Effects of Climate Change on average and extreme Wave Conditions at selected Locations in the German Baltic Sea

N. Dreier[1], C. Schlamkow[2], P. Fröhle[1], D. Salecker[1]

[1] Hamburg University of Technology, Institute of River and Coastal Engineering, Germany
norman.dreier@tu-harburg.de, froehle@tuhh.de, doerte.salecker@tu-harburg.de
[2] University of Rostock, Geotechnics and Coastal Engineering, Germany
christian.schlamkow@uni-rostock.de

Abstract: On the basis of long-term time-series (1960-2100) of wind data from different model runs of the regional climate model CCLM, future wave conditions (2001-2100) were calculated and assessed at selected locations in the south-western Baltic Sea. For the future projection of the wind, the IPCC SRES emission scenarios A1B and B1 were assumed. For the statistical assessment of the changes of the wave conditions, average and extreme values for future (e.g. 2071-2100) and for actual conditions (e.g. 1971-2000) were compared. Analyses of the wind conditions from the CCLM model show that the average near surface wind velocity in the study area is going to increase up to 4% and that in general more westerly winds will occur in the future. In consequence, the average significant wave height may increase up to 8% and westerly wave directions become more dominant. Regarding the change of extreme wave heights, different signals of change and a large spread of the results (+14% to -14%) were found at the locations investigated.

Keywords: Baltic Sea, Climate Change, Cosmo-CLM, Wave Conditions, SWAN

I. Introduction

Climate change may become a severe threat for people and economies along the coast and estuaries in the future. Projections of climate related processes such as global sea-level rise are still much unknown and in controvert discussion. Recent studies (e.g. Schaeffer, M. et al., 2012 [2]) assume larger increases of the global sea-level (+1.5 to +4m to the end of the 23rd century) than compiled by the 4th Assessment Report from IPCC (2007) [5]. Especially the contribution of the melting of the great ice-shields Antarctica and Greenland is not yet included in recent numerical climate models. Another important factor which often is neglected is the isostatic uplift of land masses, so that the uncertainty of future projections of global sea-level rise remains high (Heinrich, H. et al., 2011 [3]).

Despite the uncertainty in projections of some climate related processes one can study other important aspects of regional climate change, like the impact of changing wind conditions on the local wave climate, as presented in this study, for the development of sustainable adaptation measures in the field of coastal protection.

Within the national interdisciplinary climate adaptation project RAdOst (Regional Adaptation Strategies for the German Baltic Sea Coast) future-proof adaptation strategies for the Baltic Sea coastline of Germany will be developed through a dialogue between academics, economists, policy-makers and the public. In the field of coastal protection, the most important task is the development of future protection strategies for the German Baltic Sea Coast. Therefore existing coastal protection strategies and methods have to be assessed.

As a basis for these investigations, future changes of the local wave climate and the morphology of coastal areas (latter not shown in this paper) were examined.

To analyse the local wave climate, wave information within the investigation area are needed. There are several methods available to obtain this information like e.g. wave measurements, simple parametric approaches, statistical methods and numerical wave simulations. For the investigations presented in this paper a hybrid approach has been established based on statistical and numerical methods to calculate wave information. The approach uses wind data from numerical climate simulations as input data.

In this study the changes in mean wind conditions were applied from the regional climate model (RCM) CCLM (COSMO-Climate Local Model). 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 local sea level rise could be neglected. Furthermore two future emission scenarios A1B and B1 from the Special Report on Emissions Scenarios (SRES, 2000) [4] were taken into account.

II. Method

Evaluation Periods

From a statistical point of view, climate change can be defined as the change of “the statistical description in terms of the mean and variability of relevant quantities” of the climate state over a specific period of time; as mentioned in Appendix I, 4th Assessment Report from IPCC (2007) [5]. For the assessment of climate change and climate change inducted processes, the World Meteorological Organization (WMO) recommends a time period of 30 years.

