave heights decreases, meanwhile the frequency of lower wave heights increases (cp. Figure 5 top left). As for the other locations, the signal of change is more explicit to the end of the 21st century (scenario 2100). In consequence, the average significant wave height at this location decreases down to 3% in the middle of the second half of the 21st century (2041-2070) (cp. Figure 5 bottom left).

The changes of the frequency of occurrence of the wave direction is exemplarily shown for Warnemünde and Travemünde in Figure 4 top right resp. Figure 5 top right.

From both figures it can be seen that the changes of the frequency of the wave direction are similar except for a few velocities resp. directions. In general, westerly wave directions become more dominant, due to the fact that north-easterly wave directions can decrease in the future, especially to the end of the 21st century (scenario 2100). Due to the shift of the frequency of occurrence of the wave direction towards westerly directions, the average wave direction is changing towards westerly directions, too. The average wave direction can change up to 8° in the case of Warnemünde (cp. Figure 4 bottom right) and up to 6° in the case of Travemünde (cp. Figure 5 bottom right) and Westermarkelsdorf (not shown here).

Moreover statistical hypothesis tests (parametric z-tests) are performed to assess the statistical significance of the changes of the frequency of occurrence of the significant wave heights and wave directions.

Figure 4 resp. Figure 5 top left and right show the results of the significance tests for each velocity resp. direction of the frequency of occurrence using different background colours. If the changes for both scenarios 2050 and 2100 are statistical significant at a level of 5% (0.05), a green background colour is used. If the changes are only significant to the end of the 21st century (scenario 2100), the background colour is yellow and if no significance was found, the background colour is red.

The main changes of the frequency of occurrence of the wave heights with less than 2m significant wave height (cp. green coloured areas in Figure 4 resp. Figure 5 top left) and of the wave directions from N to E and SW to NW (cp. green coloured areas in Figure 4 resp. Figure 5 top right) are statistical significant at the 5% level, esp. to the end of the 21st century.

3.2 Changes of Future Extreme Wave Heights

To assess the future changes of extreme wave heights, the compiled 4 transient long-term time series of wave parameters (see section 2.2 Hybrid Approach) were analysed using methods of extreme value statistics.

From the time series of wave parameters, we selected annual maximum significant wave heights over time periods of 40 years. After the selection of the samples, different extreme value distribution functions (log-normal, Gumbel, Weibull, GEV) were fitted to the data. The fitting parameter of the distributions where estimated with the help of the maximum-likelihood method. The log-normal function showed the best fitting properties (e.g. the smallest root-mean-square deviations between the empirical and theoretical distribution function) and was chosen for further calculations.

The extreme wave heights were calculated on the basis of the log-normal function and for a return level of 200 years and compared between the future (2001-2100) and actual conditions (1961-2000). Example results for the change of extreme wave heights are shown in Figure 7.

At the location Warnemünde (cp. Figure 7 top left), the calculated changes of extreme wave heights show an increasing trend up to 5%, except for one realisation (C20_2+A1B_2) which shows a decreasing trend. At the other locations (cp. Figure 7 top right and bottom) the range of the changes of extreme wave heights is larger. Near Travemünde (cp. Figure 7 top right) future extreme wave heights can increase up to 14% and decrease down to 5% for each two of four realisations. Similar trends are found at the location of Westermarkelsdorf (cp. Figure 7 bottom), where each two of four realisations increase up to 10% and decrease down to 14%. To conclude, the statistical analyse of extreme wave heights shows no clear trend towards a general increase or decrease of future extreme wave heights. The results spread widely and depend on e.g. the location, realisation and the projection period.

Groll et al. (2013) compile further results on the changes of the 99th percentile of significant wave heights. Figure 6 right shows exemplarily the calculated changes for the first realisation of the scenario A1B to the end of the 21st century (1971-2100) compared to actual conditions (1961-1990). In agreement with our results, increases of the 99th percentile of significant wave heights up to 5% were found e.g. near the location of Warnemünde (cp. Figure 6 right). Moreover decreases of the 99th percentile of significant wave heights down to 5% were found e.g. in the Bay of Lübeck. The latter is in contrast to our results of the changes of the extreme wave heights for the realisation A1B_1+C20_1 (cp. Figure 7 top right), which shows an increase of 8% to the end of the 21st century (2061-2100).

