LONG-TERM CHANGES AND POTENTIAL FUTURE DEVELOPMENTS OF THE NORTH SEA WAVE CLIMATE

Ralf Weisse and Marek Stawarz

GKSS Research Center
Institute for Coastal Research
Geesthacht, Germany

1. INTRODUCTION

Long-term changes in the prevailing wind and wave conditions may have profound impact for the planning of coastal protection or the safety of navigation and offshore operations at sea, among others. Reliable and homogeneous long-term observations from which these changes can be analyzed are often not available. The similar holds for scenarios of potential future developments that provide the information on a scale required by the decision makers and that take existing uncertainties and natural variability into account.

In the following we present an example on how such information may be inferred in the case of limited observational material. The example is presented for the case of the North Sea and is based on the combination of a high-resolution met.-ocean hindcast for the past 45 years and scenarios of potential future developments.

2. THE HIPOCAS HINDCAST AND SCENARIOS FOR 2071-2100

Within the recently completed European project HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe, Soares et al. 2002) a high-resolution met.-ocean hindcast for the Eastern North Atlantic and the North Sea covering the period 1958-2002 has been performed (Weisse et al. 2003). The hindcast consists of a regional atmosphere model simulation driven by the NCEP re-analyses (Kalnay et al. 1996; Kistler et al. 2001) at a resolution of about 50 x 50 km (Feser et al. 2001), a barotropic ocean model simulation with a resolution of about 5 km in the open waters increasing up to about 80 m near the coast, and a nested wave model simulation with about 50 km resolution in the Atlantic and about 5 km in the Southern North Sea (Weisse et al. 2003). Data from this hindcast are available every hour for the period 1958-2002, providing the basis for an as much as possible homogeneous and consistent picture of recent long-term changes in the prevailing wind, wave and storm surge conditions.

Data from this hindcast have been validated extensively with existing observations. Weisse et al. (2004) discussed long-term changes in storminess and showed that storm statistics are reasonably reproduced within this hindcast. Weisse and Feser (2003) demonstrated that the skill of regional atmospheric hindcasts improved considerably when even relatively simple assimilation techniques have been applied. The latter was, because of the lack of additional data and computational constraints, the case for the HIPOCAS hindcast. In addition, García-Sotillo (2003) demonstrated that compared to the driving large-scale re-analyses a considerable improvement in the representation of extreme wind events could be inferred. Table 1 shows as an example a comparison between observed and hindcast return values for near-surface wind speed and significant wave height for three stations in the Southern North Sea. For wind speed modeled and observed extreme values compare reasonably within error bounds. For two stations the same holds also for the significant wave height while for the third station, characterized by relatively complicated bathymetry, near-by coast line and shallow water depth some overestimation of the most severe extreme events could be inferred. Statistics of extreme storm surge events and residual currents compare well with the limited amount of observations available (Pluess, Callies pers. comm.).

A similar model set-up has been used to produce consistent scenarios of future met.-ocean conditions. In this case the regional atmosphere model was driven by climate change scenarios obtained from the HadAM3 model (Rockel, pers. comm.). The model was run for both, present day (1961-1990) and future (2071-2100) climate conditions. Woth (pers. comm.) used the wind fields derived from these simulations to drive a storm surge model for the North Sea. In addition she repeated the procedure with different wind fields obtained from several different regional atmosphere models under the same greenhouse gas forcing (i.e., these models use identical boundary conditions from the global HadAM3 model) and with wind fields directly from different global models. This way she was able to quantify the common response and the uncertainty due to the use of different stat-of-the-art atmosphere models.

		Wind [m/s]						Waves [m]					
		Hipocas			*Observed*			*Hipocas*			*Observed*		
	Years	x_r^{90}	x_r	x_r^{90}	x_r^{90}	x_r	x_r^{90}	x_r^{90}	x_r	x_r^{90}	x_r^{90}	x_r	x_r^{90}
K13	**2**	24.38	**25.17**	25.96	24.05	**25.21**	26.37	7.12	**7.49**	7.86	6.41	**6.77**	7.13
	5	25.86	**27.28**	28.70	25.75	**27.64**	29.53	7.84	**8.44**	9.04	6.93	**7.54**	8.15
	25	28.44	**31.33**	34.22	28.09	**32.77**	37.45	8.99	**10.35**	11.71	7.52	**9.21**	10.90
EUR	**2**	22.50	**23.16**	23.82	23.16	**24.03**	24.90	5.89	**6.15**	6.41	5.52	**5.84**	6.16
	5	23.76	**24.82**	25.88	24.33	**25.94**	27.55	6.34	**6.83**	7.32	5.89	**6.46**	7.03
	25	25.67	**28.00**	30.33	26.43	**29.75**	33.07	6.90	**8.20**	9.50	5.99	**7.88**	9.77
SON	**2**	23.29	**24.15**	25.01	23.11	**24.03**	24.95	6.78	**7.06**	7.34	5.60	**5.84**	6.08
	5	24.89	**26.32**	27.75	24.15	**25.94**	27.73	7.37	**7.79**	8.21	5.97	**6.46**	6.95
	25	26.68	**30.70**	34.72	26.42	**29.75**	33.08	8.04	**9.03**	10.02	6.34	**7.88**	9.42

