# STATISTICS OF WAVES IN THE ESTUARIES OF THE RIVERS EMS AND WESER - MEASUREMENT VS. NUMERICAL WAVE MODEL

**by**

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## ABSTRACT

The availability of long-term measurements of wave parameters is, in contrast to long-term measurements of water level and wind, often very poor. Therefore two indirect ways of deriving wave statistics from the statistics of water levels and wind are presented. Numerical modelling of wave propagation using SWAN is a central part of both methods. For two locations on the German North Sea coast both approaches are tested and compared with measurements of radar level gauges that are now becoming operational in Germany.

## 1. INTRODUCTION

The design of structures within the coastal zone requires information on the wave climate. Especially for the estimation of the serviceability of structures, like offshore wind farms, long-term wave statistics are essential. However, in contrast to measurements of water levels, long-term measurements of waves are only rarely available.

To fill this gap in the future the existing conventional water level gauges on the German coasts are being equipped with radar sensors to measure water level and waves (BLASI and BARJENBRUCH, 2007). However, in order to be able to provide estimates of the wave climate today, numerical wave modelling is carried out deriving the wave conditions from wind and water level data. Two approaches are used to derive wave statistics from wind data and water levels: on the one hand statistical analysis of results of long-term numerical simulation of waves based on long-term series of wind and water level and on the other hand transfer of the statistics of water level and wind into wave statistics based on short-term numerical simulations of waves for single situations of water level and wind (MAI and ZIMMERMANN, 2003).

In the following, a comparison of both the indirect methods of deriving wave statistics from wind and of the direct method of deriving wave statistics from measurements is given. The comparison is carried out for two sites on the German North-Sea coast. One is located west of the island of Borkum in the estuary of the River Ems, and the other one is situated within the estuary of the River Weser near the fairway, about 42 km away from the port of Bremerhaven (Fig. 1). Both measurement and modelling are described in more detail in the following.

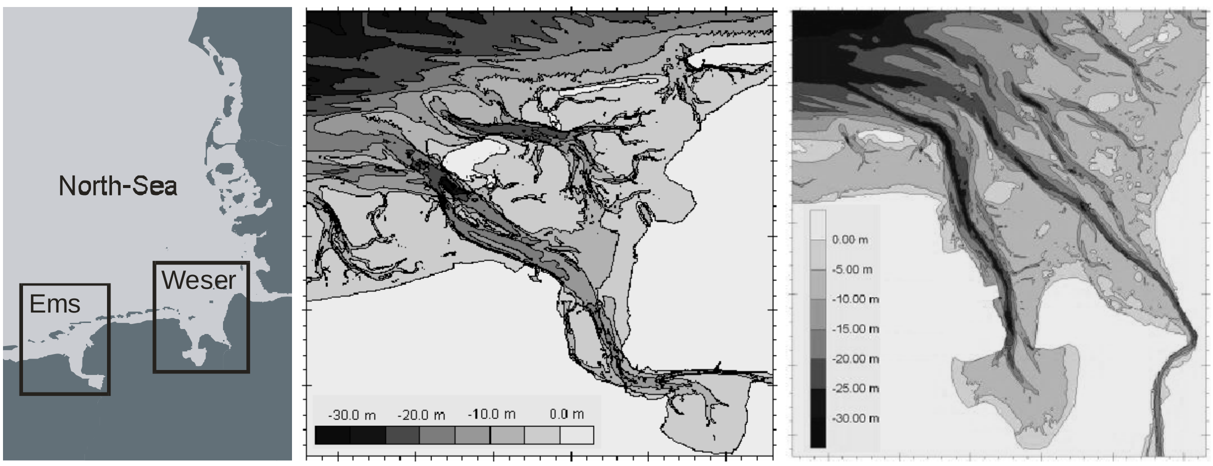


**Figure 1: Test sites at the German North Sea Coast**

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## 2. WAVE MEASUREMENTS

Continuous wave measurements have been carried out at the official water level gauge "Borkum-Südstrand" (geographic position 53.57694 N / 6.66139 E) since August 2002 and at the official water level gauge "Leuchtturm Alte Weser" (geographic position 53.86333 N / 8.1275 E) since September 2006. Both sites are equipped with pulse radars, floaters in sills, and a meteorological station (i.e. wind sensors etc.). A view of both sites is given in Fig. 2. Pulse radars of the type "Vega Puls 42" are used. The radars are operated with frequencies of 5.8 GHz. The sampling frequency of the level measurements was chosen at 2 Hz.

