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Future Changes in Wave Conditions at the German Baltic Sea Coast Based on a Hybrid Approach Using an Ensemble of Regional Climate Change Projections

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Abstract: In this study, the projected future long-term changes of the local wave conditions at the German Baltic Sea coast over the course of the 21st century are analyzed and assessed with special focus on model agreement, statistical significance and ranges/spread of the results. An ensemble of new regional climate model (RCM) simulations with the RCM REMO for three RCP forcing scenarios was used as input data. The outstanding feature of the simulations is that the data are available with a high horizontal resolution and at hourly timesteps which is a high temporal resolution and beneficial for the wind–wave modelling. A new data interface between RCM output data and wind–wave modelling has been developed. Suitable spatial aggregation methods of the RCM wind data have been tested and used to generate input for the calculation of waves at quasi deep-water conditions and at a mean water level with a hybrid approach that enables the fast compilation of future long-term time series of significant wave height, mean wave period and direction for an ensemble of RCM data. Changes of the average wind and wave conditions have been found, with a majority of the changes occurring for the RCP8.5 forcing scenario and at the end of the 21st century. At westerly wind-exposed locations mainly increasing values of the wind speed, significant wave height and mean wave period have been noted. In contrast, at easterly wind-exposed locations, decreasing values are predominant. Regarding the changes of the mean wind and wave directions, westerly directions becoming more frequent. Additional research is needed regarding the long-term changes of extreme wave events, e.g., the choice of a best-fit extreme value distribution function and the spatial aggregation method of the wind data.

Keywords: REMO; EURO-CORDEX; SWAN; wind–wave correlations; regional climate change projections; average wave conditions; extreme wave events; model spread; variability; uncertainty

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1. Introduction

Human-made emissions of greenhouse gases have caused warming of the global climate system and the mean global temperatures are expected to increase further and cause long-term changes in all climate system compartments including the oceans [1–3]. Moreover, the changes in global temperatures are expected to affect the wind conditions on different regional and temporal scales but also the mean and extreme (storm surge) sea levels. As a consequence, the changes of the wind conditions and water levels will affect the local wave climate and the wave-induced loads on coastal protection structures as well, e.g., on the wave-induced sediment transport. These processes include the long-shore sediment transport, that influences the long-term morphology of the coast (including coastal erosion) [4].

Hence, information on the future long-term changes of the wind climate and its impacts on the local hydrodynamic conditions along the coast are needed to support regional and local adaptation planning and to encounter the increase of potential hazards for coastal areas due to climatic changes [4–8].

The future changes of the wind and wave conditions along semi-enclosed basins, e.g., the Baltic Sea, which are investigated within this study, depend on the (i) forcing global climate model/GCM (model uncertainty) [9], (ii) future forcing scenario (scenario uncertainty), (iii) realization of the climate projection (internal variability), (iv) future time period (temporal variability) and (v) location (spatial variability) [10,11].

Statistical significant changes of average wind and wave conditions have been found in previous studies, independent of the approach for the calculation of the wave conditions [11,12], and hence show an agreement of the climate change signals which depend on the GCM, location, forcing scenario and time period, and finally the considered wind and wave variables. No agreement has been found so far regarding future changes of extreme wave events in the Baltic Sea [13,14]. The actual advance of this work is the fact that the extreme value analysis is sensitive to the spatial aggregation method applied to the climate projection data, as we show in this paper.

Recent studies on the changes of the wave climate in semi-enclosed seas, like, e.g., the Baltic Sea and the Mediterranean Sea, have often been conducted on the basis of a single RCP forcing scenario, e.g., RCP8.5 (see [15,16]), RCP4.5 (see [17]), but do not cover the uncertainty that is associated with different forcing scenarios (scenario uncertainty).

An overview of the projected wave climate for the North Sea (see [18]) confirms that the future changes depend mainly on the global forcing model (model uncertainty), and that natural variability dominates over the long-term trend of the wind conditions and wind-influenced characteristics including wind–waves and sea levels.

Moreover, [19] found that changes of the local wind fields can be linked to large-scale atmospheric patterns such as the North Atlantic Oscillation (NAO). In addition, no robust changes of maximum wind speeds along the North Sea coast were found and both increases and decreases of maximum wind speeds are projected ([19]).

For the latest stat-of-the-art climate change projections of the CMIP6 models mainly global wave climate projections have been conducted yet and hence will not discussed here because the present study focuses on regional climate change projections based on a high spatial and temporal resolution.

Results from other ensemble studies show a high uncertainty of the future changes of both average and extreme wind conditions over the Baltic Sea [9,20]. Moreover, [9] concluded that the future projections of the wind conditions over the Baltic Sea are more uncertain than other atmospheric parameters, e.g., precipitation, and highly depend on the future changes of the large-scale atmospheric circulation which is simulated by the forcing GCM.

Multi-method and multi-model ensembles have been used for global [21] and regional (NW-Mediterranean Sea) [22] wave climate projections, but in the regional study, the model uncertainty introduced by different forcing GCMs was not taking into account.

A systematic comparison of future wave projections that takes into account these uncertainties should be based on a consistent ensemble of high-resolution RCM simulations driven by different GCMs and downscaled with the same horizontal resolution and for the same model domain etc. Different realizations from each GCM should also be taken into account.

In addition, different forcing RCP scenarios are needed to account for the scenario uncertainty that is associated with climate change projections. Finally, the future changes need to be assessed with respect to their statistical significance and model agreement on the direction of the changes which until now have not been assessed yet on the basis of an ensemble of high-resolution RCM data.

The purpose of this study is, therefore, a systematic comparison of future wave projections based on a consistent ensemble of high-resolution RCM simulations driven by different GCMs, which also include different GCM realizations. Wind–wave modelling requires both a high spatial and temporal resolution of the wind input data which often is not available for ensemble simulations.

Moreover, possible ranges of the future changes of the average and extreme wave conditions are analyzed and assessed on a local scale and with special focus on the assessment of (i) model agreement and statistical significance (ii) the spatial, seasonal and temporal variability of the results. This work builds up on our previous studies using a hybrid approach [12] that enables the fast compilation of future long-term time series of significant wave height, mean wave period and wave direction for an ensemble of RCM data.

