Changes of 21st Century's average and extreme wave conditions at the German Baltic Sea Coast due to global climate change

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ABSTRACT

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On the basis of hourly simulated wind data from a regional circulation model (Cosmo-CLM) long-term time series (1960-2100) of wave parameters were compiled for two of the SRES scenarios A1B, B1 at three locations along the German Baltic Sea Coast. The time series of wave parameters were calculated with the help of statistical correlations between observed wind and wave data, which were derived for the three locations in the study area. Furthermore, we applied a wave model for the Western Baltic Sea to correct some of the calculated wave information. The key findings of this study are that: (i) significant changes of average wind conditions can directly be linked to significant changes of the average wave conditions, (ii) a spatial pattern for the changes of average wave conditions can be found, (iii) no general trend can be found for the changes of extreme wave conditions. Comparisons of wind conditions, as simulated by the regional circulation model, for the past and the future are showing two main changes: (a) increases of average wind velocities to the end of the 21st century up to +4% and (b) more wind events from westerly and less events from easterly directions. The changes of the average wind velocities are resulting 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 future changes of the wave directions, with more wave events from W-NW and fewer events from N-NE, can be connected to the future changes of wind directions. Analyses of extreme wave heights with a return period of 200 years are showing both increasing and decreasing changes of up/down to +/-14%. At one location of the study area (Warnemünde) a slight increasing trend for the change of extreme wave heights to the end of the 21st century exists.

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

INTRODUCTION

For the future safe design of coastal and flood protection structures, the influences of climate change on water levels (mean sea level and extreme water levels) but also on the local wave climate (average and extreme events) have to be analysed. This study is focusing on changes of the local wave climate induced by changes in wind conditions as simulated by runs of the regional circulation model Cosmo-CLM (Lautenschlager *et al.*, 2009).

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 number of studies and the results are differing widely. The state-of-the-art modelling of projections on the wave climate is depending on: (i) the atmospheric forcing factors, like e.g. the used driving model (global circulation model) and 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 (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. Using a statistical downscaling approach on the basis 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 (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 the wind data for the calculation of the wave information.

A recent study on wave climate changes in the Baltic Sea was carried out by HZG (Groll *et al.*, 2012). In their study dynamical downscaled wind (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 was used to calculate the wave climate with the help of the spectral wave model WAM (Hasselmann *et al.*, 1988). The results are showing increases of the 99th percentile of significant wave heights up to +0.5m for the south-eastern part of the Baltic Sea.

Our study presented in this paper uses the same coupled atmosphere-ocean global circulation model and SRES scenarios, but a different impact model. The calculation of the wave information in the study area is performed using statistical

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correlation methods between local wind and waves and has been already described e.g. by Dreier *et al.* (2011).

For the investigations presented in this paper, we extended this approach to a hybrid approach with the aim to analyse also the changes of extreme wave events. A more detailed description of this 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 (quasi deep water conditions) the future sea level rise was neglected for the wave simulations.

METHODS

Climate Data

For our investigations we are using dynamical downscaled wind data of the regional circulation model Cosmo-CLM (Rockel *et al.*, 2008) which has been 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) as compiled in Table 1.

For the modelling of the future climate, only the first 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.

The realisations for the past and the future have been combined to 4 transient time series (cp. Table 1) of near surface wind conditions (10 m above surface) covering a period from 1960-2100.

Table 1. Cosmo-CLM model runs (remark: ‘x’ denotes no experiment).

20th century observed anthropogenic forcing	**21st century forced by emission scenario A1B**	**21st century forced by emission scenario B1**	**transient time series of wind parameter**
C20_1	A1B_1	X	C20_1+A1B_1
C20_1	x	B1_1	C20_1+B1_1
C20_2	A1B_2	X	C20_2+A1B_2
C20_2	x	B1_2	C20_2+B1_2
C20_3	x	X	x

Hybrid Approach

For the statistical assessment of the changes of the wave climate, induced from changes of future wind conditions, we are using wind-wave-correlations that have been derived for three locations at the German Baltic Sea Coast (Fröhle and Fittschen, 1999; Fröhle, 2000). Figure 1shows the three locations which have been used in the present study: Warnemünde (cp. Figure 1 right), Travemünde (Bay of Lübeck, cp. Figure 1 bottom) and Westermarkelsdorf (Island of Fehmarn/Bay of Kiel, cp. Figure 1 top).