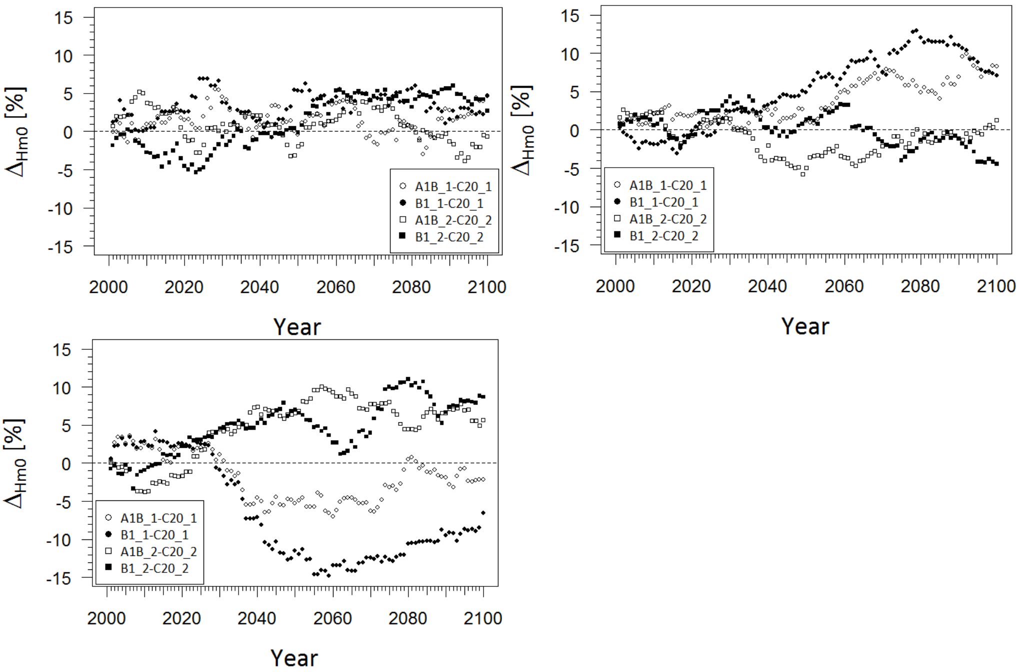

Figure 7 Changes of significant wave heights with a return level of 200 years based on a log-normal distribution function and for time periods of 40 years for different realisations of the climate change scenarios A1B and B1 compared to the control period (1961-2000), near Warnemünde (top left), Travemünde (top right) and Westermarkelsdorf (bottom left).

4 CONCLUSIONS

In this study, we extracted long-term time series (1960-2100) of near surface wind velocity and direction from the regional circulation model Cosmo-CLM for two of the SRES scenarios A1B, B1 at three locations along the German Baltic Sea Coast. On the basis of the wind data, long-term time series (1960-2100) of wave parameters were compiled using wind-wave-correlations and stationary runs of the wave model SWAN. Finally the changes of the wave parameters were analysed statistically for average and extreme wave events.

Compared to actual conditions, the future average wind velocities may increase up to 4% to the end of the 21st century. Changes of the frequency of wind directions, with more wind events from westerly and less events from easterly directions, may change the average wind directions up to 8° towards more westerly directions.

The changes of the average wind velocities result in increases of the average significant wave heights at westerly wind exposed locations up to 7% and small decreases of the average significant wave heights at easterly wind exposed locations. The changes of the wave directions, with more wave events from W-NW and fewer events from N-NE, can be connected to the changes of the wind directions.

Analyses of the changes of extreme wave heights (significant wave heights with a return period of 200 years) show both, increases and decreases of up/down to 14% depending on the location, realisation and projection period. Near the location of Warnemünde a slight increasing trend up to 5% for the change of the extreme wave heights esp. to the end of the 21st century exists.

The spatial changes of the wave climate will be analysed in a next step from results of non-stationary simulations of a high-resolution wave model SWAN with boundary conditions from runs of the wave model WAM for the entire Baltic Sea (Groll et al., 2013).

Regarding the changes of extreme events the uncertainty of the used statistical approach will be assessed within the future work.

ACKNOWLEDGEMENT

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