The approach that is described in Section 2 can potentially be extended to other areas of interest under two limitations:

a. The wind–wave correlation method explained here is limited to a mean water level and hence is only valid under deep water conditions, but the correlation can be extended to a wind–wave–water level correlation method to be used in other areas where the wave conditions depend on the local water levels.
b. The regional climate model data is available for the whole EURO-CORDEX domain (see [23]) and can be applied within this area.

2. Materials and Methods

2.1. Multi-Model and Multi-Member Ensemble

Climate models are the only tool to estimate potential future climate evolutions at different spatial scales, e.g., global ($\geq$50 km), regional (~50 down to ~10 km) to local (down to ~1 km), and temporal scales (e.g., centennial, multi-decadal, annual to seasonal). These models are commonly used to study the impacts of potential future anthropogenic emissions on the climate system and on climate-driven processes, e.g., wind–wave dynamics, in impact modelling studies.

There are different types of uncertainties associated with climate change projections, which are related to natural and anthropogenic forcing and to modelling uncertainties [24].

Ensemble model experiments are state-of-the art methods to assess those uncertainties and quantify possible ranges of projected future climate changes and associated climate change impacts.

The RCM REMO [25] was used for the dynamical downscaling of global climate projections of the 5th phase of the Coupled Model Intercomparison Project (CMIP5) within the world initiative on coordinated regional downscaling experiments (CORDEX). EURO-CORDEX, the European branch of CORDEX, generated new high-resolution climate change projections for European impact research, [23]. The data is available at a 0.11° horizontal resolution (~12 km) and for different representative concentration pathway (RCP) forcing scenarios (RCP2.6, RCP4.5 and RCP8.5) used within AR5 of IPCC [26], via the Earth System Grid Federation (ESGF) node in Germany (see https://esgf-data.dkrz.de/search/cordex-dkrz). The RCP2.6 scenario is a scenario with substantial emission reduction, which is likely to keep the average global warming below 2 degrees by 2100. In contrast the RCP4.5 scenario has higher emissions and RCP8.5 having the highest emissions, resulting in an average global warming of about 4 degrees by 2100 (for more information on the different scenarios see [26]).

Nevertheless, the publicly available data of the EURO-CORDEX ensemble is only provided on a daily resolution, which is too coarse for impact assessment studies on the future changes of the local wind–wave climate.

Hence, the present study is based on additional hourly RCM data provided by the Climate Service Center Germany (GERICS). Multi-model (different forcing GCMs) and multi-member (different GCM realizations of the same forcing scenario) ensembles have been compiled for the RCP forcing scenarios and an evaluation run of REMO forced by ERA-Interim was provided (see Table 1). The sub-ensemble of REMO simulations forced by different GCMs and forcing scenarios has been analyzed and compared against the EURO-CORDEX ensemble, e.g., the changes of the 30-year annual and seasonal averages of the mean wind speed. As a result of the comparison, the sub-ensemble covers only a part of the total bandwidth of the average changes especially at the end of the 21st century during autumn and winter.

Table 1. REMO simulations of the multi-model and multi-member ensemble forced by different future RCP scenarios and GCMs respectively a reanalysis simulation (r1 = first realization, r2 = second realization).

Simulation	RCP2.6	RCP8.5	RCP4.5	Evaluation
MPI-ESM-LR-MPI-OM r1, r2	x	x	x	
MIROC-MIROC5 r1	x	x		
ICHEC-EC-EARTH r1	x	x		
MOHC-HadGEM2-ES r1	x	x		
NOAA-GFDL-GFDL-ESM2G r1	x			
IPSL-IPSL-CM5A-LR r1	x			
ERA-Interim				x

A multi-model ensemble with one realization was available for each of the RCP2.6 and RCP8.5 forcing scenarios. In addition, a multi-member ensemble with a second realization exists for a set of regional climate simulations with REMO forced by MPI-ESM-LR-MPI-OM including all RCP forcing scenarios. A REMO run driven by ERA-Interim reanalysis data was used for evaluation purposes.

Hourly mean values of wind speed and direction in 10 m height above the surface are used for the calculation of the wave conditions with the hybrid model (see the following Section 2.2). The target wind variables have been compiled from the original wind vector components of the REMO model output with the help of the CDO software [27].

According to the guidance on the data use of climate projections [28], it is recommended to use several grid boxes for spatial analysis, for instance by using an average over the grid boxes, rather than analyzing the output for single grid boxes only. The reason for this is because the model results are not exact values at the points, but represent mean values in space and time, respectively. Moreover the values depend also on the horizontal, respectively, time resolution of the model [29].

A sensitivity analysis on the selected number of grid points, their geographical locations with respect to the land fraction variable of the model grid and different spatial aggregation (averaging) techniques was conducted, in order to find what is the effect of the aggregation method and scale on the changes of the wind and wave conditions; this is discussed in Section 4.3. As a result, land fraction weighted spatial averages of 4 $\times$ 4 grid boxes were used as input for the calculation of the wave conditions.

2.2. Hybrid Approach

For the derivation of long-term transient time series of the wave conditions, a hybrid approach has been developed and used within previous assessments of the long-term changes of future wave conditions at the German Baltic Sea coast, e.g., [30]. The approach is based on a mean water level and hence the local water levels and the future sea level rise are neglected. The results are only valid under deep water conditions where the influence of the local water levels on the local wave conditions can be neglected.

The following wave variables are calculated: significant wave height (H_{m0}), mean wave period (T_{m02}) and mean wave direction (Θ_m). The calculations are done using a hybrid approach, which combines results from a statistical method (wind–wave correlations) and a numerical wave model. The correlation approach is used if the maximum wind speed in the different wind directions that has been used for the derivation of the correlations is covered by the wind measurements and for a given error margin (5%). If the latter is not the case, the wave conditions are calculated with the help of the numerical wave model, which is approximately the case for 3% of the values in a period of 30 years.

