

# ASSESSMENT OF CHANGES OF EXTREME WAVE CONDITIONS AT THE GERMAN BALTIC SEA COAST ON THE BASIS OF FUTURE CLIMATE CHANGE SCENARIOS

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**Key words:** Baltic Sea, regional climate change, Cosmo-CLM, SWAN wave model, extreme wave conditions.

## ABSTRACT

Information on possible changes in extreme wave heights is needed to determine the future effectiveness and safety of coastal and flood protection structures. In this study, an assessment of possible changes in the extreme wave heights at selected locations along the German Baltic Sea coast has been carried out on the basis of numerical simulations of waves in the western Baltic Sea and regional climate model data for the past and the future (1961-2100). The future climate change signal of significant wave heights with a return period of 200 years mainly depends on: (i) the location, (ii) the climate change scenario run, (iii) the time period of the comparison, and (iv) the approach adopted to calculate the wave climate. The results show increases of up to +0.5 m and decreases of up to -0.5 m of the extreme wave heights. The increases might have considerable effect on the constructional design of coastal and flood protection structures—such as breakwaters, sea dykes, and vertical walls—because the extreme wave heights are used as input parameters for the design of the structures.

## I. INTRODUCTION

Besides a regional sea-level rise, one of the most important

effects of climate change on near-shore hydrodynamics are the changes in the local sea state caused by the changes in the local wind fields over the sea. Changes in the local sea state play an important role in the functional and constructional future safe designing of coastal and flood protection structures. Thus, the influence of climate change on water levels (the mean sea level and extreme water levels) as well as on the local wave climate (the average and extreme events) has to be analyzed. Moreover, knowledge of the changes in near-shore wave conditions is essential for developing appropriate adaptation measures for the constructions.

Future projections of the local wave climate can be derived from future projections of the wind conditions of a regional climate model. The projections in general depend on: (i) atmospheric forcing factors, such as the forcing global circulation model, (ii) emission scenarios, (iii) the downscaling approach (statistical or dynamical), (iv) the coupling or interaction of the global or regional circulation model with an ocean/sea-ice model, and (v) the used impact model (for example, a numerical wave model). All these factors result in a large uncertainty of the future projections of the wave climate.

The BACC report (BACC Author Team, 2009) compiles results from different studies on future projections of wind waves in the Baltic Sea, but the results are, in general, not comparable among the studies due to different models used in each of the studies, including different emission scenarios, climate and wave models, downscaling approaches, and analyzed wave parameters.

In this study, dynamic downscaled wind from the regional climate model Cosmo-CLM (Rockel et al., 2008; Lautenschlager et al., 2009) was used with two realizations each of the Special Report on Emission Scenarios (SRES) A1B and B1 from IPCC (Nakićenović et al., 2000). Cosmo-CLM was forced by the coupled atmosphere-ocean global circulation model ECHAM5/MPI-OM. On the basis of the wind data from Cosmo-CLM, the wave climate in the western Baltic Sea area was calculated for the past and the future by applying the

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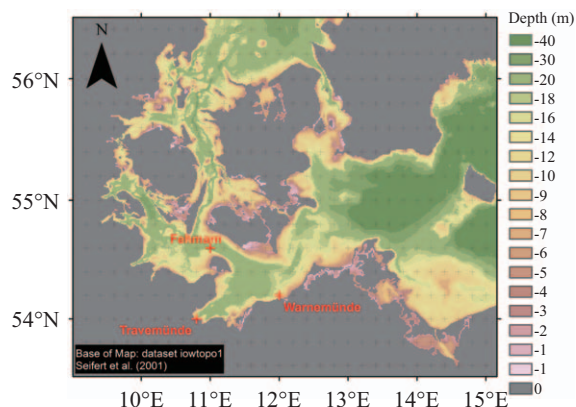


Fig. 1. Bathymetry of the western Baltic Sea and locations of Cosmo-CLM grid points of data stream 3 (indicated by grey crosses) and selected locations for extreme value analyses (marked with red bold crosses).

spectral wave model SWAN (Booij et al., 1999).