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. At the three locations the average deviations between the 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 correlated wind velocities and resulting 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 and Fittschen (1999), has been applied for a 5% error margin (Equation 1).

$$U_{cut} = 1.16 \times U_{\max,correlation} \qquad (1)$$

If the used wind data of the

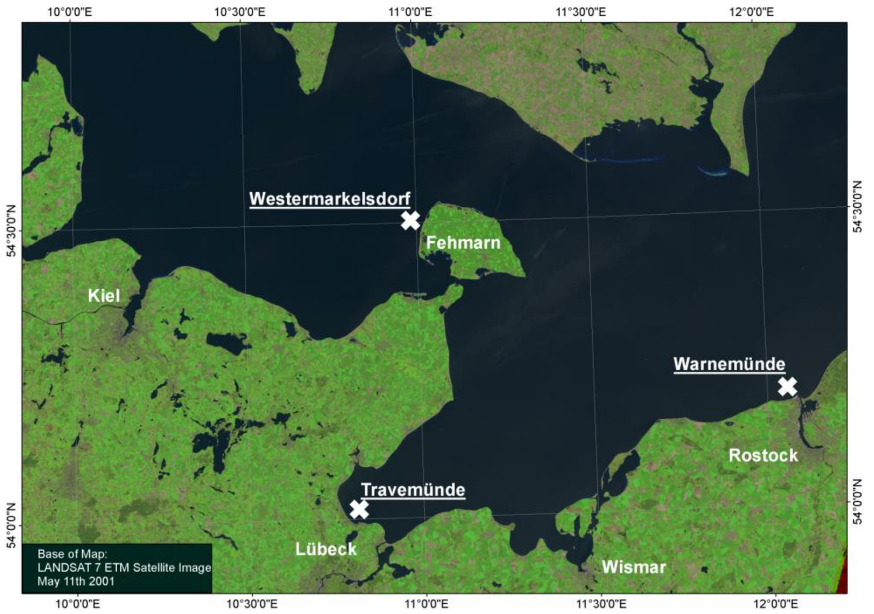

Figure 1. Locations of the study area at the German Baltic Sea Coast.

regional circulation model are exceeding the maximum wind velocities used for the derivation of the statistical relations between the observed wind and wave data, the calculated wave heights are becoming 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 using 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 and at a mean sea level. 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 compiled 4 transient time series of wave parameters on the basis of the 4 transient time series of wind conditions (cp. Table 1 on the previous page) using either wind-wave-correlations or the wave model for the calculation of the

The advantage of this combined approach is that it compiles long-term time series of more reliable 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.

RESULTS

Changes of Future Wind Conditions

For the assessment of future changes in wind, wind data for different time periods, each consisting of 30 years wind data as simulated from the Cosmo-CLM model were extracted at grid points close to the locations of the study area (cp. Figure 1). The data were extracted for the scenario 2050 (2021-2050) and 2100 (2071-2100) and the control period 1971-2000.