For the assessment of future changes in wind respectively wave climate different time periods were used. To illustrate changes of average conditions, like average wind and wave conditions, differences of occurrence of wind respectively wave parameters for two projection periods of 30 years, the so called scenario 2050 (2021-2050) and scenario 2100 (2071-2100) were compared to the control period 1971-2000.

To analyse the changes of extreme wave heights the time periods for the comparisons were extended. For the analysis of extreme events extreme wave heights were calculated over a time period of 40 years and for each year within the time period 2001-2100 and compared to values for the period 1961-2000. The reason for the extension of the time periods from 30 to 40 years is to increase the sample size for the extreme value analysis (for details see chapter IV).

Hybrid Approach

Wave measurements are often expensive and time consuming, thus usually available for short-term periods. The statistical assessment of average wave conditions, extreme events and morphological changes is only useful on the basis of gapless long-term time series of wave parameters (e.g. by time periods of 30 years). Long-term time series of wave parameters can be obtained by using different wave prediction techniques (e.g. calculation with the help of a numerical model, statistical or empirical approach).

For the derivation of long-term time series of wave data a hybrid approach was developed that calculates the wave data with the help of wind-wave-correlations and numerical simulations based on wind data from different runs of the RCM CCLM (for details on the CCLM model runs see chapter III).

On the basis of available synchronized local field data for wind and waves (e.g. data from wind gauge measurements and directional wave buoys) wind-wave-correlations were derived for different locations at the German Baltic Sea Coast. Fig. 1 shows the selected locations which were used in the present study: Warnemünde (right), Travemünde (Bay of Lübeck, bottom) and Westermarkelsdorf (Island of Fehmarn/Bay of Kiel, top).

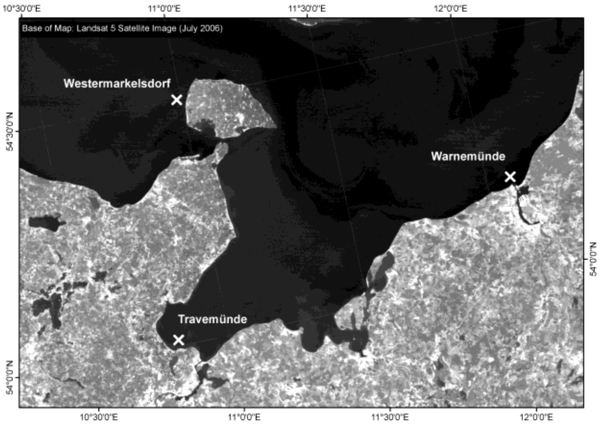

Fig. 1 Locations of the Study Area [U. Floth]

With the help of statistical correlation methods the nonlinear relation between the wind field and the resulting wave conditions can be obtained for a certain area of interest, where field data are available. In this study the wave parameters significant wave heights H_{m0}, mean wave directions Θ_m and mean wave periods T_{m02} were calculated from mean wind velocities U_{10} and mean wind directions Θ_w.

The statistical correlations between the wind velocities and the resulting wave heights in each directional class are connected to a certain error margin. Based on a sensitivity analysis of different cut off wind speeds (Fröhle, P. and Fittschen, T. 1999) [6], a cut off criteria for maximum wind velocities has been applied for a 5% error margin (1).

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

If the wind data used for the calculation of the past and future wave conditions are exceeding the maximum wind velocities used for the derivation of the correlations, the calculated wave heights are becoming unreliable and cannot be used for the statistical assessment of extreme wave heights. This can exemplarily be seen in Fig. 2 on the next page, which shows significant wave heights calculated from wind-wave-correlations only, without applying the cut off criteria.

For the area of the south-western Baltic Sea, calculated waves with significant wave heights larger then 5m are regarded as implausible and have to be calculated with other wave prediction techniques instead using wind-wave correlations only.

