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Future wave conditions at the German Baltic Sea Coast on the basis of wind-wave-correlations and regional climate change scenarios

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Abstract: Regarding coastal and flood protection, it is necessary to assess and adapt existing protection policies and strategies with respect to possible sea level rise and climate change in the future. For the development of future protection strategies, possible changes of the near-shore hydrodynamics and consequences for sediment transport and the morphology of coastal areas have to be analysed. Due to changes in wind conditions simulated from the regional climate model COSMO-Climate Local Model, our results for the South Western Baltic Sea are showing that the average significant wave heights increase up to 8% to the end of the 21st century compared with actual conditions. Moreover westerly wave directions are becoming more dominant. Depending on the alignment of the coast and the change of the local wave climate, the long-shore sediment transport can be affected significantly. E.g., for the location of Warnemünde the net-transport capacity increases up to 40% compared to actual conditions.

Keywords: *Baltic Sea; Climate Change; Wave Conditions; Sediment Transport.*

I INTRODUCTION

The coastal engineering group of the University of Rostock is a member of the core consortium of the interdisciplinary climate change project RADOST (Regional Adaptation Strategies for the German Baltic Sea Coast). The main objective of this project is the development of adaptation strategies for the Baltic coastline of Germany 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 were examined. The changes are resulting from regional climate change impacts on windiness, as shown in this paper, and sea-level rise.

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 are 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) have been taken into account (Nakićenović, 2000).

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II METHOD

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 RCM 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 have been derived for different locations at the German Baltic Sea Coast. Fig. 1 shows the three locations which have been used in the present study: Warnemünde (cp. Fig. 1 right), Travemünde (Bay of Lübeck, cp. Fig. 1 bottom) and Westermarkelsdorf (Island of Fehmarn/Bay of Kiel, cp. Fig. 1 top).

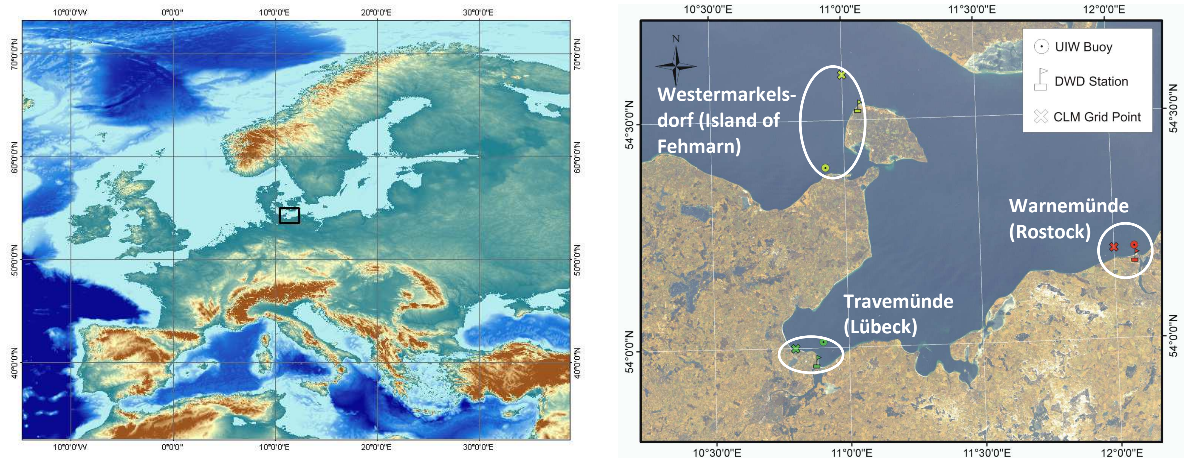

Fig. 1. example area (left) and locations used for the investigations (right)

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 we calculate the wave parameters significant wave heights H_{m0}, mean wave directions Θ_m and mean wave periods T_{m02} from mean wind velocities U_{10} and mean wind directions Θ_w.