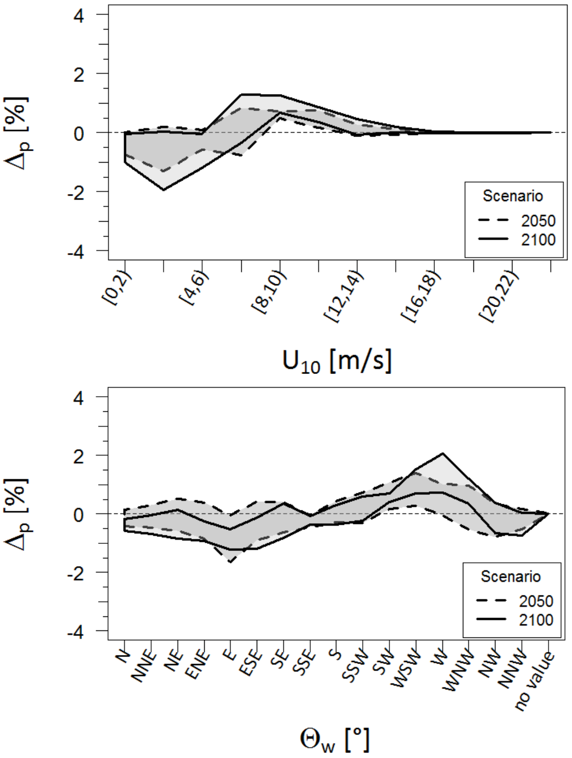

Figure 2. Change of frequency distribution of near surface wind velocities U_{10} (top) and wind directions Θ_w (bottom) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period 1971-2000, near Warnemünde.

In the next step the differences of the frequencies of occurrence for the wind velocities and directions were calculated between each combination of the 4 realisations for the 21st century (A1B_1, A1B_2, B1_1, B1_2) and the 3 realisations for the 20th century (C20_1, C20_2, C20_3); cp. Table 1. From the ensemble of 12 differences, the minimum and maximum differences of the frequency of occurrence for the wave heights and wave directions were identified for the scenarios 2050 and 2100. Examples for the change of the average wind conditions at the location Warnemünde are shown in Figure 2.

Figure 2 shows the change of the frequency of occurrence for the wind velocities and directions for the two scenarios 2050 (dashed line) and 2100 (solid line) compared to the control period (1971-2000). Regarding the change of the **wind velocities** (cp. Figure 2 top) it is concluded that the frequency of occurrence of wind events with lower velocities decreases and the frequency of wind events with medium and higher wind velocities increases. This change is more explicit for the scenario 2100 than for the scenario 2050. The average wind velocity increases at this location up to +4% to the end of the 21st century (not shown here).

Regarding the change of the frequency of the **wind directions** (cp. Figure 2 bottom) it is obvious that the frequency of easterly wind directions decreases while the frequency of westerly wind directions is increasing up to +2% to the end of the 21st century. In consequence the average wind direction is changing to more westerly directions at this location (not shown here).

The changes of the frequency for the wind velocities and directions near the locations of Travemünde and Westermarkelsdorf are showing in general the same tendency, except for a few velocities resp. directions. The changes of the wind conditions have also consequences on the local wave climate, as shown in the next section of this paper.

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 change of the average wind velocities 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 velocities 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%).

Changes of Future Average Wave Conditions

For the statistical assessment of the change of average wave conditions, the frequency of occurrence for the future scenarios 2050 (2021-2050) and 2100 (2071-2100) were compared to the values for the control period (1971-2000). The change of the frequency for average wave parameters is calculated with the same method as for the change of the wind conditions (for details, see section before). Example results for the change of the frequency for the wave heights and wave directions at the three locations are given in Figure 3 on the next page.