Statistical correlations between the wind and wave conditions have been derived for four locations at the German Baltic Sea coast (see Figure 1) on the basis of available synchronized local field data for wind and waves (e.g., wind data from local wind gauge measurements of the German Weather Service (DWD) and data from local waves measurements with a directional wave buoy (Datawell) of the University of Rostock. More information on the statistical approach are given in [31,32]. The locations used in the present study have been selected in accordance with local wind measurements of the DWD, namely "Rostock-Warnemünde" and "Lübeck-Travemünde", as shown in Figure 1.

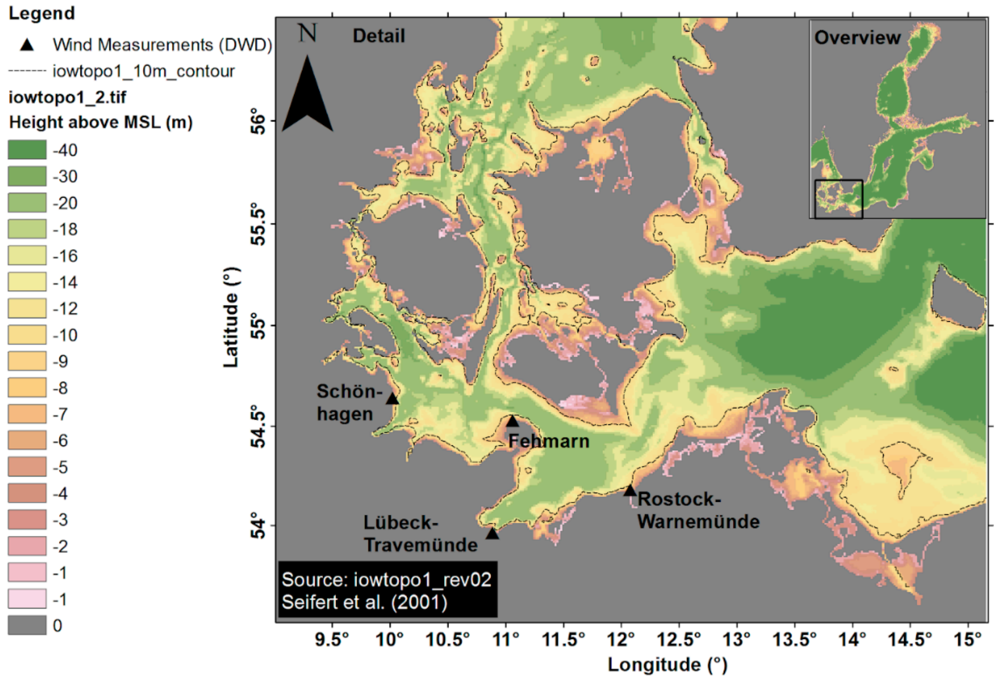

Figure 1. Selected locations with wind measurements of the Deutscher Wetterdienst (DWD, see black triangles) and bathymetry data of the SWAN wave model for the Western Baltic Sea area. Source of the bathymetry: [33].

The selection of the locations has been made on the basis of the availability of wind and wave measurement data. The wave conditions at the two selected locations reflect the spatial variability of the results due to different exposures of the coast and fetch lengths. The locations that are discussed thus represent a range of future outcomes for the Baltic Sea, which is relevant for the method, but also for readers interested in the projections of changes in waves for the Baltic Sea.

The quality of the wind–wave correlation method has been assessed in previous studies (e.g., [31]). The accuracy (mean average error) of the wind–wave correlation results compared to wave observations at the selected locations of this study ranges between 8–11 cm for the significant wave height H_{m0} (for $H_{m0} \geq 0.05$ m), 0.5–0.6 s for the mean wave period T_{m02} (for $T_{m02} \leq 10$ s) and 7–8° for the mean wave direction Θ_m (for $H_{m0} \geq 0.5$ m).

In addition, the stationary numerical wave model SWAN [34], which is a 3rd generation spectral wave model, has been set up for the area of the Western Baltic Sea (see model domain in Figure 1) and at a mean sea level. The spectral wave variables at every grid point of the computational grid are computed within stationary numerical wave simulations. Both model domain and horizontal resolution (dx = 1′~1 km, dy = 0.5′~1 km) have been chosen in accordance with available bathymetric data from [33]. The spectral respectively directional resolution of the model was chosen from our experiences in other coastal engineering studies on the modeling of wind–waves in the Baltic Sea area with 42 frequencies between 0.02 and 1 Hz, respectively, 2.5° (144 bins).

Spatially constant wind conditions are applied as meteorological boundary conditions in the stationary wave simulations with a resolution of ΔU_{10} = 1 m/s for the wind speed and $\Delta\Theta_w$ = 10° for the wind direction in accordance with the resolutions of the wind measurements of the DWD.

SWAN has been applied in previous coastal engineering studies, e.g., to derive hydrodynamic parameters for the design of coastal protection structures [35] or to derive wave input parameter for the calculation of the wave-induced long-shore sediment transport along the German Baltic Sea coast [36]. The results of the wind–wave correlations have been validated against available field wave measurements at the selected locations at the German Baltic Sea coast of the present study. The mean absolute errors (MAE), as shown in Table S1 of Supplementary Materials, indicate a good agreement between measured and calculated wave data.

One of the advantages of the approach is the high accuracy for the calculation of wave conditions in comparison with other approaches (e.g., nonstationary numerical wave simulations or empirical approaches). Another advantage is the fast compilation of time series of wave conditions which is less computationally expensive than running long-term numerical wave simulations in nonstationary mode and for larger climate model ensembles.

2.3. Assessment of Model Agreement and Statistical Significance

The future changes of the average wind and wave conditions are analyzed by calculating both seasonal and annual averages over time periods of 30 years and comparing the values for the 21st century (2006–2100) to the values for the reference period 1971–2000 and a moving average approach for each RCP forcing scenario separately.