For the assessment of the general accuracy between calculated and measured wave heights, mean absolute deviations were used (Eq. 1). The mean absolute deviations for the wave periods and wave directions are calculated similar to Eq. 1. The results given in Tab. 1 are indicating a good agreement between measured and calculated wave data.

$$\left|dH_{m0}\right| = \frac{\sum_{i=1}^{n}\left|H_{m0,observed} - H_{m0,calculated}\right|}{n} \qquad (1)$$

Table 1. Mean absolute deviations between measured and calculated wave parameters

Location	$\vert dH_{m0}\vert$ [m]	$\vert dT_{m02}\vert$ [s]	$\vert d\Theta_m\vert$ [°]
Warnemünde	0.10473	0.44819	6.48415
Travemünde	0.08785	0.45050	7.44012
Westermarkelsdorf	0.07481	0.21654	7.01464

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 and Fittschen, 1999), a cut off criteria for maximum wind velocities has been applied for a 5% error margin (Eq. 2).

$$U_{cut} = 1.16\, U_{max,correlation} \tag{2}$$

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. In this case the wave parameters are calculated with the help of stationary numerical simulations using SWAN (Booij et al., 1999) instead of calculating them from wind-wave-correlations. The numerical simulations are 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. Fig. 2 is showing exemplarily the calculated significant wave heights and the mean wave directions within the example area.

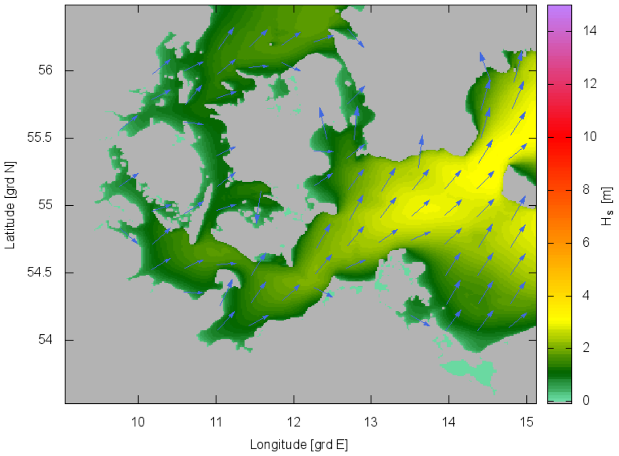

Fig. 2. Calculated wave heights and wave directions (arrows)

Evaluation periods

From a statistical point of view, climate change is 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). For the assessment of climate change and climate change inducted processes, the World Meteorological Organization (WMO) recommends a time period of 30 years.

In this study we use different time periods for the assessment of future changes in wind respectively the wave climate and sediment transport. To illustrate changes of **average conditions**, like average wind and wave conditions, we compare differences of occurrence of wind respectively wave parameters for two projection periods of 30 years (2021-2050 and 2071-2100) to values for the control period (1971-2000).

Regarding the changes of **extreme events** and the long-shore sediment transport, which is calculated from wave statistics, we compare the changes for time periods of 40 and 30 years respectively. The values are calculated for each year within the time period from 2001-2100 and compared to values from 1961-2000 in the case of extreme wave events and to values from 1971-2000 for the long-shore sediment transport. The reason for the extension of the evaluation period of 30 to 40 years is to increase the sample size for the extreme value analysis (see chapter IV).

III CHANGE OF FUTURE WIND CONDITIONS

The future changes in wind are still uncertain. Analyses of the BACC-Group (BACC, 2008) are showing 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. Moreover future wind conditions in RCM runs are highly depending on the forcing global climate model (Räisänen et al., 2003, Pryor and Barthelmie, 2004). Only RCM simulations driven with the global Atmosphere-Ocean General Circulation Model (AOGCM) ECHAM4/OPYC3 are showing 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).

The North German Climate Bureau compiles further results on possible future changes of wind conditions for the area of the German Baltic Sea Coast (Meinke et al., 2010). 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 are indicating 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 we use dynamical downscaled wind from the RCM CCLM (Rockel et al., 2008). The RCM runs have been forced by the AOGCM ECHAM5/MPI-OM. There have been carried out different CCLM model runs (Lautenschlager et al., 2009), covering the 20th century (1960-2000) and the 21st century (2001-2100) as compiled in Tab. 2.

As shown in Tab. 2, there are existing 3 independent realisations of the climate for the 20th century, each forced with observed anthropogenic forcing and started 25 years apart from each other (C20_1 to C20_3). For the modelling of 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. The realisations for the past and the future have been compiled to 4 transient time series covering a period from 1960-2100.

Table 2. CCLM 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
	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, we selected time slices of 30 years from the simulated wind data at the locations of the example area (cp. Fig. 1, used grid points are marked with 'x'), namely the scenario 2050 (2021-2050) and 2100 (2071-2100) to compare them to values for the control period 1971-2000. In the next step we calculated the differences of the frequencies of occurrence for the wind velocities and directions between each combination of the 4 realisations for the future and the 3 realisations for the past. From the ensemble of 12 differences we plotted the minimum and maximum values of the differences in each velocity resp. directional class and surrounded the area in between these values 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.