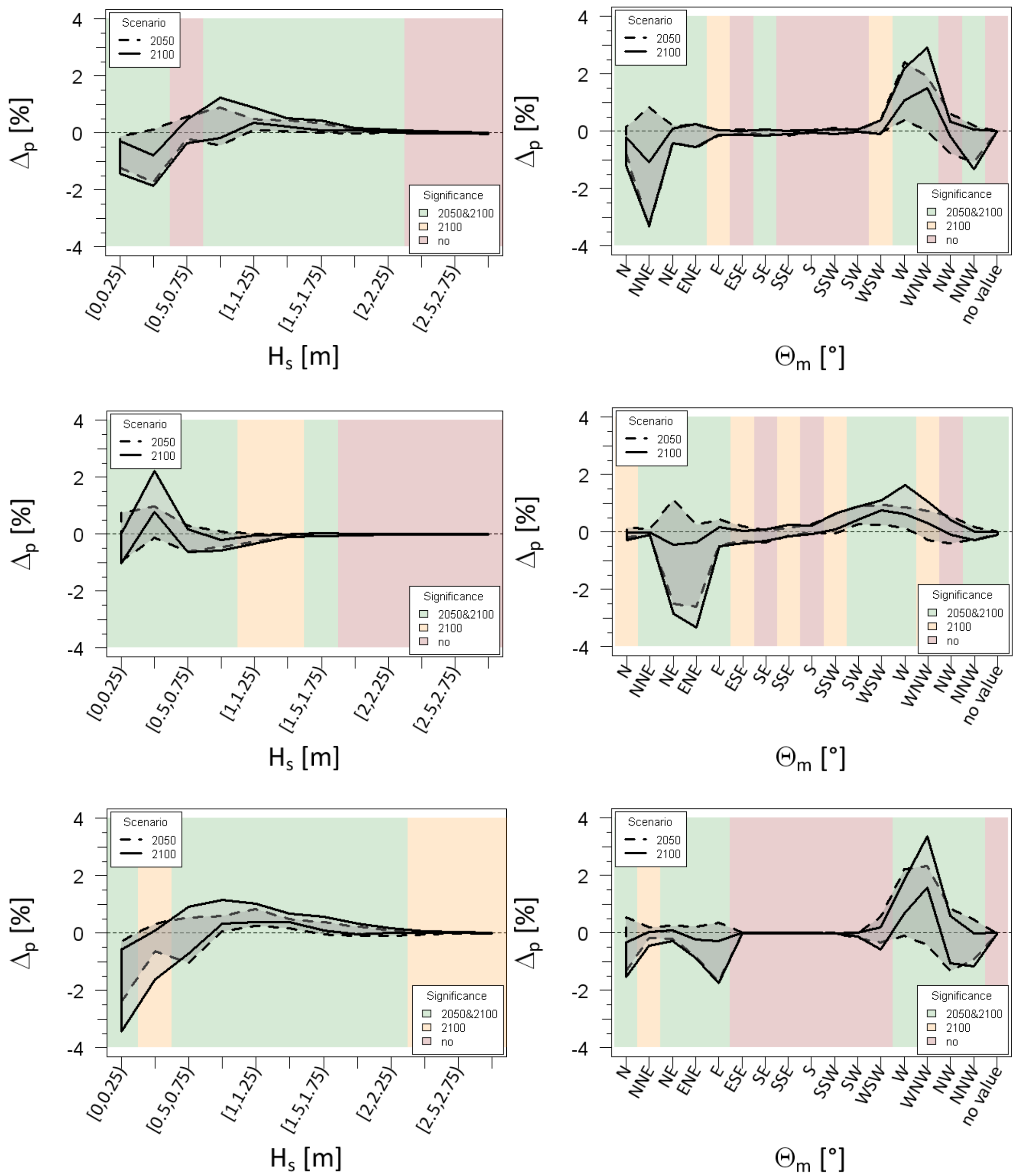

Figure 3. Change of frequency distribution of significant wave heights H_s (left) and mean wave directions Θ_m (right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Warnemünde (top), Travemünde (centre) and Westermarkelsdorf (bottom). Results of parametric significance test at 95% significance level coloured.

Regarding the **wave heights** it can be concluded that for locations exposed to westerly winds (e.g. location Warnemünde, as shown in Fig. 3 top left, and Westermarkelsdorf, as shown in Figure 3 bottom left), the frequency of occurrence of waves with medium and higher wave heights increases and the frequency of waves with lower wave heights decreases. This signal of change is more explicit for the scenario 2100 (cp. Figure 3, solid line) than for the scenario 2050 (cp. Figure 3, dashed line).