A recent study on changes in the wave climate in the entire Baltic Sea was carried out by Groll et al. (2013). In comparison with the model set-up presented in this paper, they used the same regional climate model (Cosmo-CLM) and emission scenarios (A1B, B1), but a different spectral wave model (WAM) (Hasselmann et al., 1988) for the calculation of the wave conditions.

The results of Groll et al. (2013) show, for example, increases in the average significant wave heights and the 99<sup>th</sup> percentile of significant wave heights of up to +0.5 m for the south-eastern part of the Baltic Sea due to changes in the wind conditions over the sea.

In contrast to the analyses of Groll et al. (2013), our study focuses on methods of extreme value analysis for the assessment of the changes in extreme wave conditions because these methods are widely used in coastal engineering practice.

## II. METHOD

### 1. Model Set-Up

A wave model (WBSSC, Fig. 1) for the area of the western Baltic Sea has been set up using the third-generation spectral wave model SWAN with a high temporal ( $\Delta t = 1$  hour), horizontal ( $\Delta x = \Delta y = \text{ca. } 2$  km), and directional ( $\Delta \theta = 2.5^\circ$ ) resolution with 42 spectral frequencies ( $f_{\text{low}} = 0.05$  Hz,  $f_{\text{high}} = 1$  Hz). The model grid contains  $369 \times 359$  grid cells, and the default physical processes, parameters, and coefficients of the third-generation model are used within the computations. Dissipation through bottom friction and non-linear wave interactions in shallow water (Triads) have been explicitly added to the default processes. A first-order backward space, backward time (BSBT) propagation scheme was employed in the geographical space and the maximum number of iterations was restricted to 20.

The local wave model was set up based on the following boundary conditions: (i) bathymetric data of the western Baltic

Table 1. Cosmo-CLM model runs and combined transient data sets (“x” denotes no experiment).

20 <sup>th</sup> century (1960-2000) observed anthropogenic forcing	21 <sup>st</sup> century (2001-2100) forced by emission scenario A1B	21 <sup>st</sup> century (2001-2100) forced by emission scenario B1	Transient data set (1960-2100) of near-surface wind parameter (10 m above surface)
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

Sea from Seifert et al. (2001) with a horizontal resolution of ca. 1 km, (ii) hourly wave spectra along the northern and eastern boundaries from the WAM model, and (iii) hourly wind data from Cosmo-CLM on a regular geographical grid with a horizontal resolution of ca. 18 km (Lautenschlager et al., 2009).

The Cosmo-CLM model was forced by six-hourly data from the global atmosphere/ocean-ice model ECHAM5/MPI-OM with observed anthropogenic emissions and the future IPCC emission scenarios, A1B (global economic) and B1 (global environmental) (Nakićenović et al., 2000), with two realizations each. The different realizations represent the climate variability. The realizations for the past and the future have been combined to four transient gridded data sets (cp. Table 1) of near-surface wind conditions (10 m above surface) covering the total period from 1960 to 2100.

The wind data of Cosmo-CLM was further interpolated using bi-linear interpolation to a horizontal resolution of ca. 1 km of SWAN. The temporal frequency (hourly instantaneous values) of Cosmo-CLM was adopted for the SWAN wave simulations.

The spectral wave data of WAM was transferred to SWAN at 51 locations along the northern and eastern boundaries with the help of the SWAN command “BOUNDNEST2 WAMNEST”. A free exchange format (machine-independent) was used because SWAN and WAM were run on different machines. As the spectral output of the WAM model is not standardized, it has to be converted to be properly read into SWAN. The interpolations between the different spectral directions and frequencies of both models were done by SWAN automatically.

Moreover, the local wave model was run under sea ice-free conditions and at a mean water level. Since the wave conditions were derived for locations in the Baltic Sea near the 10 m depth contour line ca. 1 km off the coast (at quasi deep water conditions), the future sea level rise was neglected for the wave simulations. For all computations of SWAN, a parallel implementation via shared memory systems (OMP) has been used on high-performance cluster systems.