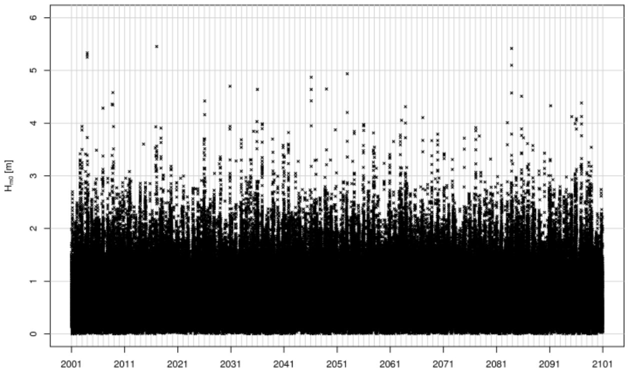

Fig. 2 Timeserie of significant waveheights for scenario A1B-1 without cut off criteria

In this case the wave parameters were calculated with the help of stationary numerical simulations using SWAN (Booij et al., 1999) [7] instead of calculating them from wind-wave-correlations. The numerical simulations were performed at a mean sea level and the resolution of ΔU_{10}=1m/s for the wind velocities and $\Delta\Theta_w$=10° for the wind directions as boundary conditions.

III. Change of Future Wind Conditions

The future changes in wind are still uncertain. Analyses of the BACC-Group (BACC, 2008) [8] show that regional dynamical downscaled wind (using the RCMs RCAO and HIRHAM; see list of used climate model abbreviations at the end of this paper) from global climate simulations (ECHAM4/OPYC3, HadAM3H) provides no robust signal on the change of windiness for the Baltic Sea Basin, regarding the SRES scenarios A2 and B2. Räisänen et al. 2003 [9] and Pryor and Barthelmie, 2004 [10] found that future wind conditions in RCM runs depend highly on the forcing global climate model. Only RCM simulations driven with the global Atmosphere-Ocean General Circulation Model (AOGCM) ECHAM4/OPYC3 show statistical significant changes of mean daily wind speed for winter at the 95% level. Mean daily wind speed from RCAO runs forced with ECHAM4/OPYC3 increases up to 8% for the SRES scenario A2 on an annual basis over Scandinavia. This increase can become more than twice during winter (DJF) over the Baltic Sea (Räisänen et al., 2003) [9].

The North German Climate Bureau (Meinke et al., 2010) [11] compiles further results on possible future changes of wind conditions for the area of the German Baltic Sea Coast. The 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 GCMs (e.g. ECHAM5/MPI-OM, ECHAM4/OPYC3 and HadAM3H) and RCMs (CCLM, REMO, RCAO) and SRES scenarios (A1B, B1, B2 and A2). The results show an increase of the mean wind velocity, as area mean value for the German Baltic Sea coast, up to 4% to the end of the 21st century compared to actual conditions. Further increases of the storm intensity (maximum wind speed) up to 4% and the number of days with storm conditions (Bft. >8) up to 4.6 days were found while the number of days with no wind decreases down to 1.3 days.

In this study dynamical downscaled wind from the RCM CCLM (Rockel et al., 2008) [12] has been used. The RCM runs were forced by the AOGCM ECHAM5/MPI-OM. There were carried out different CCLM model runs (Lautenschlager et al., 2009) [1], covering the 20th century (1960-2000) and the 21st century (2001-2100) as compiled in Tab. 1.

As shown in Tab. 1, there are 3 independent realisations available for the climate of the 20th century, each forced with observed anthropogenic forcing and started 25 years apart from each other (C20_1 to C20_3). For modelling the future climate only the first two of the runs for the 20th century were continued and forced by the SRES scenarios A1B (global economic) and B1 (global environmental), resulting in 4 independent realisations. In our study the realisations for the past and the future were combined to 4 transient (continuing) time series covering the period 1960-2100.