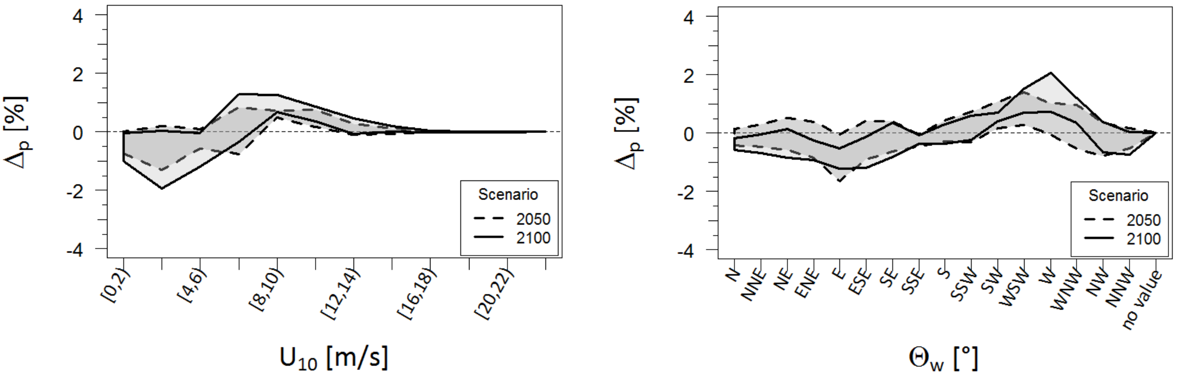

Fig. 3. Spread of change of frequency distribution of wind velocities (left) and wind directions (right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Warnemünde

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 left) 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, thus 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 right) 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 change of the frequency for the wind velocities and directions near the locations of Travemünde and Westermarkelsdorf shows in general the same tendency, booth in spread of the results and amplitude, with only some small variations in single velocity resp. direction classes. The change of the wind conditions has also consequences on the local wave climate, which we illustrate 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 (BACC, 2008). Regarding the change of mean wave conditions, Miętus (1999) 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) utilised a wave model on the basis of different scenarios derived from runs of the AOGCM ECHAM4/OPYC3. The results are indicating 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, we compared the frequency of occurrence for the future scenarios 2050 (2021-2050) and 2100 (2071-2100) 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. 5 and Fig. 6 respectively.

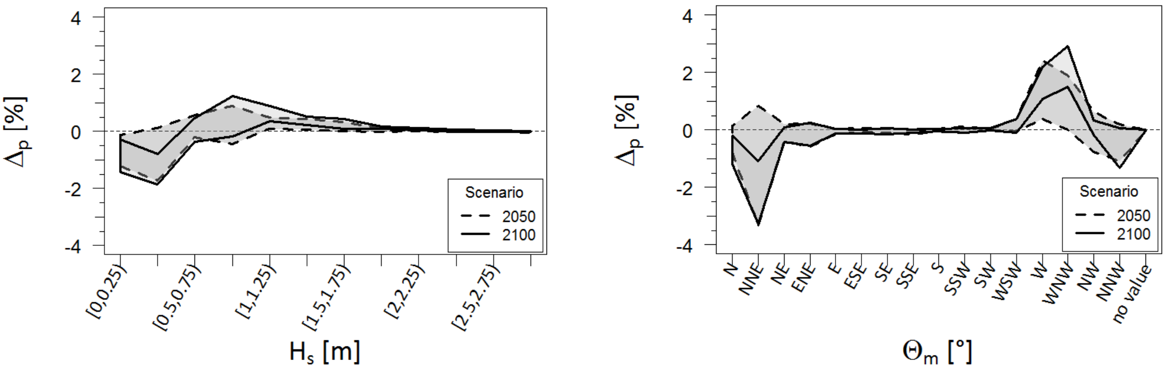

Fig. 5. Spread of change of frequency distribution of wave heights (left) and wave directions (right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Warnemünde

Regarding the **wave heights** it is concluded that for locations exposed to <u>westerly</u> winds (e.g. locations Warnemünde in Fig. 5 and Westermarkelsdorf), 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. 5 left). This will amount to increases of the mean significant wave heights at the location Warnemünde up to 6% and at the location Westermarkelsdorf up to 8% to the end of the 21st century compared to the control period.

