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On the Long-term Changes of Extreme Wave Heights at the German Baltic Sea Coast

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ABSTRACT

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The assessment of extreme wave heights is of great importance for the design of coastal protection strucutres. This paper aims to present long-term changes of extreme wave heights at several selected locations at the German Baltic Sea Coast. Annual maximum significant wave heights were selected from the hourly wave data obtained from a hybrid approach (wind-wave-correlations combined with numerical simulations on the basis of the SWAN model) for a total period of 140 years, spanning from 1961 to 2100. The future projections of wind data were dreived from the regional COSMO-Climate Local Model for two emission scenarios A1B and B1. The extreme wave heights at each location were estimated from the respective best-fitting distribution, log-normal or Weibull distribution. The results indicate that, the long-term changes of extreme wave heights are related to the emission scenarios used in the regional climate model, the distribution chosen for the estimating (up to +9.6%) and also the sample size for the extreme value analysis (up to +8.7%). These factors should be carefully considered in the future coastal structure design.

ADDITIONAL INDEX WORDS: *Baltic Sea, extreme wave heights, extreme value distribution, Cosmo-CLM, SWAN*

INTRODUCTION

Coastal areas are the densely populated and highly industrialised parts of the world. The human activities there suffer from the coastal disasters caused by the local storms or wind waves. The coastal protection structures, such as groins, beach nourishments, breakwaters, are extensively used in these areas to eliminate those adverse effects. The design of these structures is dependent on the local wave conditions, especially the extreme wave conditions, which could be estimated by using the concept of return periods. Most of the existing coastal protection structures were designed based on the dataset of wave conditions in the past. Observed by IPCC (2007), climate change leads to significant changes of sea levels and wind events. These changes should be considered when determining the extreme wave conditions in the future design of coastal protection structures.

Recently, the future projection of the regional wave climate has become an interesting topic. It could be realised by applying spectral wave models, such as SWAN (Booij *et al.*, 1999) and WAM (The Wamdi Group, 1988). These models were driven by wind data obtained from regional climate models (RCMs). The boundary conditions of the RCMs were derived from the general circulation models (GCMs). Examples are given in the works of Grabemann and Weisse (2008), Casas-Prat and Sierra (2013), Groll *et al.* (2013). Examples of frequently used RCMs are the models Cosmo-CLM, HIRHAM5, RACMO2, and RCA3. The projection uncertainties are caused on the one hand side by different models and different scenarios of future climate change, which should be taken into account in the climate impact research (*e.g.*, Wang and Swail, 2006). On the other hand, the determination of extreme wave heights also relies on the distribution used and the time period for the selection of the samples.

This paper aims to present the long-term changes of extreme wave heights at selected locations along the German Baltic Sea Coast. Studies on the projections of the wave climate in the Baltic Sea have been conducted by different researchers, see BACC Author Team (2008, 2015). While most of the studies were focusing on the general changes in the region of Baltic Sea, we are focusing on several selected locations along the German Baltic Sea Coast in this study. Hourly wave data were obtained using the hybrid approach (wind-wave-correlations combined with the SWAN model simulations). The future projections of wind data were derived from the regional COSMO-Climate Local Model for two emission scenarios A1B and B1 from the IPCC Special Report. The extreme wave

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heights were estimated by fitting annual maxima values of significant wave heights of 30 and 40 years to the Gumbel, Weibull and log-normal distribution. The confidence intervals were estimated by the Monte Carlo method. The results could be used to provide guidance in future coastal structure design.

METHODS

A hybrid approach was developed to calculate the wave data with the help of wind-wave-correlations and SWAN model simulations (Dreier *et al.*, 2013). On the basis of available synchronized local field data for wind and waves, the wind-wave-correlations have been derived for different locations at the German Baltic Sea Coast. The study area and the selected locations are shown in Figure 1. If the wind data used for the calculation of the past and future wave conditions exceeded the maximum wind velocities used for the derivation of the wind-wave-correlations, the wave heights were calculated with the help of stationary numerical simulations using SWAN. 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.

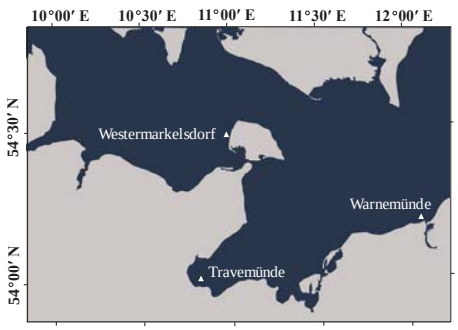

Figure 1. Study area and selected locations.