Tab. 1 CCLM model runs (note: ‘x’ denotes no experiment)

20th Cent. observed anthropo-genic forcing	21st Cent. forced by emission scenario A1B	21st Cent. forced by emission scenario B1	transient time series of wind parameter
C20_1	A1B_1	x	C20_1+A1B_1
	x	B1_1	C20_1+B1_1
C20_2	A1B_2	x	C20_2+A1B_2
	x	B1_2	C20_2+B1_2
C20_3	x	x	x

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 CCLM model were extracted at grid points close to the locations of the example area (cp. Fig. 1). The data were extracted for the scenario 2050 (2021-2050) and 2100 (2071-2100) and the control period 1971-2000. 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 and the 3 realisations for the 20th century named in Tab. 1. From the ensemble of 12 differences the minimum and maximum values of the differences in each velocity resp. directional class were plotted and the area in between these values was surrounded with a different line type and a specific colour. Examples for the change of the average wind conditions at the location Warnemünde are shown in Fig. 3 on the next page.

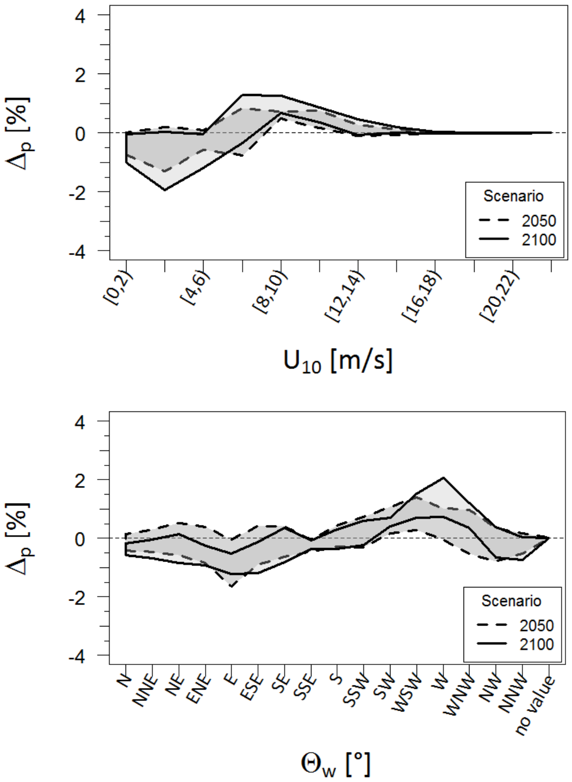

Fig. 3 Spread of change of frequency distribution of wind velocities (top) and wind directions (bottom) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period 1971-2000, near Warnemünde

Fig. 3 shows how the frequency of occurrence for the wind velocities and directions changes for the two projection periods 2050 and 2100 compared to the control period. Regarding the change of the wind velocities (cp. Fig. 3 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 mean wind velocity increases at this location up to 4% to the end of the 21st century.

Regarding the change of the frequency of the wind directions (cp. Fig. 3 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. As a result the mean wind direction is changing to more westerly directions.

The changes of the frequency for the wind velocities and directions near the locations of Travemünde and Westermarkelsdorf show in general the same tendency, both in spread of the results and amplitude, with only some small variations in single velocity resp. direction classes. The changes of the wind conditions have also consequences on the local wave climate, as shown in the next section of this paper.

IV. Change of Future Wave Conditions

Average Wave Conditions

Due to the absence of strong tides and the limitation of fetch lengths, the local sea state is generated by the local wind-field over the Baltic Sea. Changes in wind conditions over the Baltic Sea can have different impacts on e.g. wind-inducted sea level heights, storm surge heights and mean wave conditions (see BACC, 2008 [8]). Regarding the change of mean wave conditions, Miętus (1999) [13] applied a statistical downscaling method to the global climate model ECHAM3 and found no significant changes in mean wave heights, but increases in the wave height range, wind speed variability and the occurrence of strong and very strong winds. Meier et al. (2006) [14] utilised a wave model on the basis of different scenarios derived from runs of the AOGCM ECHAM4/OPYC3. The results show increases of the annual mean significant wave heights by 0.4m and of the 90th percentile by 0.5m with the largest increase in the Gulf of Bothnia and the Eastern Gotland Sea.