In addition, changes of the frequency of occurrence have been calculated between two selected time periods, labelled 2050 (2021–2050) respectively 2100 (2071–2100), and compared to the values for the reference period (1971–2000). The significance of the changes of the frequency of occurrence has been assessed on the basis of two-sided parametric hypothesis tests (z-test) and a significance level of 5% (p = 0.05).

The changes of the selected wind and wave variables for the different ensembles of REMO simulations for each forcing scenario (see Table 1) and a selected future period were analyzed and assessed if they fulfill the following conditions:

(i). Model agreement: The changes of the 30-year annual or seasonal averages of the ensemble members are in the same direction and the selected minimum, respectively, maximum threshold (see Table S2) is reached or exceeded by a majority (at least 50%) of the ensemble members.

(ii). Statistical significance: The changes of the frequency of occurrence of the ensemble members are statistically significant at a level of 5% (p = 0.05) and for at least 50% of a selected number of frequency classes depending on the wind or wave variable.

The chosen conditions are discussed more in detail in Section 4.1.

3. Results

In order to gain confidence in the model performance, a verification step was performed. Comparisons between 30 years of wind data of REMO (1971–2000) forced by different GCMs and 21 years of wind data of REMO (1979–2000) forced by ERA-Interim were made to assess model uncertainty and bias of the wind data for past average wind conditions.

The REMO simulation can contain a significant bias for both near surface wind speed and mean wind direction; within the range of −1.9% to +4.8% for the wind speed, respectively, −28° to +3° for the wind direction for the 30-year annual averages.

The biases of the 30-year annual averages of the wind variables result in biases for the wave variables within the range of −5.3% to +14.3% for the significant wave height, −3.9% to +4.6% for the mean wave period and −19.2° to +28.9° for the mean wave direction. However, depending on the location and season, larger biases of the 30-year seasonal averages have been quantified (e.g., near the location of "Rostock-Warnemünde" and during winter −5.7% to +15.8% for the significant wave height, −5.0% to +1.3% for the mean wave period and −11.4° to +15.8° for the mean wave direction). Moreover, the calculation of the average values of the wind, respectively, wave direction can lead to a misinterpretation of the biases, if the frequency distribution of the wind, respectively, wave direction is characterized by two main directions instead of one single main direction. In such cases, it is recommended to assess the biases of the directions on the basis of the changes of the frequency of occurrence instead of deriving them from changes of average values, which might be suspect to errors.

Nevertheless, the biases are assumed to be negligible because the relative changes of the future wind and wave variables are analyzed and not the absolute values. Moreover, the assumption is made, that the bias characteristics are comparable for today's and future climate simulations.

The comparisons of the wind data of REMO and the wind data of ERA-Interim show that the wind data of the selected ensemble members can be used for the quantification of the future changes of the wind and wave conditions at both selected locations.

It has to be noted that due to the selection of the sub-ensemble from the ensemble of EURO-CORDEX simulations, the results and conclusions shown in this study are only valid for the sub-ensemble. The total bandwidth of possible future climate change signals might be larger and not be represented completely by the sub-ensemble.

The reader is referred to additional figures and tables which are included in Supplementary Materials, which provides a more detailed information on the future changes of average wind and wave conditions as well as extreme wave events which are summarized in the following sections.

3.1. Future Changes of Average Wind and Wave Conditions

The ranges of future average wind and wave conditions, respectively, extreme wave conditions have been analyzed and assessed with special focus on the model agreement, statistical significance and the spatial and temporal variability of the results.

The advancement with respect to the state-of-the-art is the fact, that the changes of average wind and wave conditions can be calculated independent of the spatial averaging approach which results in an easier preprocessing of the regional climate model data to be used as input data for the wave calculations.

Note that in the following the terms "westerly/easterly wind exposed locations" or "locations exposed to westerly/easterly winds" are used synonymously, e.g., for the selected locations near "Rostock-Warnemünde"/"Lübeck-Travemünde".

Different climate change signals have been noted at the selected westerly and easterly wind-exposed locations where a majority of the ensemble members shows statistical significant changes in the same direction. The variables where future changes of average wind and wave conditions have been analyzed and assessed (see Section 2.3) near the selected locations, "Rostock-Warnemünde" and "Lübeck-Travemünde", are summarized in Tables 2 and 3, respectively.

Results of the relative changes of the 30-year annual averages of selected wind and wave variables for all ensemble members (independent of model agreement or statistical significance) of the forcing scenario RCP8.5 near the location of "Rostock-Warnemünde" are shown in Figure 2 as an example. The results for the ensemble members of the forcing scenarios RCP2.6 and RCP4.5 are shown in Figures S2 and S3.

The bandwidth (from minimum to maximum) and the direction of the changes, taking into account model agreement and statistical significance (see also Section 2.3), of the 30-year annual, respectively, seasonal averages of the wind and wave variables for the selected time periods 2021–2050 and 2071–2100 and for each of the three forcing scenario (RCP8.5, RCP4.5 and RCP2.6) are given exemplarily near the location of "Rostock-Warnemünde" in Tables S3–S5.

Table 2. Variables with future changes of the average wind and wave conditions (mean wind speed U_{10}, wind direction Θ_w, significant wave height H_{m0}, mean wave period T_{m02} and mean wave direction Θ_m) near the selected westerly wind-exposed location "Rostock-Warnemünde" for the forcing scenarios RCP2.6, RCP4.5, RCP.8.5 in two selected time periods 2021–2050, 2071–2100 and for annual (column "AVG"), respectively, seasonal averages (over three months periods, columns DJF = winter, MAM = spring, JJA = summer, SON = autumn).