Due to the shift of the frequency distribution towards higher significant wave heights, the average significant wave height is going to increase in the range of +3% to +5% in the case of Warnemünde and +4% to +7% in the case of Westermarkelsdorf, to the end of the 21st century (2071-2100) compared to the control period 1971-2000 (not shown here).

For locations exposed to easterly directions (e.g. location Travemünde, as shown in Figure 3 centre left) a contrary signal of change exists: the frequency of occurrence of waves with medium and higher wave heights decreases, meanwhile the frequency of waves with lower wave heights increases. 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 -1% of in the middle of the second half of the 21st century (2041-2070) (not shown here).

The change of the frequency of the **wave directions** is exemplarily shown for the three locations in Figure 3 on the right hand side.

It can be seen from Figure 3 that the change of the frequency of the wave directions is similar at all three locations except for a few velocities resp. directions. In general, westerly wave directions become more dominant, while north-easterly directions decrease, especially to the end of the 21st century (scenario 2100). Due to the shift of the distribution of wave directions towards more westerly directions, the average wave directions are changing to more westerly directions too, with up to 6° in the case of Westermarkelsdorf and up to 8° in the case of Warnemünde (not shown here).

At easterly wind exposed locations like e.g. Travemünde, the average wave direction can change towards more easterly directions with up to 6° (not shown here).

To assess the statistical significance of the changes of the frequency distributions for the wave heights and directions, parametric significance tests were performed.

Figure 3 shows the results of the performed significance tests for each velocity resp. direction of the frequency distribution. If the changes were assessed to be statistical significant for both scenarios 2050 and 2100, a green background colour was plotted. If the changes are only significant to the end of the 21st century, the background colour is yellow and if no significance was found, the background colour is red.

The main changes of the frequency of occurrence for the wave heights below a significant wave height (H_s) of 2m (cp. green coloured areas in Figure 3 left hand side) and for the wave directions from N to E and SW to NW (cp. green coloured areas in Figure 3 right hand side) were assessed to be statistical significant at the 95% level esp. to the end of the 21st century.

Changes of Future Extreme Wave Heights

To assess the changes of extreme wave heights, the compiled 4 transient long-term time series of wave parameters 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 (not shown here) and was chosen for further calculations.

On the basis of the log-normal function and a chosen return level of 200 years, extreme wave heights over time periods of 40 years were calculated for each year within the time period 2000-2100. The derived extreme wave heights for the future (2001-2100) were compared to values for the control period 1961-2000. Example results for the change of extreme wave heights are shown in Figure 4.

At the location Warnemünde (Figure 4 top), the calculated changes of extreme wave heights are showing an increasing trend up to +5%, except for one transient scenario run (C20_2+A1B_2) which indicates a decreasing trend. For the other locations (cp. Figure 4 centre and bottom) the range of the changes of extreme wave heights is larger.