Table 1: 2, 5, and 25 year return values of near-surface wind speed and significant wave height for three stations in the Southern North Sea (K13, EUR, SON) as derived from the HIPOCAS hindcast and from direct observations. The return values are shown in bold face together with the 90%-confidence interval as obtained from 10,000 Monte-Carlo simulations each.

We have applied a similar procedure for obtaining future wave scenarios. In the following, preliminary results will be presented. We start with a discussion of recent long-term changes in wind and wave conditions as obtained from the HIPOCAS hindcast followed by a scenario for a potential future development and the uncertainties related with it. So far, only one wave scenario has been completed. The assessment of related uncertainties therefore relies on the conclusions obtained by Woth (pers. comm.) for their storm surge simulations and recent findings from the literature.

3. OBSERVED LONG-TERM CHANGES 1958-2002

We analyzed long-term changes in extreme wave events from both, the HIPOCAS hindcast and the future wave scenarios. We considered an event as extreme event whenever it exceeded the threshold given by the local long-term annual 99 percentile. In order to distinguish whether any analyzed changes are caused by an increase or decrease of the frequency, intensity or the duration of the extreme events, we first counted the annual number of these events and subsequently computed their average duration and intensity (maximum of the event minus the threshold value). As an example Figure 1 shows the linear trend 1958-2002 for the annual 99-percentile of significant wave height in the Southern North Sea computed locally for each grid point. It can be inferred that near the German and Netherlands coast extreme wave heights have indeed increased over the past 45 years. In the German Bight the 99-percentile increased by up to 1.8 cm per year corresponding to about 81 cm for the period 1958-2002. The analysis of the number, intensity and duration of extreme events reveals that this increase is primarily due to an increase in the frequency of extreme events. For most of the area the annual number of extreme events increased by about 0.1-0.15 events per year, corresponding to an increase of about 4-6 events per year when the earlier and the later years of the simulation are compared (Figure 1). For the average intensity and duration of these events no significant changes have been analyzed.

These results may have different consequences for coastal protection and offshore operations. While the intensity and the duration of extreme events are of greater relevance for coastal protection, an increase in fields obtained from two regional climate model simulation for present day (1961-1990) and future (2071-2100) climate conditions. South of about 55 N an increase of the most extreme wave heights of up to 0.75 m can be inferred while extreme wave heights are generally decreasing north of about 55 N. Generally, this would be consistent with a north-south shift of the North Atlantic stormtrack. Analysis of near-surface

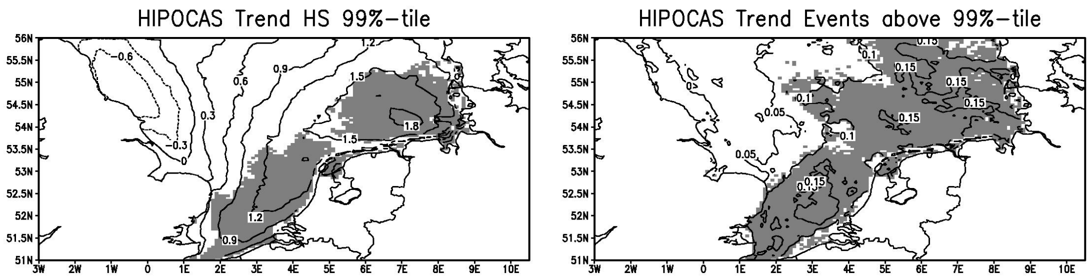

Figure 1: Linear Trend 1958-2002 of the intra-annual 99-percentile of total significant wave height (left) in cm/year and linear trend 1958-2002 of the annual number of significant wave height events exceeding the threshold defined by the local 45-year 99-percentile (right) in events per year/year. Areas where the trends according to a Mann-Kendall test (Mann 1945) applied to the pre-whitened time series (Kulkarni and von Storch 1995) are significantly different from zero at the 95% confidence level are indicated in grey. Data are from the HIPOCAS hindcast (Weisse et al. 2003).

the frequency of extreme events may have implications for the safety of navigation at sea, design and/or weather downtime.