Table 1. *Cosmo-CLM runs. (Dreier et al., 2013)*

20th century (1961-2000) observed anthropogenic forcing	21st century (2001-2100) forced by emission scenario A1B	21st century (2001-2100) forced by emission scenario B1	transient time (1961-2100) series of wind parameter
C20_1	A1B	/	C20_1-A1B
C20_1	/	B1	C20_1-B1
C20_2	A1B	/	C20_2-A1B
C20_2	/	B1	C20_2-B1

The hourly wind data used in the hybrid approach were derived from the regional climate model Cosmo-CLM (Rockel *et al.*, 2008). The model Cosmo-CLM was forced by the global atmosphere-/ocean-ice-model ECHAM5/ MPI-OM. As shown in Table 1, two independent runs were available for the climate of 20th century (C20_1 and C20_2). For the future climate modelling both the two climate model runs for the 20th century were continued and forced by the SRES scenarios A1B (global economic) and B1 (global environmental), resulting in 4 independent runs, covering a period from 1961 to 2100. Figure 2 shows the comparisons of calculated and observed wave heights near Warnemünde. The calculated wave heights agree well with the observed data. More details of the model description and validation were given by Dreier *et al.* (2013).

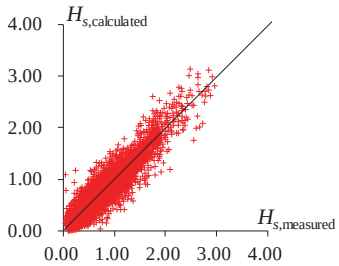

Figure 2. Comparisons of calculated and observed wave heights near Warnemünde.

From the time series of significant wave heights for each simulation run, the maximum wave height for each year was taken at the three locations shown in Figure 1. The annual maxima at each location in every 30/40-consecutive-year were fitted to three selected distributions, namely the Gumbel, Weibull and log-normal distribution. The cumulative distribution function (CDF) of Gumbel distribution is as follows,

$$F(x) = P(x < X) = \exp\{\exp[-(x-\alpha)/\beta]\} \quad (1)$$

where X is the random variable of the annual maxima, x is a possible value of X, α and β are location and scale parameters, respectively. The CDF of Weibull distribution is described as,

$$F(x) = P(x < X) = 1 - \exp\left[-(x/\beta)^{\alpha}\right] \quad (2)$$

where α and β are called the shape and scale parameters, respectively. The CDF of normal distribution is obtained by numerical integration of the probability density function (PDF). The PDF of normal distribution is described as,

$$f(y) = \frac{1}{\sigma(2\pi)^{0.5}} \exp\left[-(y-\mu)^2/(2\sigma^2)\right] \quad (3)$$

where μ and σ are the mean and standard deviation, respectively. If Y follows the normal distribution, and Y=ln(X) (X>0), X will follow the log-normal distribution. Then the PDF of the log-normal distribution can be derived. The parameters in the above theoretical CDFs or PDFs can be estimated using the maximum likelihood method. The empirical CDF was estimated as,

$$F_n(x_i) = \frac{i}{n+1} \quad (4)$$

where i= 1, 2, . . . , n denotes the rank of the annual maxima $x(i)$ in ascending order and n=30 or 40 in this study. The difference between the theoretical and empirical CDFs was represented by the absolute value of the average difference (D),

$$D = \frac{1}{n}\sum_{i=1}^{n}\left|F_n(x_i) - F(x_i)\right| \quad (5)$$

By comparing the D values regarding to different types of CDFs, the best-fitting CDF was determined. With the help of these theoretical CDFs, the return periods of extreme wave heights can be calculated. The relative changes of the extreme wave heights at the year m, which are calculated by using the data of the former 40 consecutive years, are defined as,

$$\Delta H_{s,m} = \frac{H_{s,l\sim m} - H_{s,1961\sim 2000}}{H_{s,1961\sim 2000}} \times 100\% \quad (6)$$

where m=2001,2002,…,2100 and l=1962, 1963,…,2061.