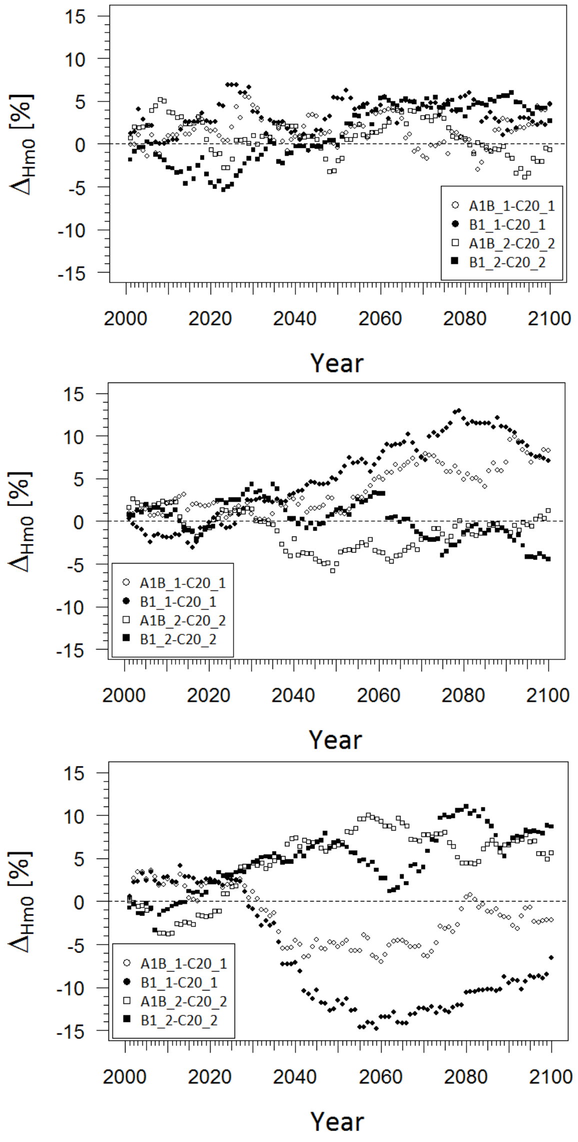

Figure 4. Change of extreme wave heights over time periods of 40 years for different transient runs of the climate change scenarios A1B and B1 compared to the control period (1961-2000), near Warnemünde (top), Travemünde (centre) and Westermarkelsdorf (bottom).

Near Travemünde (cp. Figure 4 centre) future extreme wave heights are increasing up to +14% and decreasing down to -5% for each two of four transient time series.

The same tendency can be found for the changes of extreme wave heights near the location of Westermarkelsdorf (cp. Figure 4 bottom), with each two of four transient time series increasing up to +10% and decreasing down to -14%.

To conclude, the statistical analyse of extreme wave heights shows no clear tendency towards a general increase or decrease of future extreme wave heights. The results spread widely depending on the different scenario runs and the chosen projection period.

This is in agreement with analyses of the Institute for Coastal Research, Helmholtz-Zentrum Geesthacht (Groll *et al.*, 2012) on the changes of wave conditions derived from non-stationary numerical simulations for the Baltic Sea using the wave model WAM (Hasselmann *et al.*, 1988) and wind boundary conditions from the Cosmo-CLM model runs listed in Table 1 (see second section of this paper). The results are showing both increasing values for the 99th percentile of the wave heights up to +0.5m (+10%), but also decreasing values for some coastal areas which are not exposed to westerly winds (like e.g. the Bay of Lübeck, Pomeranian Bay, Gdańsk Bay etc.).

CONCLUSION & DISCUSSION

In this study, we extracted long-term time series (1960-2100) of near surface wind velocities and directions 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 time series of wave parameters were analysed statistically for average and extreme wave events.

Compared to actual conditions, 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 are resulting 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 extreme wave heights (return period of 200 years) are showing both, increasing and decreasing changes of up/down to +/-14% depending on the location and scenario run. At one location of the study area (Warnemünde) a slight increasing trend for the change of extreme wave heights to the end of the 21st century exists.

Nevertheless, some uncertainties of the projected changes of the wave climate are still remaining. The changes are depending on the wind boundary conditions used for the calculation of the wave data. The forcing global circulation model, the downscaling methodology and the emission scenario are influencing the projections of wind conditions, hence also the projections of wave conditions. The uncertainty of the projection could become larger if multi-model-ensembles would be taken into consideration. But a possible trend of change could also become more stable if most of the ensemble members agree in the sign of the trend.

Moreover, comparisons between modelled and observed wind data for the past at the three locations are showing that the variability (in terms of the standard deviation) of the modelled wind data is less than the variability of the observed wind data.

The spatial changes of the wave climate will be analysed in a next step from results of non-stationary simulations using high-resolution numerical modelling with the wave model SWAN with boundary conditions from runs of the Cosmo-CLM model and runs of the wave model WAM for the entire Baltic Sea.

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

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