### 2. Model Validation

Comparisons between calculated and observed wave parameters have been done in previous coastal engineering

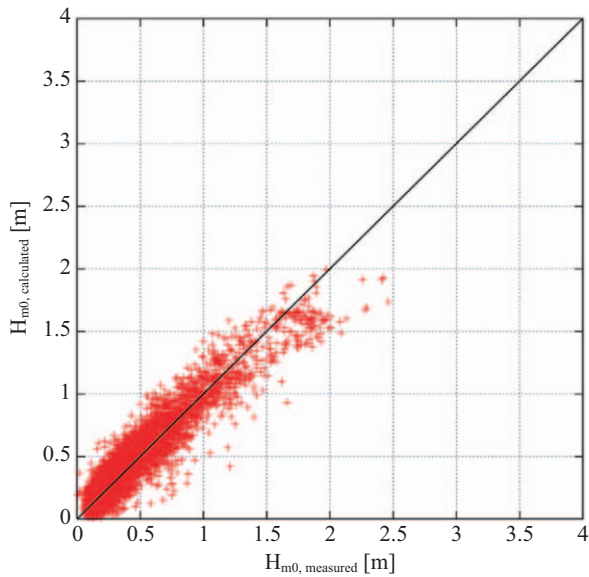


Fig. 2. Calculated (left axis) and observed (bottom axis) significant wave heights (m) near Warnemünde (Schlamkow and Fröhle, 2009).

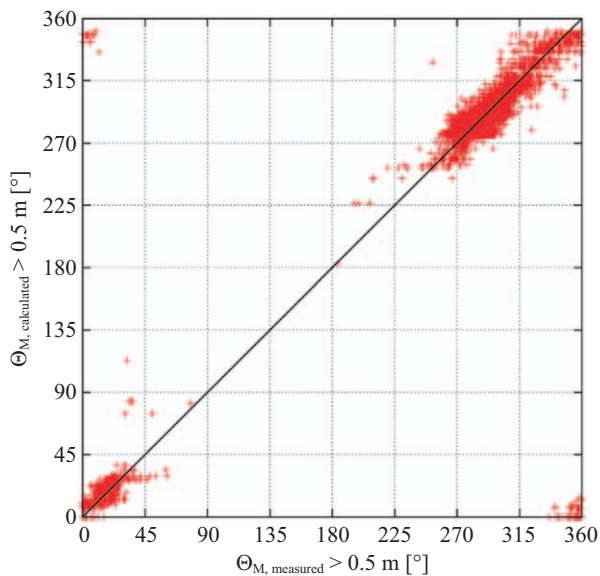


Fig. 3. Calculated (left axis) and observed (bottom axis) mean wave directions ( $^\circ$ ) near Warnemünde (Schlamkow and Fröhle, 2009), for significant wave heights larger than 0.5 m.

studies (Schlamkow and Fröhle, 2009). Examples for the comparisons of wave heights and directions near Warnemünde are given in Fig. 2 and Fig. 3.

Fig. 2 shows a slight underestimation of wave heights larger than 1.5 m due to differences in the wind data of the Local Model from the German Meteorological Service (Deutscher Wetterdienst) that was used in previous studies.

The mean wave directions of significant wave heights larger than 0.5 m show a good agreement between observed and calculated values (see Fig. 3).

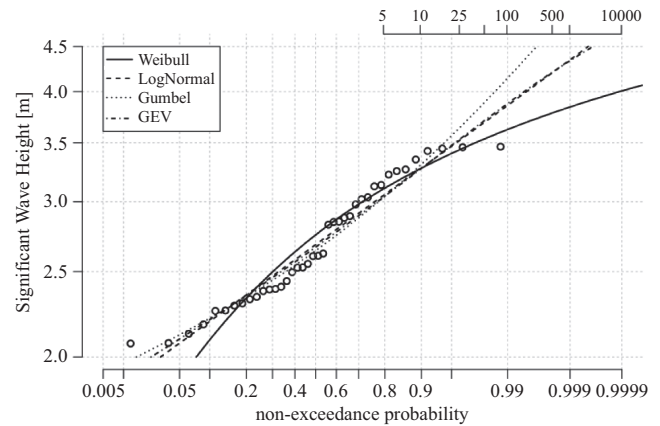


Fig. 4. Fitted extreme value distributions to samples of simulation run B1\_1 (1977–2016) at the location near Fehmarn, plotted on log-normal paper at plotting positions calculated by the formula of HAZEN.