The confidence intervals of return periods were estimated by the Monte Carlo method, instead of the bootstrap resampling method. The Monte Carlo method is used to simulate the random process by a computer random number generator (see Chu, 1995). Based on the known theoretical CDF, 1000 batches of the simulated significant wave heights were generated by this method. Each batch contains 1000 significant wave heights, which means 1000 return periods calculated by the empirical CDF. There are 1000 significant wave heights with the same return periods for the 1000 batches. The confidence intervals can be estimated by sorting the above 1000 significant wave heights.

RESULTS

The performance of each theoretical CDF is examined by comparing with the corresponding empirical CDF, which is obtained by using the annual maxima data in every 40 consecutive years. The D values of each simulation run at three locations are shown in Figure 3 for the location Westermarkelsdorf and Figure 4 for the location Travemünde. Near the location of Westermarkelsdorf, the log-normal distribution is the best for the overall goodness of fit because the discrepancy is smallest, the same for the location Warnemünde. Near the location of Travemünde, the D values of log-normal and Weibull distributions are in the same level for the simulation runs C20_1-A1B and C20_1-B1, while the Weibull distribution fits better with the empirical CDF for the simulation runs C20_2-A1B and C20_2-B1. The Weibull distribution is chosen for the analysis of extreme wave heights near Travemünde.

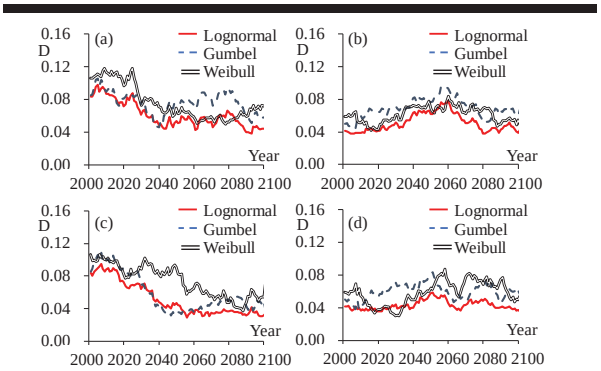

Figure 3. D values between theoretical and empirical CDFs of each simulation run near Westermarkelsdorf, (a) C20_1-A1B, (b) C20_1-B1, (c) C20_2-A1B, (d) C20_2-B1.

Figure 5 shows the relative changes of the extreme wave heights near Westermarkelsdorf, which are represented by the significant wave heights with a return period of 200 years obtained from the log-normal distribution. An increasing trend of relative changes is found for the simulation runs C20_2-A1B and C20_2-B1, while a decreasing trend is found for the other two runs. It should be also noted that, the magnitudes of the changes derived from log-normal distribution are depending on the sample size. Based on the analysis of the data in 30 consecutive years, the amplitude of changes for the simulation run C20_2-B1 is +19%, which is about twice of that obtained from the analysis of the data in 40 consecutive years. Similar results is found for the simulation run C20_2-A1B, while the differences between the results are slightly small for the simulation runs C20_1-A1B and C20_1-B1, around -8% and -16% respectively.

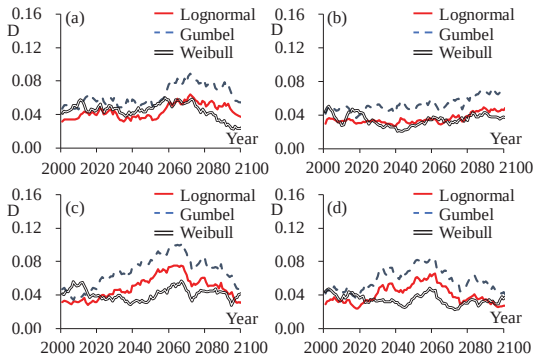

Figure 4. D values between theoretical and empirical CDFs of each simulation run near Travemünde, (a) C20_1-A1B, (b) C20_1-B1, (c) C20_2-A1B, (d) C20_2-B1.

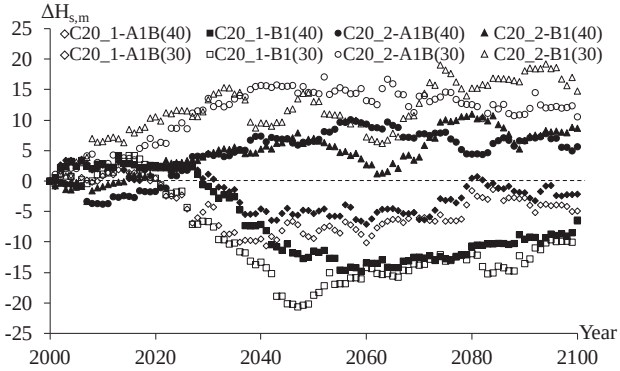

Figure 5. Changes of extreme wave heights near Westermarkelsdorf.