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 chapter III). Example results for the change of the frequency for the wave heights and wave directions at the locations Warnemünde and Travemünde are given in Fig. 4 and Fig. 5 respectively on the next page.

Regarding the wave heights it is concluded that for locations exposed to westerly winds (e.g. locations Warnemünde cp. Fig. 4 and Westermarkelsdorf – not shown here), the frequency of occurrence of waves with medium and higher wave heights increases and the frequency of waves with lower wave heights decreases (cp. Fig. 4 top). This will amount to increases of the mean significant wave height up to 6% in the case of Warnemünde and up to 8% in the case of Westermarkelsdorf, to the end of the 21st century compared to the control period 1971-2000.

For locations exposed to easterly directions (e.g. location Travemünde cp. Fig. 5) a contrary change has been observed; the frequency of occurrence of waves with medium and higher wave heights decreases, meanwhile the frequency of waves with lower wave heights increases (cp. Fig. 5 top).

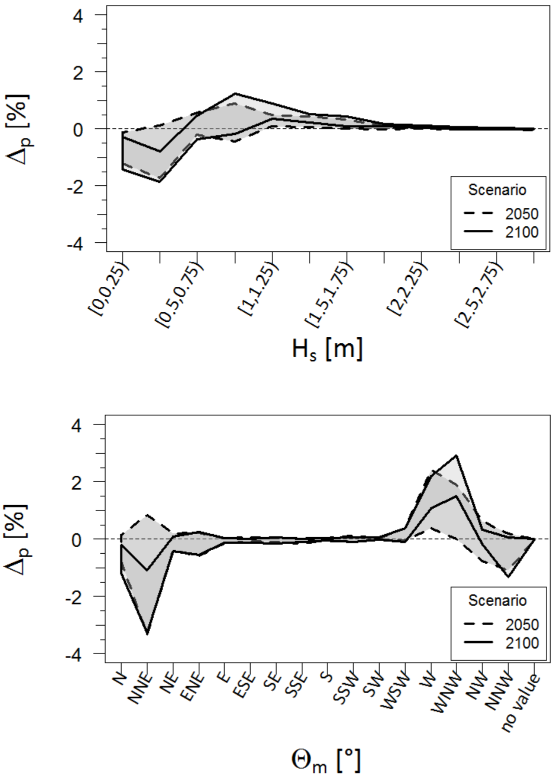

Fig. 4 Spread of change of frequency distribution of wave heights (top) and wave directions (bottom) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Warnemünde

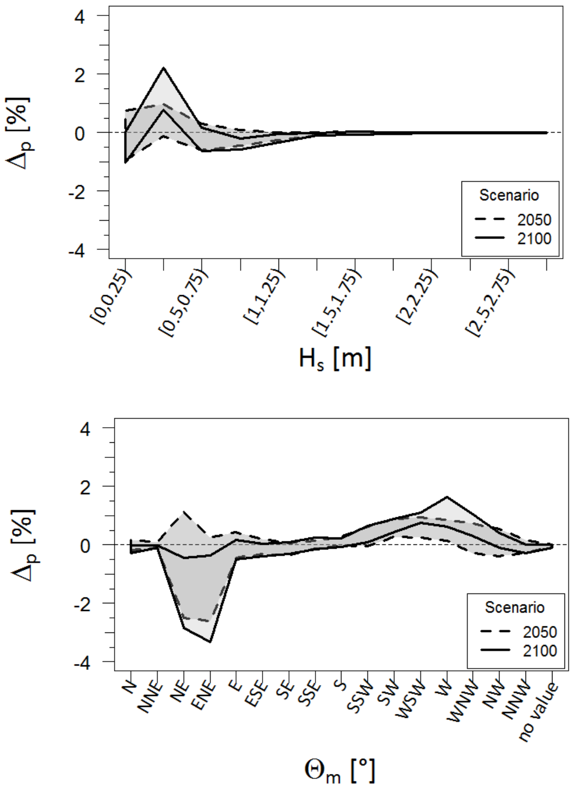

Fig. 5 Spread of change of frequency distribution of wave heights (top) and wave directions (bottom) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Travemünde

In consequence, the mean significant wave height at the location Travemünde decreases up to 3% in the middle of the second half of the 21st century (2041-2070).