Regarding the mean wave periods, a systematic underestimation between observed and calculated values was found and is well-known from previous SWAN studies (not shown here).

### 3. Extreme Value Analysis

For the statistical assessment of the changes in the extreme wave events induced by regional climate change, long-term (transient) time series of wave parameters are needed. The wave data was calculated on the basis of the available wind data (see Table 1 on the previous page) of the past 1960–2000 (simulation runs C20\_1 and C20\_2) and for the future 2002–2100 (simulation runs A1B\_1, A1B\_2, B1\_1, and B1\_2). Finally, a long-term time series of each single simulation run was compiled and combined into four transient time series of significant wave heights from 1960 to 2100 near the locations of Warnemünde, Travemünde, and Fehmarn (see Fig. 1).

After the compilation of the four transient long-term time series of wave parameters, the time series were analyzed with the help of methods of extreme value statistics.

First, samples of the time series of significant wave heights were selected using the annual maxima method (Coles, 2001) over a time period of 40 years.

Second, different extreme value distribution functions (log-normal, Gumbel, Weibull, and GEV) were fitted into the samples. The fitting parameters of the functions were estimated with the help of the maximum-likelihood method which is exemplarily shown in Fig. 4.

Third, the Lilliefors test (also known as the modified Kolmogorov–Smirnov test) (Wilks, 2011) was used for assessing the goodness of fit between the empirical distribution function (EDF) and different theoretical extreme value distributions (EVDs). For this purpose, difference values—like the largest difference (1) or the root mean square difference (2)—were calculated between the EDF and the fitted EVDs (for example, log-normal, Gumbel, and Weibull distribution).

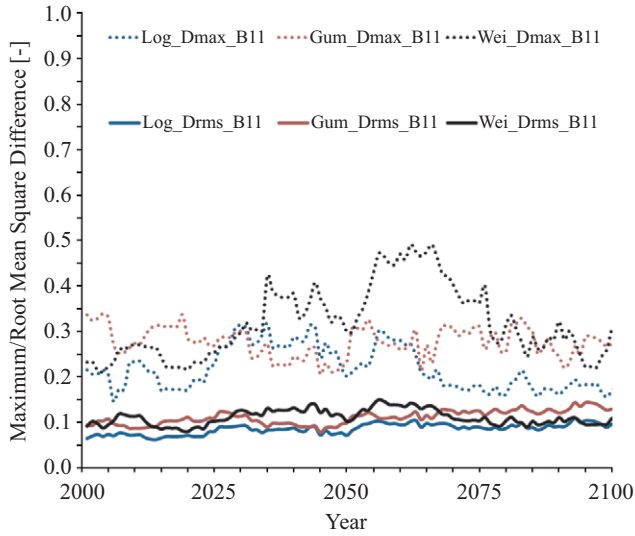


Fig. 5. Maximum differences (dotted lines) and root mean square differences (solid lines) between empirical distribution of significant wave heights and theoretical extreme value distribution functions: log-normal (blue), Gumbel (red), and Weibull (black) of simulation run B1\_1 at the location near Fehmarn.

$$D_{max} = \max_x |F_n(x) - F(x)| \quad (1)$$

$$D_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^n (F_n(x) - F(x))^2} \quad (2)$$

$F_n(x)$ : empirical distribution function (EDF)

$F(x)$ : theoretical, extreme value distribution function (EVD)

$$F_n(x_{(i)}) = i / n \quad (3)$$

$$i = 1, 2, \dots, n$$

$n$ : total number of elements

$i$ : index of list of sorted elements from lowest value to highest value

The EVD with the smallest root mean square difference was assessed to be the best estimator for the sample. Fig. 5 shows exemplarily the calculated differences for each EVD of the simulation run B1\_1 from 2002-2100 at the location near Fehmarn.