The relative changes of the extreme wave heights near Travemünde are shown in Figure 6. The results derived from the Weibull distribution for the sample size of 30 *resp.* 40 consequtive years are close to each other. The maximum difference is below ±3%. The changes of the extreme wave heights are around ±2.5% before the year 2030. After that, the changes could reach up to +10% or -6.5%, depending on different simulation runs. Figure 7 shows the relative changes of the extreme wave heights near Warnemünde. The results of log-normal distribution based on the analysis of the data in 40 consecutive years are not drawn here for the readability. From the beginning of the year 2040, the change of the extreme wave heights near Warnemünde shows in general a slight increasing trend with a maximum increase of up to +8%, except for the run C20_2-A1B which shows a maximum decrease of down to -7%.

Finally, the 95% confidence intervals of the 200 year return period for the extreme wave heights in all simulation runs at

three locations are illustrated in Figure 8. The absolute changes of the extreme wave heights for each simulation run and each location can be clearly seen in Figure 8. For example, the maximum extreme significant wave heights among the four simulation runs near the location of Warnemünde are 5.17m, 5.2m, 5.34m for the scenarios of 2000, 2050 and 2100, respectively. The extreme wave heights will not exceed 3m for all the scenarios of 2000, 2050 and 2100 near Travemünde. It is also found that the confidence intervals are quite broad, roughly 20% of the corresponding extreme wave heights.

DISCUSSION

As shown in Figure 5~7, the changes of the extreme wave heights at each location vary with different simulation runs. These differences may be attributed to the uncertainties in future social and economic development, which are represented by the different emission scenarios in this study. We are not able to state which scenario is more realistic in the near future. Each scenario should be considered equally in the analysis. Thus, the idea of ensemble projection could be applied in the estimation of the changes of the extreme wave heights along the German Baltic Sea Coast. Many studies (Donat *et al.*, 2010) suggest that an ensemble mean is better than a single model. For example, Grabemann and Weisse (2008) have conducted an ensemble study on the extreme wave conditions in the North Sea influenced by climate change. In our study, only two emission scenarios of one RCM were used for the simulation of the future wind conditions. In the next step, more samples of scenarios and models would be considered for deriving a robust conclusion.

Apart from the above uncertainties, some other aspects should also be considered with caution in the analysis of the future extreme wave heights. One is that the selection of the extreme value distribution, which might be a problem at certain locations. For example, the log-normal and Weibull distributions perform quite close with each other in the simulation runs C20_1-A1B and C20_1-B1 near the location of Travemünde. But, the extreme wave heights obtained from the log-normal distribution are 2.72m, 2.85m, 2.91m and from the Weibull distribution of 40 years 2.56m, 2.60m, 2.74m for the scenarios of 2000, 2050, 2100 respectively, for the simulation run C20_1-B1. The differences are ranging between +6.2% and +9.6%, which are quite large and will have a significant effect in the design of the coastal protection structures. The performances of different distributions are recommended to be compared comprehensively by use of more judging indexes.

The results of the extreme wave heights, which were obtained from the analysis of two sample sizes (30 and 40 years), are presented in this study. The difference between

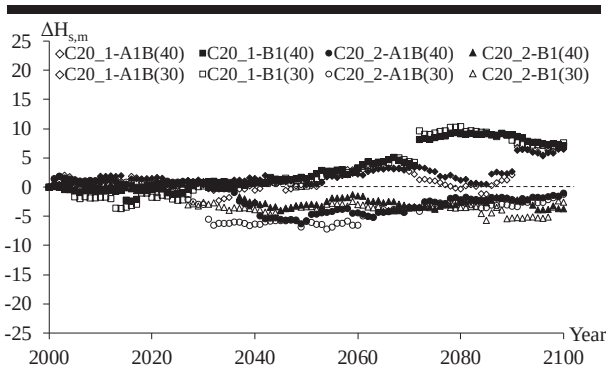

Figure 6. Changes of extreme wave heights near Travemünde.