For locations exposed to <u>easterly</u> directions (e.g. location Travemünde in Fig. 6) 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. 6 left). 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).

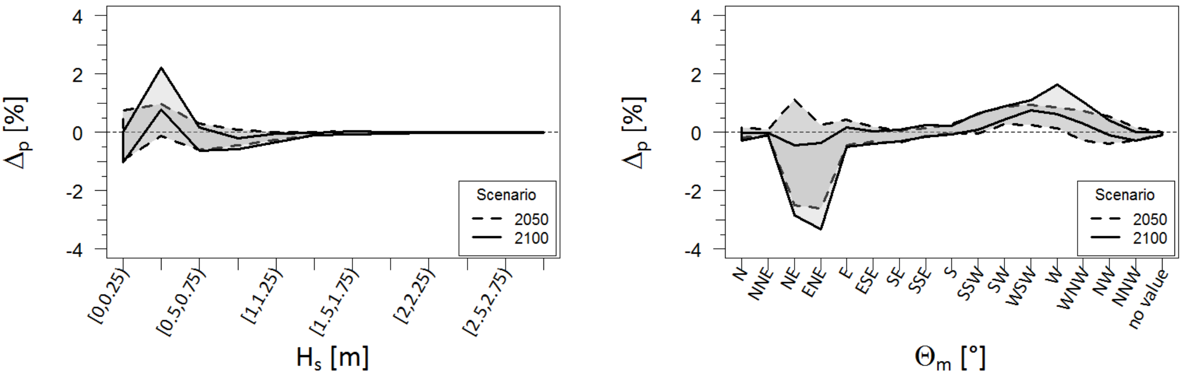

Fig. 6. Spread of change of frequency distribution of wave heights (left) and wave directions (right) for the scenarios 2050 (2021-2050) and 2100 (2071-2100) for climate change scenarios A1B and B1 compared to the control period (1971-2000), near Travemünde

The change of the frequency of the **wave directions** is nearly the same at all 3 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. 5 right, and Travemünde in Fig. 6 right.

In general, westerly wave directions are becoming more dominant, while north-easterly directions are decreasing, 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° for the location of Warnemünde. For easterly wind exposed locations like e.g. Travemünde, a shift of the mean wave direction to 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.

Extreme wave heights

For the statistical assessment of the change of extreme wave heights we analysed 4 transient long-term time series of wave parameters, which were calculated on the basis of the 4 transient time series of wind conditions (cp. Tab. 2) 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 from 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 control period (1961-2000). Example results for the change of the extreme wave heights are shown in Fig. 7.

At the location Warnemünde (Fig. 7 top left), in general the calculated extreme wave heights are increasing up to 5%, except for one transient scenario run (C20_2+A1B_2) which indicates a slight decreasing trend. For the other locations the range of the change of extreme wave heights is wider.