In the overall assessment, the log-normal extreme value distribution (see the blue lines in Fig. 5) has the smallest differences, in most of the comparisons from 2001-2100 and for all simulation runs. Thus, it is concluded that the log-normal distribution is best fitted to the EDF.

On the basis of the log-normal function, the significant wave heights (consecutively called the extreme wave heights) were calculated for time periods of 40 years and a return level of 200 years. To analyze the climate change signal, the ex-

treme wave heights of the future (2001-2100) were compared to the extreme wave heights of the control period 1961-2000. The relative changes in the future extreme wave heights were calculated using the moving averages method (4).

$$H_{s(change)} = \frac{H_{s(l-m)} - H_{s(1961-2000)}}{H_{s(1961-2000)}} * 100\% \quad (4)$$

$$l = 2001, 2002, \dots, 2061$$

$$m = 2040, 2041, \dots, 2100$$

Example results for the changes in the extreme wave heights at the selected locations are shown in the next section of this paper.

### III. RESULTS AND DISCUSSION

#### 1. Changes in Future Wind Conditions

The wind data of the Cosmo-CLM data stream 3 were analyzed for different time periods, each with 30 years of wind data. The data was extracted for the scenarios 2050 (2021-2050), 2100 (2071-2100) and the control period 1971-2000 at the selected locations of Warnemünde, Travemünde, and Fehmarn (see Fig. 1).

For the assessment of changes in the wind conditions, differences in the frequencies of occurrence for the wind velocities and directions were calculated between each combination of the Cosmo-CLM runs for the 21<sup>st</sup> century (A1B\_1, A1B\_2, B1\_1, and B1\_2) and the 20<sup>th</sup> century (C20\_1 and C20\_2). From the ensemble of the differences, the bandwidth of changes between the minimum and maximum differences of the frequency of occurrence was identified for the scenarios 2050 and 2100. Fig. 6 shows the bandwidth of the calculated changes in the frequency of occurrence for the wind velocities and directions for the two scenarios 2050 (the dashed line) and 2100 (the solid line) compared to the control period (1971-2000) near the location of Fehmarn.

Regarding the change in the wind velocities (cp. Fig. 6 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 scenario 2100 than for scenario 2050. As a consequence, the average wind velocity increases by up to +4 percent towards the end of the 21<sup>st</sup> century (cp. Fig. 7 top).

Moreover, the frequency of easterly wind directions decreases while the frequency of westerly wind directions increases by up to +2 percent toward the end of the 21<sup>st</sup> century (cp. Fig. 6 bottom). As a result of the changes in the frequencies, the average wind direction changes to more west at this location for the first realizations of the emission scenarios A1B and B1 (cp. Fig. 7).

The changes in the frequencies of the wind velocities and wind directions near Travemünde and Warnemünde show the



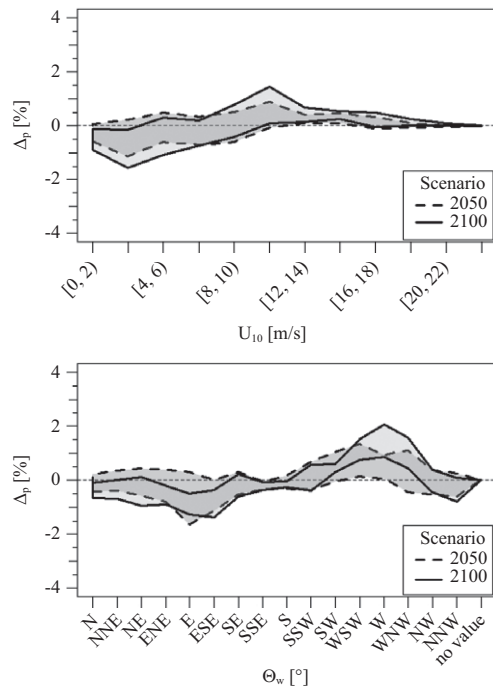


Fig. 6. Relative changes in frequency of occurrence  $\Delta_p$  [%] of wind velocities  $U_{10}$  (top) and wind directions  $\Theta_w$  (bottom) for climate change scenarios A1B and B1, and for scenarios 2050 (2021-2050; as indicated by dashed lines) and 2100 (2071-2100; as indicated by solid lines) compared to control period 1971-2000, near Fehmarn.