The change of the frequency of the wave directions is nearly the same at all three locations except some small variations in amplitude for single direction classes. The change of the frequency of the wave directions is exemplarily shown for the locations Warnemünde in Fig. 4 bottom and Travemünde in Fig. 5 bottom.

In general, westerly wave directions become more dominant, while north-easterly directions decrease, especially to the end of the 21st century. This will result in shifts of the mean wave direction to more westerly directions up to 6° in the case of Westermarkelsdorf and up to 8° in the case of Warnemünde. For easterly wind exposed locations like e.g. Travemünde, a shift of the mean wave direction towards more easterly directions up to 6° to the year 2050 (2021-2050) is possible for single scenario runs but also a shift towards more northerly directions up to 3° or no change is possible depending on the different scenario runs.

Finally tests on the statistical significance of the results for the changes of the average wave conditions were performed. The main changes of the frequency of occurrence for the wave heights ($H_s \leq 2$m) and wave directions (N to E and SW to NW) were assessed to be statistical significant at the 95% level esp. to the end of the 21st century.

Extreme wave heights

For the statistical assessment of the change of extreme wave heights, 4 transient long-term time series of wave parameters were analysed, which were calculated on the basis of the 4 transient time series of wind data (cp. Tab. 1) covering a total time period from 1960-2100. In the next step samples of wave heights were selected by using annual maximum significant wave heights for time periods of 40 years based on each transient time series of wave data.

After the selection of the samples different extreme value distribution functions were fitted to the data. The log-normal function showed the best fitting properties and was chosen for further calculations.

Finally the extreme wave heights over time periods of 40 years were calculated for each year within the time period 2001-2100 on the basis of the log-normal function and for a return level of 200years.

The derived extreme wave heights were compared to values for the period 1961-2000. Example results for the change of the extreme wave heights are shown in Fig. 6.