The analyzed long-term changes in significant wave height are closely related to large scale changes in the wind field. Analysis of hindcast Northeast and North Atlantic storminess reveals that the storm activity has increased from about 1960 onwards, reached maximum values around 1990-1995, and decreased afterward (Weisse et al. 2004). An exception is provided by the Southern North Sea where storm activity remained high after 1990, however, the rate of increase weakened considerably (Weisse et al. 2004). These results obtained from the HIPOCAS hindcast are in agreement with studies analyzing proxies for storm activity (e.g. Alexandersson et al. 2000; Schmidt 2001).

4. POTENTIAL FUTURE DEVELOPMENTS AND UNCERTAINTIES

Figure 2 shows the difference of average annual 99-percentiles of significant wave height between two wave model simulation driven by near-surface wind wind fields (Figure 2) and geopotential height suggest that this may indeed be the case for the climate change simulation. According to a local t-test most of the differences shown in Figure 2 are significantly different from zero at the 95% confidence level.

While the simulations provide a consistent picture of what might happen in the future, the questions remains on how much of this signal is shared between different simulations when wind fields from different climate models under similar greenhouse gas forcing are adopted. While such ensemble simulations are presently not available for ocean waves they do exist for the atmosphere (e.g. Rauthe et al. 2004) and have recently been completed also for storm surges in the North Sea (Woth, pers. comm.). The analysis of the latter reveals that although there is considerable variation among the different simulations, all simulations driven by different regional atmosphere models using identical boundary conditions share a common signal of raised surge levels in the German Bight that is significantly different from zero (Woth pers. comm.). Using the same near-surface wind fields we would expect a similar conclusion to hold also for the ocean wave scenarios.

When wind fields from different global models are applied the situation changes considerably. Based on the analysis of a different global climate model Knippertz et al. (2000) describe a northward displacement of the North Atlantic stormtrack. Rauthe et al. (2004) analyzed the extra-tropical circulation of different global climate models and found remarkable differences, in particular for the projection of the future development of the North Atlantic Oscillation, indicating the level of uncertainty associated with analysis of future wave and storm statistics in particular for the European Atlantic region.

Future scenarios suggest an increase of extreme wave heights south and a decrease north of about 55 N. Because of uncertainties associated with the response of the extra-tropical circulation in different climate models under similar greenhouse gas forcing the latter represents a plausible but not necessarily a likely future development. Nevertheless, these types of scenarios may represent helpful tools for decision making.

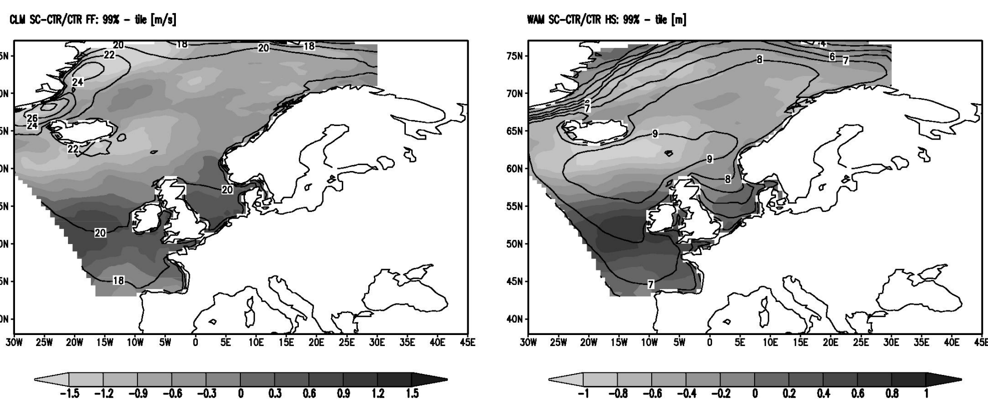

Figure 2: Differences (grey shading) of intra-annual 99-percentiles of near-surface wind speed (left in m/s) and significant wave height (right in m) between a future climate scenario (2071-2100) and a control simulation (1961-1990). The contour lines represent the 30-year averaged 99-percentile of the control simulation. The atmospheric simulations have been performed within the EU project PRUDENCE using the regional model CLM with boundary data from HadAM3 (Rockel pers. comm.). The wave simulations have been performed with the wave model WAM using CLM wind fields.

5. SUMMARY

Long-term changes in extreme wind and wave conditions as derived from a 45-year high resolution hindcast for the North Sea (Weisse et al. 2003) have been analyzed. For this area it was found that storm activity and extreme wave heights have increased from about 1960 onwards while the rate of increase was reduced since about 1990-1995. It was shown that the increase is basically caused by an increase in the frequency, rather than the intensity or the duration of the extreme events.

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