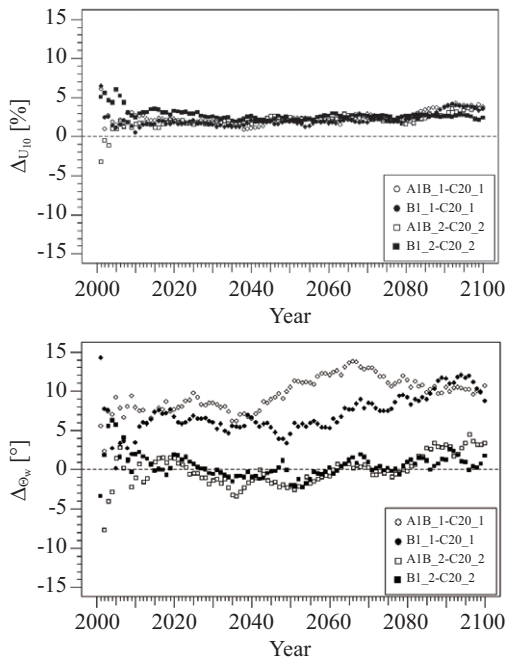


Fig. 7. Relative changes in average wind velocities  $\Delta U_{10}$  [%] (top) and absolute changes in mean wind directions  $\Delta \Theta_w$  (°) (bottom) of climate change scenarios A1B and B1 compared to the control period 1971-2000, near Fehmarn. Note: positive values of changes in mean wind directions indicate shift of the direction towards west.

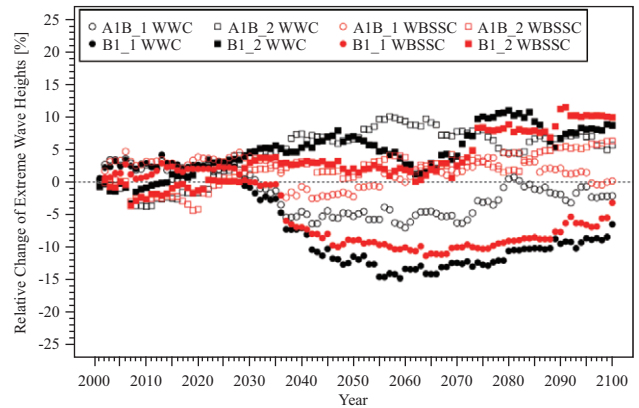


Fig. 8. Relative changes in extreme wave heights over time periods of 40 years of emission scenarios A1B and B1 compared to the control period (1961-2000), near Fehmarn. Results from the numerical approach are plotted in red (WBSSC) and results from a combined statistical-numerical approach are plotted in black (WWC).

same tendency, in general, except for a few velocities and directions (not shown here).

Moreover, Groll et al. (2013) found that other parameters of the wind velocity distribution, such as the 99<sup>th</sup> percentile of the wind velocity  $U_{10}$ , can increase by up to +0.7 m/s (ca. +5 percent) in the south-eastern Baltic Sea toward the end of the 21<sup>st</sup> century (2071-2100) for the simulation run A1B\_1, when compared to the values of the control period 1961-1990.