**Figure 2: View on the gauges "Borkum-Südstrand" (left) and "Leuchtturm Alte Weser" (right)**

The accuracy of the radar sensors with respect to tidal water levels was verified by comparison with the conventional gauging systems at both sites, i.e. floaters in sills (BLASI and BARJENBRUCH 2007). With respect to waves, the accuracy of the radar sensors was tested in the wave flume GWK ("Großer Wellenkanal") of the Universities of Hannover and Braunschweig by comparison with standard resistance wave gauges (MAI and ZIMMERMANN, 2000 and BARJENBRUCH et al., 2002). A view of the test rig of wave radars in the GWK is given in Fig. 3.

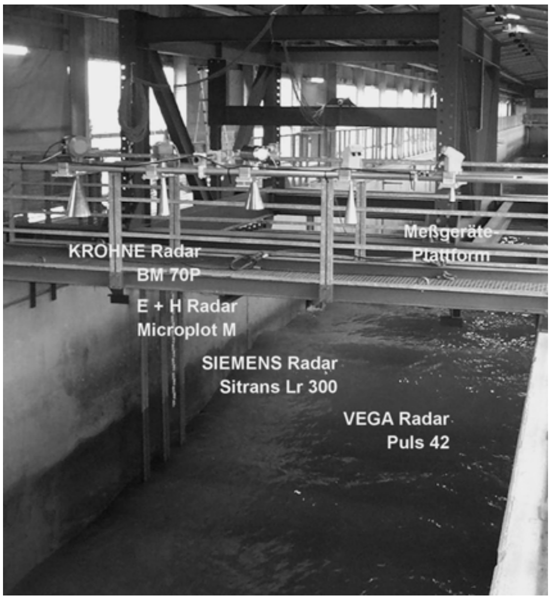


**Figure 3: View on the tests of wave radars carried out in GWK**

The tests in the GWK proved the applicability of radar sensors for wave monitoring. The accuracy with respect to wave height is more than 90 % in case of wave periods longer than 4 s. With respect to wave periods (T > 4 s), the accuracy is more than 90 % for wave heights above than 10 cm.

At the two sites in the estuaries of the rivers Ems and Weser, the series of water level elevation data, sampled at 2 Hz, are pre-processed for time intervals of 15 minutes with respect to the mean wave height, the maximum wave height, and the mean wave period. Within the pre-processing, the time-series of water level elevations is detrended and analysed using zero-downcrossing. An example of wave parameters recorded during the severe storm surge at the German coast on 1 November 2006 is given in Fig. 5 form the estuary of the River Ems and in Fig. 6 form the estuary of the River Weser.