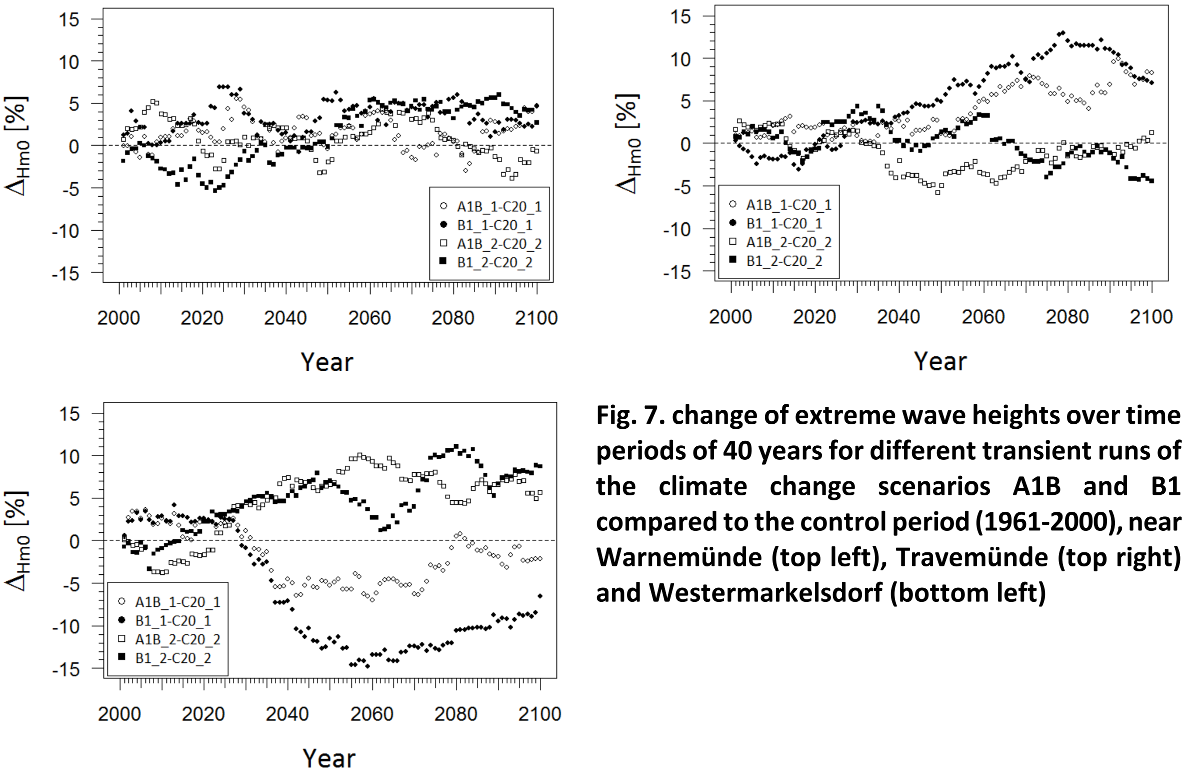

Fig. 7. change of extreme wave heights over time periods of 40 years for different transient runs of the climate change scenarios A1B and B1 compared to the control period (1961-2000), near Warnemünde (top left), Travemünde (top right) and Westermarkelsdorf (bottom left)

Near Travemünde (Fig. 7 top right) 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. 7 bottom left), 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.

V IMPACTS ON LONG-SHORE SEDIMENT TRANSPORT

The estimation of future morphological changes of coastal areas is one of the main tasks regarding the development of future coastal protection strategies for the German Baltic Sea Coast. While the change of the average significant wave heights and the average wave directions seems comparatively small, they can have considerable effects on sediment transport capacities. Therefore sediment transport calculations using the CERC-formula (Eq. 3; SPM, 1984) have been performed on the basis of joint distributions of average wave heights and average wave directions.

$$Q = 0.632 \cdot 10^{6}\, T(H_0 K_R)^2 \sin(2\alpha_b) \qquad (3)$$

The CERC-formula combines the input wave energy and the respective wave direction to the long-shore energy flux and uses this value to assess the local sediment **transport capacity**. The accuracy of the calculated long-shore transport rate using the SPM method with the CERC formula can be estimated to be +/-50% (SPM, 1984).

The de facto transported sediment is also influenced by different other factors like e.g. the availability of sand at a given location or the covering of a shore with ice. Regardless the absolute calculated values, this approach estimate the correct trend of sediment movements in the Baltic region according to experiences.

To assess the future change of the sediment transport both local directional and net-transport capacities have been calculated for time periods of 30 years on the basis of the 4 transient long-term time series of wave parameters (as used for the extreme value analysis of wave heights). Finally the values were compared for each year within the time period from 2001-2100 to the values for the control period (1971-2000). Example results for the change of the net-sediment transport capacities are shown in Fig. 8.