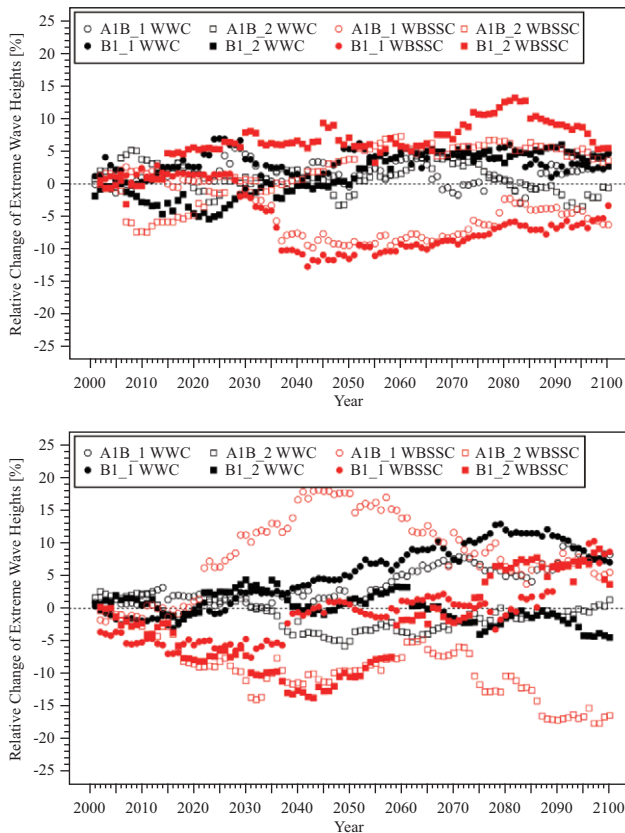
## 2. Changes in Future Extreme Wave Heights

Fig. 8 shows the relative changes in the calculated extreme wave heights (the significant wave heights with a return period of 200 years on the basis of the log-normal distribution) near Fehmarn for two different approaches for the calculation of the future wave conditions.

The results of the analysis of the long-term time series of the WBSSC wave model are plotted with points in red and are indicated by the acronym “WBSSC”. For the assessment of the uncertainty of the results, they were plotted against the results from previous studies (Dreier et al., 2013) as plotted with points in black and indicated by the acronym “WWC”. The WBSSC approach consists of non-stationary wave simulations, while the WWC approach is based on statistical correlations between observed wind and wave parameters, and stationary wave simulations.

Near Fehmarn, a consistent increasing trend of the changes in the extreme wave heights up to +11 percent (ca. +0.5 m) was found for the simulation runs A1B\_2 and B1\_2. In contrast, no significant change (WBSSC) and a decreasing trend (WWC) was noted for the simulation run A1B\_1. A decreasing trend up to −11 percent (ca. 0.5 m) was found for the simulation run B1\_1 too. Moreover, the amplitude of the changes in the extreme wave heights of the emission scenario A1B is lower for the WBSSC approach than for the WWC approach.

The changes in the extreme wave heights near Warnemünde



**Fig. 9. Relative changes in extreme wave heights over time periods of 40 years of emission scenarios A1B and B1 compared to the control period (1961-2000), near Warnemünde (top) and near Travemünde (bottom). Results from the numerical approach are plotted in red (WBSSC) and results from a combined statistical-numerical approach are plotted in black (WWC).**

are shown in Fig. 9 (top) on the next page. In contrast to the changes in the extreme wave heights near Fehmarn, the bandwidth of the results near Warnemünde is larger for the WBSSC approach than for the WWC approach (cp. Fig. 8 and Fig. 9 top).

Moreover, the same tendencies of the changes at both locations for all simulation runs of the WBSSC approach, except A1B\_1, were found. Both locations are exposed to strong winds from westerly directions. In addition, the location near Warnemünde is also exposed to strong winds from north-easterly directions.

The bandwidth of changes in the extreme wave heights near Warnemünde ranges between +13 percent (ca. +0.4 m) and -13 percent (ca. -0.5 m), and the uncertainty of the results is larger for the WBSSC approach than for the WWC approach.

Fig. 9 (bottom) shows the changes in the extreme wave heights near the location of Travemünde.