	2021–2050					**2071–2100**				
	AVG	**DJF**	**MAM**	**JJA**	**SON**	**AVG**	**DJF**	**MAM**	**JJA**	**SON**
RCP2.6				U_{10}, Θ_w, H_{m0}, T_{m02}			Θ_w, T_{m02}, Θ_m		T_{m02}	Θ_w, Θ_m
RCP4.5					T_{m02}		Θ_w, Θ_m			
RCP8.5	Θ_w, T_{m02}	Θ_w, Θ_m	Θ_m	Θ_w, T_{m02}, Θ_m	U_{10}, Θ_w, T_{m02}, Θ_m	U_{10}, Θ_w, H_{m0}, T_{m02}, Θ_m	Θ_w, H_{m0}	U_{10}, Θ_w, H_{m0}, T_{m02}, Θ_m	U_{10}, Θ_w, H_{m0}, T_{m02}, Θ_m	U_{10}, Θ_w, H_{m0}, T_{m02}, Θ_m

Table 3. Variables with future changes of the average wind and wave conditions (mean wind speed U_{10}, wind direction Θ_w, significant wave height H_{m0}, mean wave period T_{m02} and mean wave direction Θ_m) near the selected westerly wind-exposed location "Lübeck-Travemünde" for the forcing scenarios RCP2.6, RCP4.5, RCP.8.5 in two selected time periods 2021–2050, 2071–2100 and for annual (column "AVG") and seasonal averages, respectively (over three months periods, columns DJF = winter, MAM = spring, JJA = summer, SON = autumn).

	2021–2050					**2071–2100**				
	Year	**DJF**	**MAM**	**JJA**	**SON**	**Year**	**DJF**	**MAM**	**JJA**	**SON**
RCP2.6	Θ_m	Θ_m		Θ_m			Θ_w, Θ_m		Θ_m	Θ_w, Θ_m
RCP4.5										
RCP8.5	Θ_w, Θ_m	Θ_w, H_{m0}, Θ_m		Θ_w, T_{m02}, Θ_m	Θ_w, T_{m02}, Θ_m	Θ_w, T_{m02}, Θ_m	Θ_m	Θ_w, H_{m0}, T_{m02},Θ_m	Θ_w, T_{m02}, Θ_m	U_{10}, Θ_w, H_{m0}, T_{m02}, Θ_m

From the results given in Table 2, Table 3 and Tables S3–S5, it can be concluded that a majority of the changes occur at westerly wind-exposed locations, in this case exemplified by the location of "Rostock-Warnemünde". The largest changes occur, e.g., near "Rostock-Warnemünde", due to increases of the wind speed, and westerly winds are becoming more frequent.

Moreover, it can be seen from the tables that the climate change signals are more frequent for the forcing scenario RCP8.5 and at the end of the 21st century. This can be explained, e.g., by larger increases of the wind speed, respectively, larger changes of the wind directions towards more westerly directions for the forcing scenario RCP8.5 and at the end of the 21st century.

A high intra-annual (seasonal) variability of the changes exists. Most of the seasonal changes at both locations occur in autumn (SON) and for the period 2071–2100. All forcing scenarios, including RCP4.5, show seasonal changes for the period 2071–2100 during winter (DJF) and at westerly wind-exposed locations (see Table 2 and Table S3, respectively).