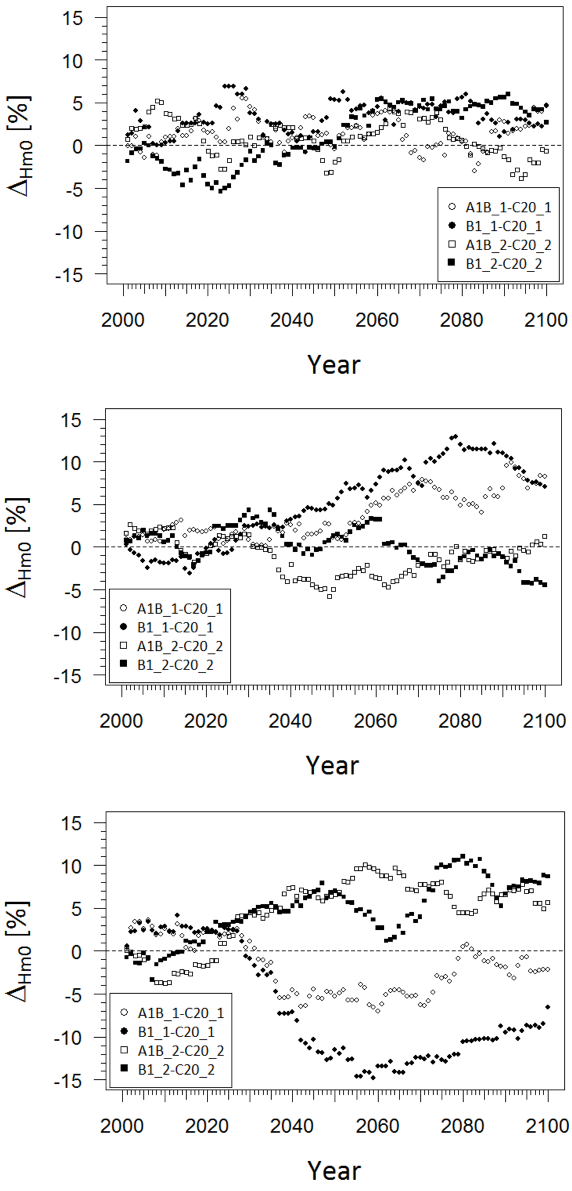

Fig. 6 Change of extreme wave heights over time periods of 40 years for different transient runs of the climate change scenarios A1B and B1 compared to the control period (1961-2000), near Warnemünde (top), Travemünde (middle) and Westermarkelsdorf (bottom)

At the location Warnemünde (Fig. 6 top), in general the calculated extreme wave heights increase up to 5%, except for one transient scenario run (C20_2+A1B_2) which indicates a slight decreasing trend. For the other locations (cp. Fig. 6 middle and bottom) the range of the change of extreme wave heights is larger.

Near Travemünde (cp. Fig. 6 middle) the change of the extreme wave heights for each two of four transient time series is increasing up to 14% and decreasing down to 5%. The same tendency can be found for the change of the extreme wave heights near the location of Westermarkelsdorf (Fig. 6 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 extreme wave heights. The results spread widely depending on the different scenario runs and the projection period.

This is in agreement with analyses from HZG (2012) [15] on the change of wave conditions derived from non-stationary numerical simulations for the Baltic Sea using the wave model WAM (Hasselmann, S. et al., 1988) [16] on the basis of the CCLM model runs named in Tab. 1. The results show both increasing values for the 99th percentile of the wave heights up to 0.4m 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.).

V. Conclusions

Analyses of future changes of average wave conditions and extreme events using regional climate change scenarios can provide a basis for the development of future coastal protection strategies and methods. In this study a hybrid approach for the determination of wave parameters was introduced, that consists of wind-wave-correlations and stationary numerical simulations. With the help of this approach long-term time series (1960-2100) of wave parameters were derived on the basis of wind data from the RCM CCLM using two different SRES scenarios A1B and B1. The compiled time series of wave parameters were analysed by comparing future average wave conditions and extreme events to actual conditions.

Regarding the change of average wave conditions, an increase of the mean significant wave height (30 years average) up to 4-8% was found for locations exposed to westerly winds. In contrast, a decrease of the mean significant wave height down to 3% is possible for locations exposed to easterly winds. The calculated main changes for the average wave conditions were assessed to be statistical significant at the 95% level esp. to the end of the 21st century.

At all 3 locations used in this study it became clear that westerly wave directions will become more dominant for the future and can have considerable effects on other related processes like e.g. the long-shore sediment transport esp. at locations exposed to westerly winds (not shown in this paper).

No clear tendency was found for the change of extreme wave heights. The results show increasing as well decreasing wave heights up to +/-14% for selected future scenarios and periods.

In the future work, results from numerical simulations using the spectral wave models WAM and SWAN on the basis of the CCLM wind data will be analysed on e.g. the spatial distribution of the changes for different wave parameters.

Used Climate Model Abbreviations

CCLM	COSMO-Climate Local Model
ECHAM5/ MPI-OM	coupled general circulation sea-ice/ocean model developed at the Max Planck Institute for Meteorology, Hamburg (MPIM)
HadAM3H	Hadley Centre Atmosphere Global Climate Model
HIRHAM	subset of the HIRLAM and ECHAM model
HIRLAM	High Resolution Limited Area Model
OPYC3	Ocean General Circulation Model developed in cooperation of MPIM/DKRZ (German Climate Computing Centre)
RCAO	Rossby Centre Coupled Atmosphere-Baltic Sea Regional Climate Model

Used Climate Data

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Acknowledgements

The results described in the paper were conducted within the research project RADOST (Regional Adaptation Strategies for the German Baltic Sea Coast, grant nr. 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).

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