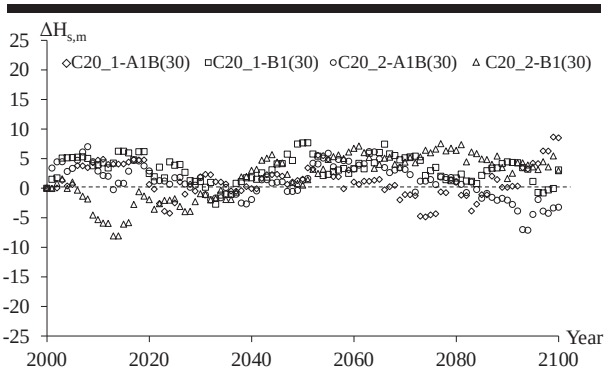

Figure 7. Changes of extreme wave heights near Warnemünde.

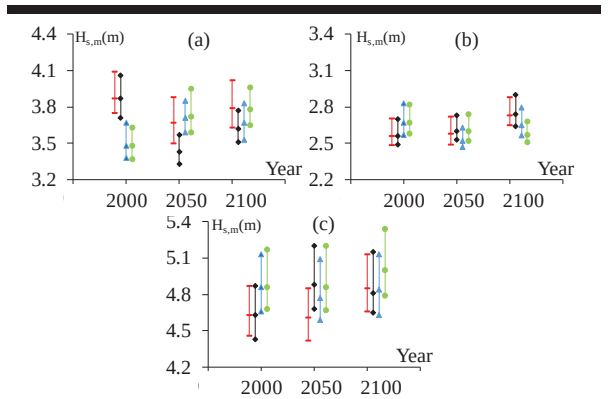

Figure 8. 95% confidence intervals of the 200 year return period for the extreme wave heights in all simulation runs (C20_1-A1B, Red‐ C20_1-B1, Black⋄ C20_2-A1B, Blue▵ C20_2-B1, Green&dot) near the locations (a) Westermarkelsdorf, (b) Travemünde, (c) Warnemünde.

them are quite obvious for some locations. As an example, the relative differences of extreme wave heights for the simulation run C20_1-B1 near the location of Westermarkelsdorf are shown in Figure 9. The maximum difference is +8.7%. The World Meteorological Organization (WMO) recommends in general a time period of 30 years for the assessment of climate

change and climate change inducted processes. In this study the sample size for the extreme value analysis was extended up to 40 years to get a larger sample size which gives better estimations of extreme wave heights due to the fitting of the extrem value function to the samples. In contrast a lower sample size (30 years) will lead to a higher uncertainty in the estimation of extreme wave heights, which is also reflected in larger confidence intervals for the 30 years sample size.

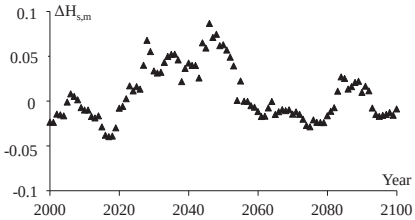

Figure 9. Relative differences of the extreme wave heights calculated for two sample sizes (30 and 40years) for the simulation run C20_1-B1 near the location of Westermarkelsdorf.

CONCLUSIONS

In this study the long-term changes of extreme wave heights were analysed at several selected locations of the German Baltic Sea Coast. Hourly wave data spanning from 1961 to 2100, were obtained using a hybrid approach. The future projections of wind data were derived from the regional COSMO-Climate Local Model for two emission scenarios A1B and B1. The log-normal distribution was assessed to be best fitted to the samples near the locations of Westermarkelsdorf and Warnemünde. In contrast near the location of Travemünde the Weibull distribution leads to the least differences in the goodness-of-fit test. Based on the analysis of the data in 30 consecutive years, an increasing up to 19% and a decreasing down to -20% were examined near the location of Westermarkelsdorf. The relative changes could reach up to 10% for increasing or -6.5% for decreasing, depending on different simulation runs for the location Travemünde. From the beginning of the year 2040, the change of the extreme wave heights near Warnemünde shows in general a slight increasing trend with a maximum increase of up to +8%, except for the simulation run C20_2-A1B which shows a maximum decrease of down to -7%. The relative differences of extreme significant wave heights obtained from the analysis of two series of data with different length (30 and 40 years) can reach up to 8.7% for the location Westermarkelsdorf.

ACKNOWLEDGMENTS

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