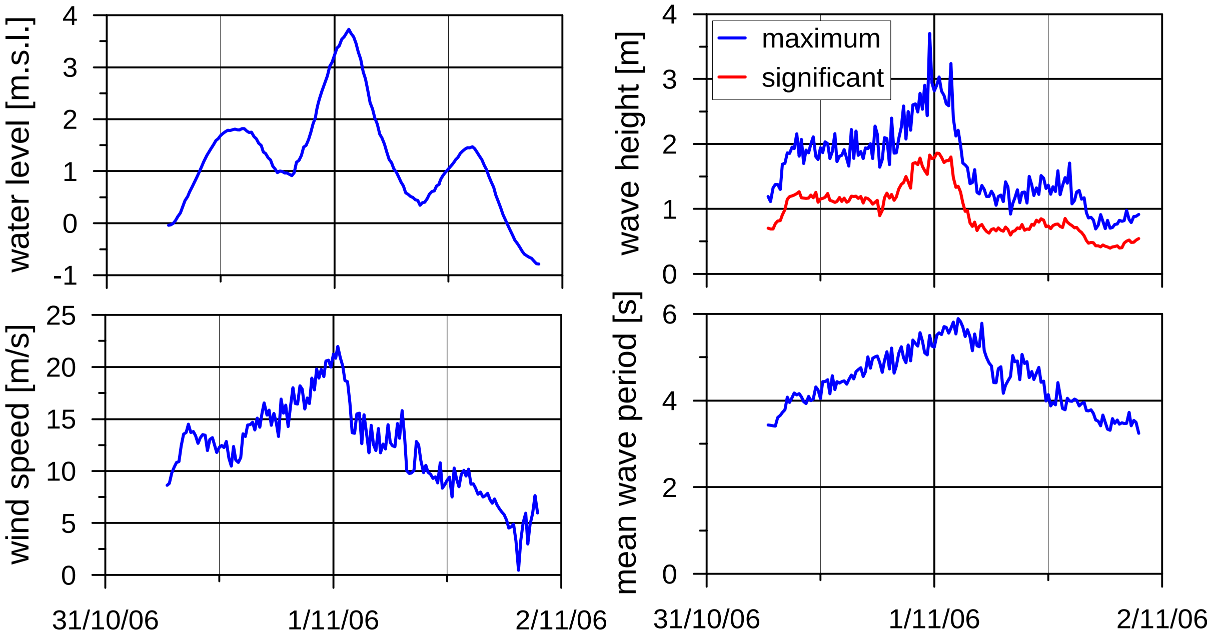


**Figure 5: Water level, wind, wave height and wave period at the gauge "Borkum-Südstrand" during the storm surge of 1 November 2006**

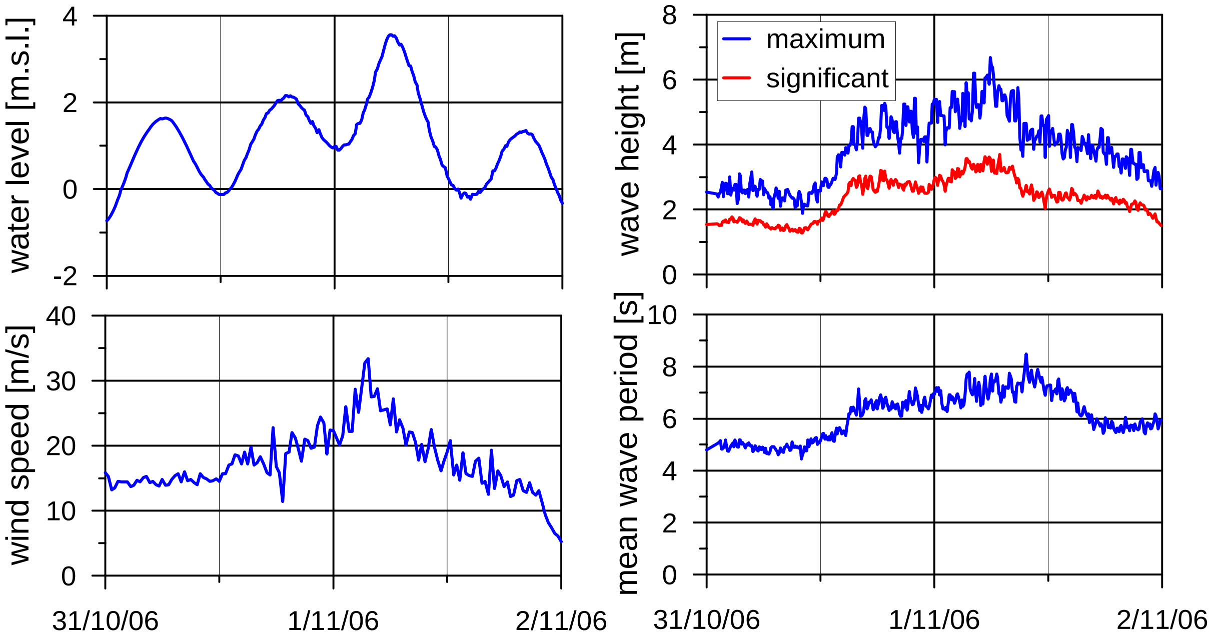


**Figure 6: Water level, wind, wave height and wave period at the gauge "Leuchtturm Alte Weser" during the storm surge of 1 November 2006**

The series of 15-min wave parameters were hourly averaged and statistically analysed for the year 01/2006 to 12/2006 ("Borkum-Südstrand") and the interval from 09/2006 to 11/2006 ("Leuchtturm Alte Weser") respectively. The statistics of wave heights and wave periods are given in Fig. 7 form the gauge "Borkum-Südstrand" and in Fig. 8 form the gauge "Leuchtturm Alte-Weser").