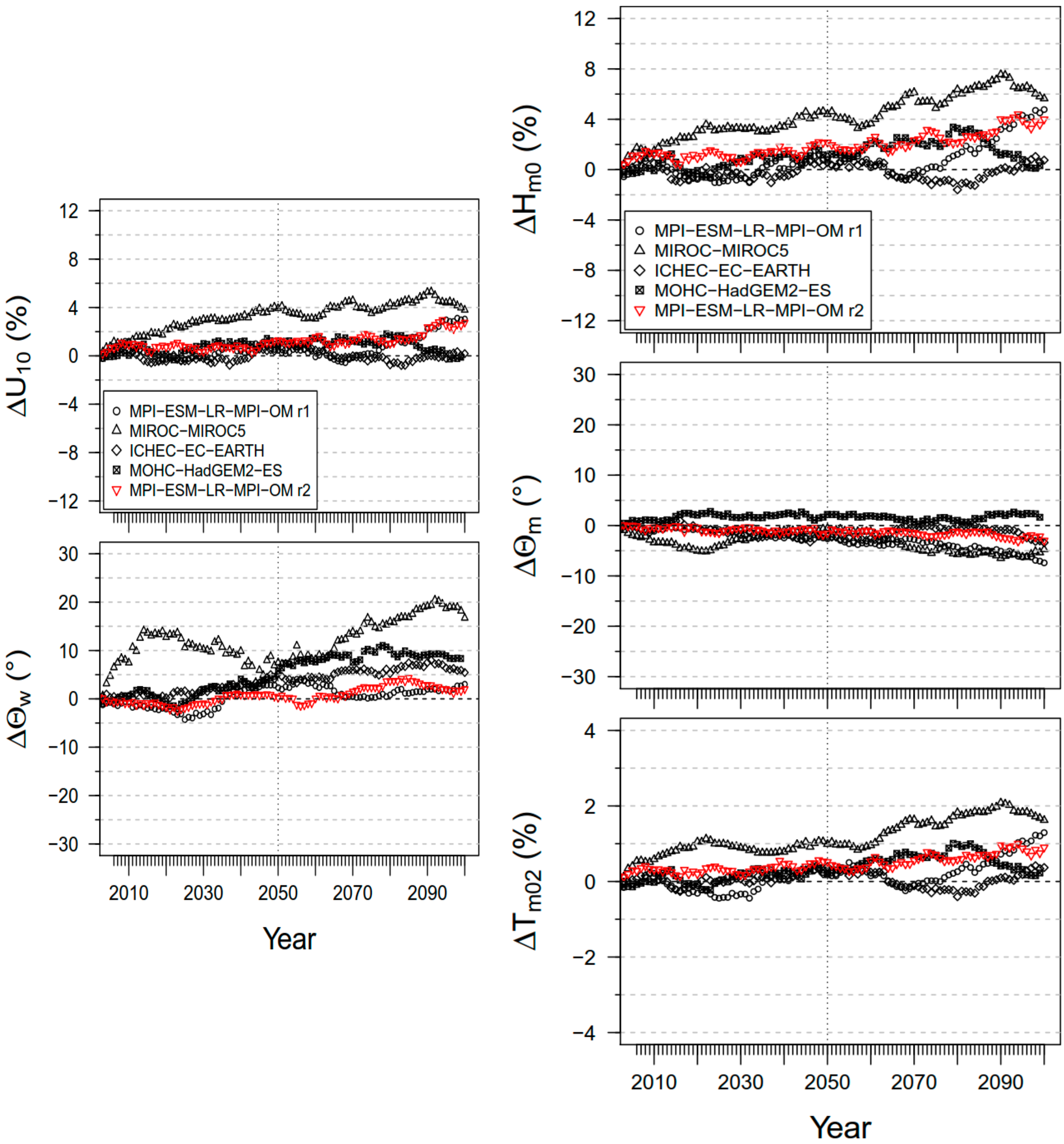

Figure 2. 30-year running mean of the future relative/absolute changes Δ (%)/Δ (°) of the mean wind speed U_{10}, wind direction Θ_w (**left**) and significant wave height H_{m0}, mean wave period T_{m02}, mean wave direction Θ_m (**right**) compared to the reference period 1971–2000 and for the ensemble members of the forcing scenario RCP8.5 (see Table 1) near "Rostock-Warnemünde".

The temporal variability of the changes of the 30-year annual averages can be exemplarily seen from the results shown in Figure 2. It has to be noted, that the largest changes do not necessarily occur at the end of the 21st century. Nevertheless, the climate change signal is more pronounced at the end of the 21st century if changes for the same direction and both of the selected periods 2021–2050 and 2071–2100 exist (e.g., changes of the mean wind speed and significant wave height during autumn/SON for RCP8.5 near "Rostock-Warnemünde" in Table S3).

As mentioned before, most of the climate change signals have been noted at westerly exposed locations in contrast to the easterly exposed locations. However, only a few changes of the wind- and wave variables can be linked together or indicate a tendency of the changes towards a certain direction of the climate change signal for more than one selected period, e.g., seasonal changes of the mean wind speed 10 m above surface

(U_{10}) in autumn (SON) towards higher values (2021–2050: +2.6% to +4.1%, 2071–2100: +3.8% to +6.7%) have been found. This results in changes of the significant wave height (H_{m0}) towards higher values (2071–2100: +6.0% to +10.8%). However, this also leads to changes of the mean wave period (T_{m02}) towards higher values (2021–2050: +1.0% to +1.5%, 2071–2100: +1.5% to +3.6%) for RCP8.5 near the location of "Rostock-Warnemünde" (see Table S3). Moreover, annual changes of the mean wind direction (Θ_w) towards more westerly directions (+5.2° to +7.5° for 2021–2050, and +5.4° to +16.7° for 2071–2100) can exemplarily result in changes of the mean wave period (T_{m02}) towards higher values (2021–2050: +0.4% to +1.0%, 2071–2100: +0.9% to +1.6%), and also to changes of the mean wave direction (Θ_m) towards more northwestern directions (2071–2100: −7.4° to −3.0°) for RCP8.5 near "Rostock-Warnemünde" (see Table S3).

A possible consequence of the annual changes of the mean wave directions towards more NW directions could be an intensification of the wave induced long-shore sediment transport, at westerly wind-exposed locations due to a more favorable wave direction for sediment losses.

No agreement on the future changes have been found for the forcing scenario RCP4.5, which is mainly due to the fact that the ensemble contains only two realizations of the same global forcing model (multi-member ensemble). This results in too few simulations for the assessment of model agreement and statistical significance. Nevertheless, the results for RCP4.5 (see Figure S3 and Table S4, respectively) show a high internal variability of both wind and wave conditions that is induced by different initial starting periods of the climate simulations.

3.2. Future Changes of Extreme Wave Heights

The future changes of extreme wave heights were analyzed on the basis of the transient long-term time series of significant wave height, which have been calculated with the help of the hybrid approach. As an input parameter, the transient time series of wind conditions from REMO, covering a total period from 1948 to 2100, were used. The following steps of the extreme value analysis have been conducted:

- Selection of samples (annual maximum significant wave heights) for time periods of 40 years;
- Fitting of the log-normal distribution as best-fitted extreme value distribution function (based on findings from previous studies [13]) to the data;
- Calculation of extreme wave heights based on the log-normal distribution and with a return period of 200 years and a moving period of 40 years within the total time period from 2006 to 2100;
- Calculation of the relative changes of the extreme wave heights between the future time periods to values of the 40-years reference period 1961–2000.

Time periods of 40 years have been selected to increase the sample size which results in a better estimation of the extreme wave heights. A lower sample size (e.g., 30 years) would result in a higher uncertainty of the estimation [30].

Exemplarily results for the future changes of the extreme wave heights near "Rostock-Warnemünde" and the forcing scenario RCP8.5 are shown in Figure 3. The results near "Lübeck-Travemünde" are shown in Figure S6 and the range of the future changes at both locations is summarized in Table 4.

Table 4. Range of future changes of extreme wave heights near the selected locations and for different forcing scenarios and time periods of 40 years between 2006–2100 compared to the reference period 1961–2000.

Location/Scenario	RCP8.5	RCP4.5	RCP2.6
"Rostock-Warnemünde"	+3% to −7.5%	+0.3% to −9.7%	+6.2% to −8.8%
"Lübeck-Travemünde"	+4.9% to −7.1%	+4% to −7.1%	+4.5% to −6.8%