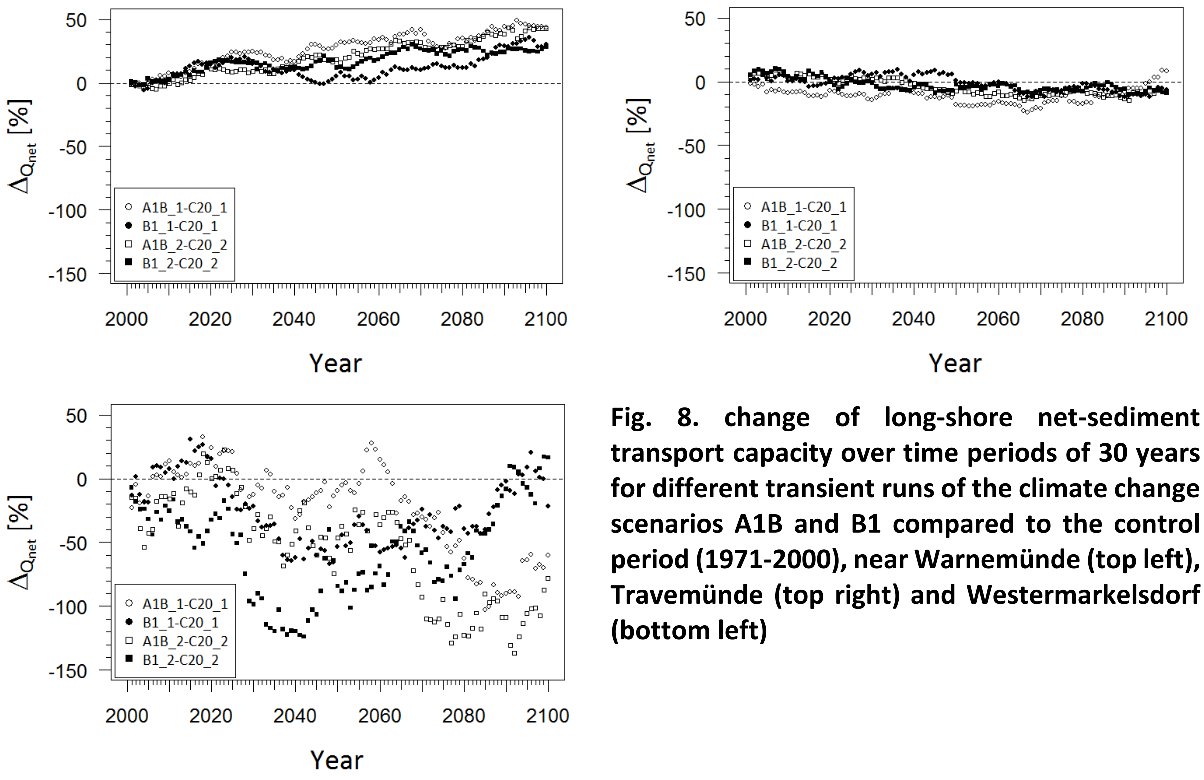

Fig. 8. change of long-shore net-sediment transport capacity over time periods of 30 years for different transient runs of the climate change scenarios A1B and B1 compared to the control period (1971-2000), near Warnemünde (top left), Travemünde (top right) and Westermarkelsdorf (bottom left)

The results for the location Warnemünde (cp. Fig. 8 top left) show that today's already eastwards dominated sediment transport may intensify and that the net-sediment transport capacity can increase up to 40% at the end of the 21st century. The strong increase of the net-transport capacity at this location is connected to a decrease of the westwards orientated transport capacity and at the same time an increase of the eastwards orientated transport capacity.

The northwest orientated sediment transport near Travemünde (cp. Fig. 8 top right) may decrease down to 20% in the middle of the 21st century. At the location Westermarkelsdorf (cp. Fig. 8 bottom left) the southwest orientated sediment transport shows strong fluctuations of the calculated net-sediment transport capacities. The change of the net-transport capacity is ranging from increasing values for some single scenarios and periods to in general decreasing values. Partly the decrease of the net-sediment transport capacity can exceed 100% for some single scenarios and periods, thus becoming contrary to the actual sediment transport direction at this location.

VI CONCLUSIONS

Analyses of future changes of average wave conditions and extreme events as well as sediment transport 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. At all 3 locations used in this study it became clear that westerly wave directions will become more dominant for the future and have considerable effects on e.g. the long-shore sediment transport at a given location. For a complete view of future changes of the local wave climate the statistical significance of the results has to be assessed and discussed as well as the spatial distribution of the average changes of wave heights and directions.

No clear trend was found for the change of extreme wave heights. The results are indicating increasing as well decreasing wave heights up to 14% for selected future scenarios and periods. Like analyses of changes of extremes of wind speed we will also have a look on the change of other parameters from the distribution function of the wave heights, e.g. the 99th percentile of significant wave heights, and not use the maximum significant wave heights like in this study.

Changes of the local wave conditions will directly affect the local sediment transport characteristics, especially at locations exposed to westerly winds. The long-shore net-sediment transport capacity might be changing significantly up to 40%. Another important consequence is that for selected future scenarios and periods the main direction of the long-shore sediment transport can become contrary to actual conditions.

USED CLIMATE MODEL ABBREVATIONS

CCLM	COSMO-Climate Local Model
ECHAM5/ MPI-OM	coupled general circulation sea-ice/ocean model developed at the Max Planck Institute for Meteorology (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
RCAO	Rossby Centre Coupled Atmosphere-Baltic Sea Regional Climate Model

USED CLIMATE DATA

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