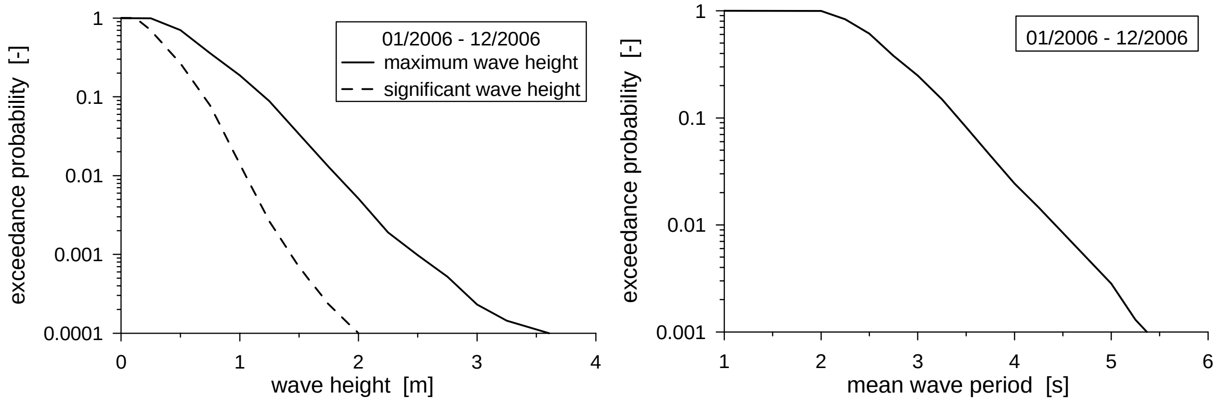


**Figure 7: Wave statistics at the gauge "Borkum-Südstrand"**
**(left: wave height, right: wave period)**

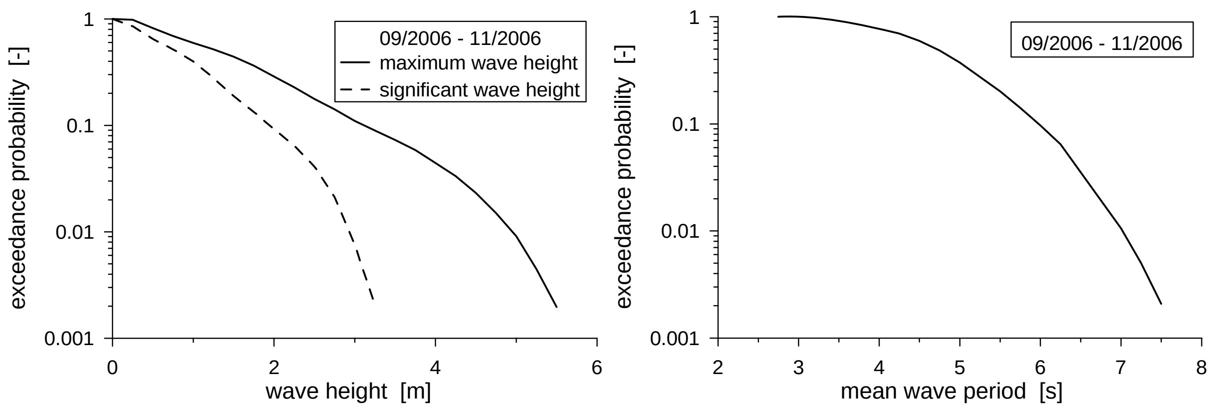


**Figure 8: Wave statistics at the gauge "Leuchtturm Alte Weser"**
**(left: wave height, right: wave period)**

## 3. NUMERICAL SIMULATIONS

Both methods of deriving wave statistics from wind require numerical modelling. Within this study the phase-averaged wave model SWAN (RIS, 1997, BOOIJ et al., 1999, RIS et al., 1999) is used. A verification of the model with buoy measurements has been made on the German coast e.g. by MAI et al. (1999) and by MAI et al. (2000). For restricted fetch conditions the model has been verified with measurements of ultrasonic level meters (SAYAH et al. 2005). While the modelling of wave propagation within the estuary of the river Weser uses a grid resolution of 100 m, the modelling of wave propagation within the estuary of the River Ems uses a grid resolution of 50 m. The water level and wind are given over the whole model areas. The wave conditions at the northern and western boundary of each estuary are taken from a large scale wave model of the North Sea operated by the German Meteorological Service (DWD) and the German Federal maritime Hydrographic Agency (BSH).

The model SWAN is operated in non-stationary mode for long-term simulations of wave propagation in the estuary. The time-step of the simulations is chosen to be 1 hour. The model inputs, i.e. water level, wind and wave conditions at the boundaries, are updated also every hour. The results of the long-term simulations, i.e. time-series of significant wave height and mean wave period, are afterwards statistically analysed. The workflow of this method is given in Fig. 9 (top).