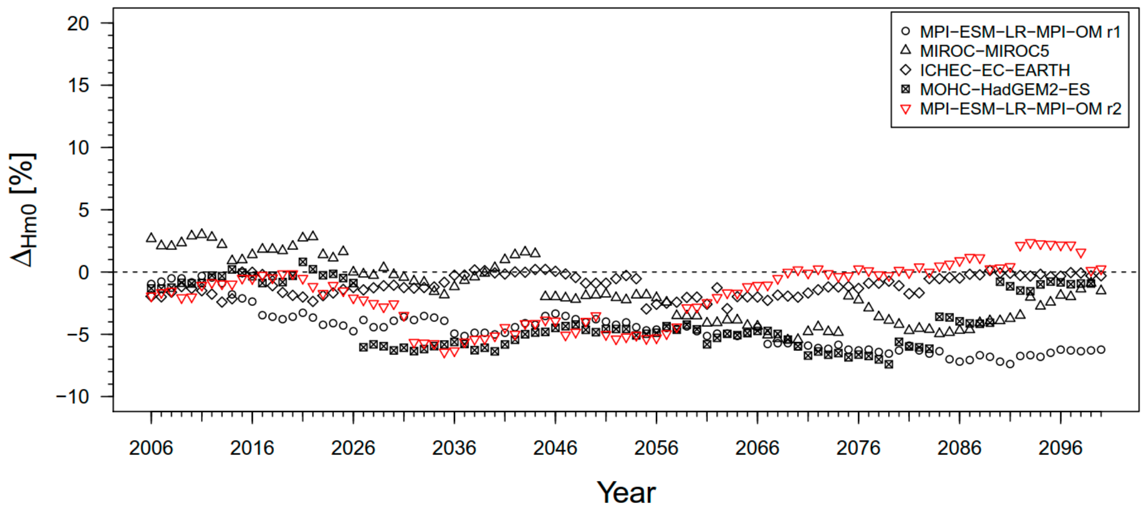

Figure 3. 40-year running mean of the future relative changes of the significant wave height (ΔH_{m0}) for the log-normal distribution function and a return period of 200 years compared to the reference period 1961–2000 for the ensemble members of the forcing scenario RCP8.5 (see Table 1) near "Rostock-Warnemünde".

In general, no agreement has been found regarding the future changes of the extreme wave heights near the selected locations.

At westerly wind-exposed locations, e.g., near "Rostock-Warnemünde", mainly decreasing trends or no trends of the future extreme wave heights are noted for all forcing scenarios RCP2.6, RCP4.5 and RCP8.5 (see Figure 3). Only a few ensemble members indicate an increasing trend for RCP2.6 or RCP8.5.

By contrast, at easterly wind-exposed locations, the results diverge more in general depending on, e.g., the forcing scenario. For RCP8.5 an increasing or no trend is more likely than a decreasing trend (see Figure S7) while for RCP4.5 and RCP2.6 decreasing values or no changes of the future extreme wave heights dominate over the 21st century.

The advancement with respect to the state-of-the-art is the fact that the analysis of the future changes of the extreme wave events is sensitive to the spatial averaging approach, so that either a selection of the regional climate model data at single points or the application of a spatial averaging approach that does take into account the land fraction characteristics of the grid boxes of the model grid, is necessary.

4. Discussion

4.1. Model Agreement, Statistical Significance and Ranges of the Results

The model agreement and statistical significance of climate change projections can be assessed differently, e.g., [21,37–39], and hence can be controversial.

The future changes of exemplarily the mean wind speed and direction from ensemble experiments can have large ranges in magnitude and can differ in the direction of the climate changes signals. This can be exemplarily seen in Figure 2 for the mean wind speed, where no trend or slight increasing trend was found. Therefore in this study, a combination of (i) model agreement for a majority of the simulations (as used, e.g., in [38,40]), (ii) signal-to-noise ratio on the basis of parametric significance tests (z-test) of the future changes of the average wind and wave conditions is used to filter the sub-ensemble before analyzing the bandwidth or spread of the future changes.

For the assessment of the model agreement of the simulations, both magnitude and direction of the changes are taken into account through thresholds for the changes of the 30-year averages of selected wind and wave variables (see Table S2). The thresholds have been chosen from experiences and with respect to the wind–wave correlations used within the hybrid approach, e.g., the relations between (i) the mean wind speed and significant wave height, (ii) the significant wave height and mean wave period and (iii) the mean wind and wave direction.

Moreover, the assessment of the model agreement of the results depends on the total number of ensemble member for each forcing scenario. For RCP4.5 only two ensemble members exist, and hence the assessment of the model agreement is more restricted than in comparison for RCP2.6 with in total seven ensemble members.

Moreover, it is worth mentioning that the analysis of the changes of the 30-year seasonal averages of the mean wind or wave direction can lead to a false interpretation of the ranges (see values in grey color in Tables S3–S8). The frequency of occurrence of the mean wind or wave direction, particular in spring (MAM) or autumn (SON), can have two instead of one main direction. Therefore, the changes of the mean wind or wave direction are analyzed and assessed based on the changes of the frequency of occurrence of the mean wind and wave direction, respectively, and not based on the changes of average values.

Finally, the assessment of the signal-to-noise ratio depends on the characteristics of the chosen significance test, which can be parametric or non-parametrical hypothesis tests, also depending on the significance level and the number of ensemble members in selected classes of the frequency of occurrence which indicate a change in the same direction (see condition ii in Section 2.3).

4.2. Uncertainty and Variability of the Results

The model uncertainty induced by different RCMs is not represented by the selected multi-model ensemble used within in this study. However, some studies on the changes of future wind variables, e.g., [9,41], indicate, that the forcing GCM dominates the climate change signal of the wind conditions.

On one hand, the internal variability may be underestimated due to the small size of the multi-member ensemble which incorporates two realizations of each forcing scenario for one GCM-RCM combination only (see Section 2.1). On the other hand, the multi-model and multi-member ensemble based on different GCMs covers such variability to a certain extent. For example, the authors of [42] show that on short time scales (near future) the internal variability is a major contributor to the total uncertainty and that on longer time scales (end of the 21st century) the scenario uncertainty becomes more dominant than internal variability.

Nevertheless, due to the selection of the sub-ensemble from the total ensemble of EURO-CORDEX simulations it does not reflect the total uncertainty associated with future climate change projections.

4.3. Comparison of the Results

As mentioned before, all results and conclusions shown in this paper are only valid for the selected sub-ensemble of the EURO-CORDEX simulations.