The amplitude of the changes is strongly dependent on the approach for the derivation of the long-term time series of wave parameters. As for the location of Warnemünde, the bandwidth of results for the WBSSC approach is much larger than for the WWC approach. The extreme wave heights near

Travemünde change between +18 percent (ca. +0.3 m) and -18 percent (ca. -0.3 m).

Moreover, the tendencies of the changes are different for each of the simulation runs at the selected locations. For example, the strongest increase near Travemünde is noticed for the simulation run A1B\_1 (cp. Fig. 9 bottom), while at the other locations, the strongest increase occurs for the simulation run B1\_2 (cp. Fig. 8 and Fig. 9 top). A possible reason for the opposite climate change signal is the fact that the selected location near Travemünde is sheltered against strong winds from westerly directions and mostly exposed to strong winds from north-easterly directions.

The calculated changes in the extreme wave heights from this study cannot directly be compared to the changes in the 99<sup>th</sup> percentile of significant wave heights in the Baltic Sea from Groll et al. (2013) due to certain reasons. First, the 99<sup>th</sup> percentile of the significant wave heights corresponds to a return period of 100 years and leads to lower significant wave heights than in the estimation of the extreme wave heights for a return period of 200 years. As a result, the amplitude of the climate change signal may become lower. Second, the climate change signal depends on the time period used for comparisons. Groll et al. (2013) compared the results for time periods of 30 years on the basis of the control period 1961-1990, while in this study, a sample period of 40 years has been used in combination with the control period 1961-2000. Finally, there are differences in the applied wave models, mainly regarding the horizontal resolution and the consideration of shallow water effects, which can lead to an over- or underestimation of wave parameters in the near-shore zone.

#### IV. CONCLUSION

In this study, we performed non-stationary numerical simulations using the wave model SWAN on the basis of long-term (1960-2100) data sets of near-surface wind velocities and directions of the regional circulation model Cosmo-CLM for two SRES emission scenarios, A1B and B1. The long-term time series of wave parameters were analyzed statistically for average wave conditions (for more information about the changes in the average wave conditions, the reader is referred to Dreier et al., 2013) and the extreme wave events near the locations of Warnemünde, Travemünde and Fehmarn along the German Baltic Sea coast.

At the selected locations, the future average wind velocities can increase by up to +4 percent towards the end of the 21<sup>st</sup> century. Regarding the changes in the frequency of wind directions, more wind events from westerly and fewer events from easterly directions were found. This can change the average wind directions by up to 14° to the west.

Due to the projected changes in the wind conditions, the average and extreme wave conditions can change. The changes in the extreme wave heights are different along the German Baltic Sea coast and depend on, for example, the alignment of the coastline towards westerly winds, the emission scenario

run, and the time period of the comparison as shown in past studies (Dreier et al., 2013).

Increases and decreases in the extreme wave heights by up to +0.5 m/−0.5 m are possible and no robust trend was found for the changes using different emissions scenarios. In areas which are sheltered against westerly winds, such as the Bay of Lübeck, the climate change signal is much more unclear as shown at the location near Travemünde.

Moreover, it was found that the bandwidth of the changes in the extreme wave heights also depends on the approach used for the calculation of the wave climate. The bandwidth and uncertainty of the results may increase when a single numerical approach is applied instead of a combined statistical-numerical (so-called “hybrid”) approach. The hybrid approach is favorable for analyzing the changes in the extreme wave events in semi-enclosed coastal seas where the wave climate is mainly generated by the local wind field and other effects—such as large swell waves, tides, and currents—are non-existent and measurements of wind and waves are available.

## ACKNOWLEDGMENTS

The results described in this publication have been achieved within the research project RADOST (Regional Adaptation Strategies for the German Baltic Sea Coast, grant n° 01LR0807F) as part of the research priority KLIMZUG (Managing Climate Change in Regions for the Future) funded by the German Ministry of Education and Research (BMBF).

The research work presented here has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under Grant agreement n° 603663 for the research project PEARL (Preparing for Extreme And Rare events in coastal regions). The research and its conclusions reflect only the views of the authors and the European Union is not liable for any use that may be made of the information contained herein.

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