For the second method, i.e. transferring the statistics of water level and wind into wave statistics based on short-term numerical simulations of waves for single events, the workflow is shown in Fig. 9 (bottom). Within this method, the time series of the input parameters water level (w), wind velocity ($u_w$), and wind direction ($\theta_w$) is used to calculate the joint probability ($p(w,u_w,\theta_w)$) of water level and wind. For a discrete set of parameter combinations of water level, wind, and the related wave conditions at the boundary of the estuaries stationary numerical simulations of wave propagation are made. Thus, the input parameters, i.e. water level and wind, are transferred into wave parameters, i.e. $H_s(w,u_w,\theta_w)$, $T_m(w,u_w,\theta_w)$, $\theta_s(w,u_w,\theta_w)$. By the combination of transfer functions and joint probabilities of water level and wind, the probability of significant wave height and mean wave period is calculated:

$$p(\tilde{H}_s) = \iiint \delta(\tilde{H}_s - H_s(w,u_w,\theta_w))\, p(w,u_w,\theta_w)\, dw\, du_w\, d\theta_w$$

$$p(\tilde{T}_m) = \iiint \delta(\tilde{T}_m - T_m(w,u_w,\theta_w))\, p(w,u_w,\theta_w)\, dw\, du_w\, d\theta_w$$

An example of the results of a single stationary simulation is given in Fig. 10 for the estuary of the River Ems and in Fig. 11 for the estuary of the River Weser.

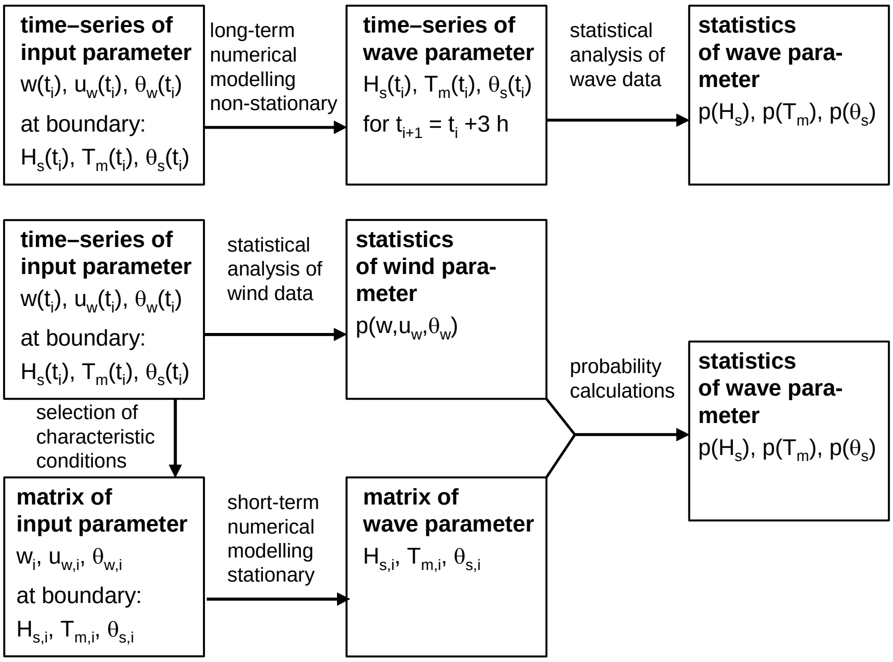


**Figure 9: Approaches to derive wave statistics from wind (top: by long-term numerical simulations, bottom: by statistical transfer of short-term simulations)**