Nevertheless, the results of this study can exemplarily be compared with the results from non-stationary numerical wave simulations on the basis of wind data from a coupled regional climate and ocean model REMO/MPI-OM forced with the coupled GCM MPI-ESM-LR/MPI-OM [11]. The data are available at 0.44° horizontal resolution (~50 km) and at 3 hourly time steps for the forcing scenarios RCP4.5 and RCP8.5. The results of the two different approaches agree in the general trend/direction of the changes of the 30-year annual/seasonal averages (model agreement), but differ slightly in the magnitude of the changes. In contrast, changes of extreme wave conditions have not been assessed for REMO/MPI-OM due to the coarse temporal resolution (3 h). For instance, the authors of [31] analyzed the effect of the temporal resolution of wave data on the results of extreme value statistical methods and found that wave data with a temporal resolution of approximately 4 h is not suitable for the calculation of extreme wave events. Therefore, we concluded that a time resolution of less than 3 h should be chosen for the assessment of extreme wave conditions within the Baltic Sea area.

In addition, the direction of the changes of the average wind and wave conditions differs with respect to the exposure of the coast towards the prevailing westerly winds, which is in agreement with other studies on future changes of the average wind and wave conditions ([11,14,15,43,44]).

On the basis of a sensitivity analysis on the preprocessing of the wind input data (see Section 2.1), it was found that the spatial aggregation technique does not affect the future changes of the average wind and wave conditions (e.g., changes of the 30-year annual/seasonal averages), but strongly effects the changes of the extreme wave conditions due to the spatial averaging of the wind input data which results in lower wind speeds and hence lower maximum significant wave heights.

From previous studies based on the hybrid approach, e.g., [13], it was found that the future changes of the extreme wave conditions can contain large model uncertainties and depend on the approach of the extreme value statistics (e.g., sample selection method, fitting of extreme value distribution function, quality of the fitting, etc.). Hence, a systematic analysis and assessment of possible future changes of extreme wave heights is needed within future research.

5. Conclusions

The main goal of this study was the assessment of the future changes of the wave conditions at the German Baltic Sea Coast, based on a multi-model- and multi-member ensemble of climate projections of the RCM REMO. A special focus has been on the assessment of the model agreement, statistical significance and possible ranges of the changes. The effect of sea-level rise was excluded in this study, but this would not significantly change the results for waves, as the simulations are based on deep water conditions.

Changes of the future average wind and wave conditions have been identified for two selected time periods (2050: 2021–2050, 2100: 2071–2100) in comparison to the reference period 1971–2000. Moreover, the changes are characterized by a strong temporal, e.g., intra-annual (seasonal), variability with a majority of the seasonal changes occurring in autumn (SON) and winter (DJF) and at the end of the 21st century. Westerly wind-exposed locations showed mainly increasing values of the wind speed, significant wave height and mean wave period have been noted. In contrast, at easterly wind-exposed locations, decreasing values are predominant. Regarding the changes of the mean wind and wave directions, westerly directions becoming more frequent.

Almost no agreement on the changes has been identified for the forcing scenario RCP4.5 due to the fact that the ensemble contains only two realizations of the same global forcing model (multi-member ensemble) which means there are not enough simulations for the assessment of model agreement and statistical significance.

A second aim of this study was the assessment of the ranges/spread of the future changes of wind and wave parameter based on the selected ensemble of regional climate simulations. Beside the model agreement and statistical significance of the changes, the spatial, seasonal and temporal variability of the changes has to be taken into account. In general, the ranges/spread depend on (i) the wind or wave variable (larger ranges for the changes of the mean wind (and eventually wave) direction, lower ranges for the changes of the mean wind speed, significant wave height and mean wave period), (ii) the forcing scenario (larger ranges for RCP8.5 than RCP2.6), (iii) the exposure of the coast (larger ranges at easterly wind-exposed locations than for westerly wind-exposed locations) and (iv) the future time period (larger ranges at the end of the 21st century than for the mid-21st century).

No overall agreement on the future long-term changes of extreme wave conditions has been found. The changes of the future extreme wave heights are within the range of +6.2% to −9.7%.

Even though some results may be assessed as non-significant changes or do not fulfill the model agreement, they can still have significant consequences for the impact modelling of wave induced coastal processes like, e.g., the local long-shore sediment transport, and hence may be important for the assessment of future coastal protection and adaptation strategies and methods, respectively.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4441/13/2/167/s1, Figure S1: Grid points of the subdomain of the REMO model output . . . , Table S1: Mean absolute errors (MAE) . . . , Figure S2: 30-year running mean of the future relative/absolute changes Δ (%)/Δ (°) for RCP2.6 . . . , Figure S3: 30-year running mean of the future relative/absolute changes Δ (%)/Δ (°) for RCP4.5 . . . , Table S2: Absolute minimum and maximum thresholds for relative respectively absolute changes . . . , Figure S4: Differences of the annual frequency of occurrence (Δ_p) of the significant wave height (H_{m0}) . . . , Figure S5: Differences of the annual frequency of occurrence (Δ_p) of the mean wave direction (Θ_m) . . . , Figure S6: Differences of the annual frequency of occurrence (Δ_p) of the mean wave period (T_{m02}) . . . , Figure S7: Future relative changes (in percent) of the significant wave height (ΔH_{m0}) . . . , Table S3: Bandwidth (minimum/maximum) and direction of the relative changes for RCP8.5 . . . , Table S4: Bandwidth (minimum/maximum) and direction of the relative changes for RCP4.5 . . . , Table S5: Bandwidth (minimum/maximum) and direction of the relative changes for RCP2.6 . . . , Table S6: 30-year annual (column "AVG") and seasonal averages for RCP8.5 . . . , Table S7: 30-year annual (column "AVG") and seasonal averages for RCP4.5 . . . , Table S8: 30-year annual (column "AVG") and seasonal averages for RCP2.6 . . . .

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Abbreviations

CMIP5	Coupled Model Intercomparison Project phase 5
DJF	three month season winter, December-January-February
DWD	German Weather Service (Deutscher Wetterdienst)
EURO-CORDEX	EUROpean branch of the Coordinated Regional Downscaling Experiment
GCM	Global Climate Model
JJA	three month season summer, June-July-August
MAM	three month season spring, March-April-May
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SON	three month season autumn, September-October-November
SWAN	Simulating WAves Nearshore

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