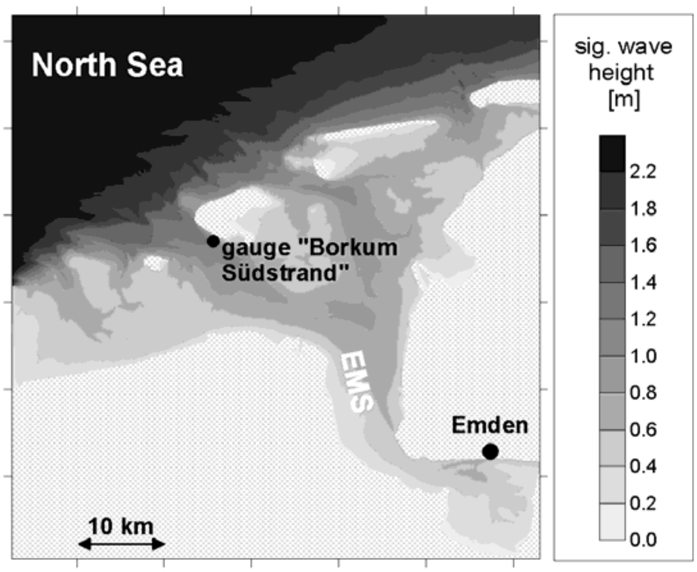


**Figure 10: Wave propagation within the estuary of the River Ems – significant wave height (water level: 2 m.s.l., wind speed: 16 m/s, wind direction: 240°)**

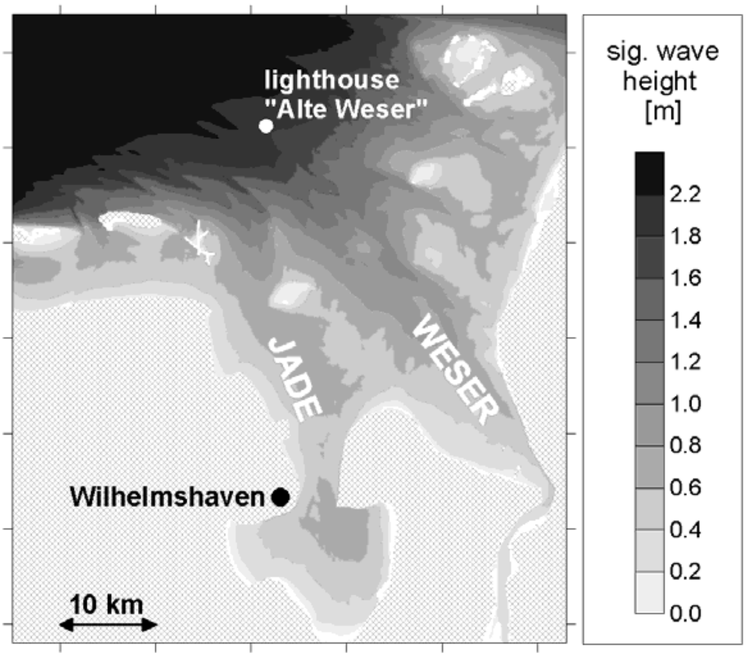


**Figure 11: Wave propagation within the estuary of the River Weser – significant wave height (water level: 2 m.s.l., wind speed: 16 m/s, wind direction: 240°)**

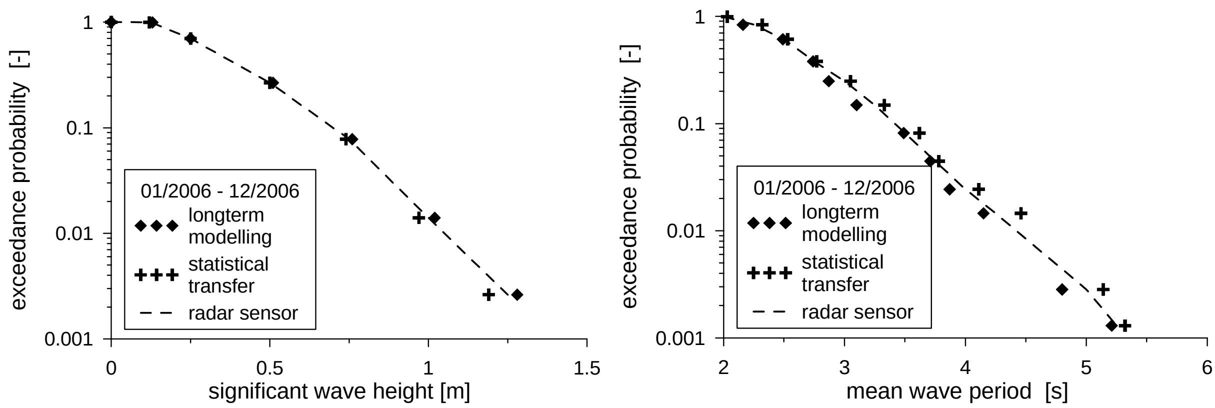


**Figure 12: Wave statistics at the gauge "Borkum-Südstrand" derived by indirect methods (left: wave height, right: wave period)**

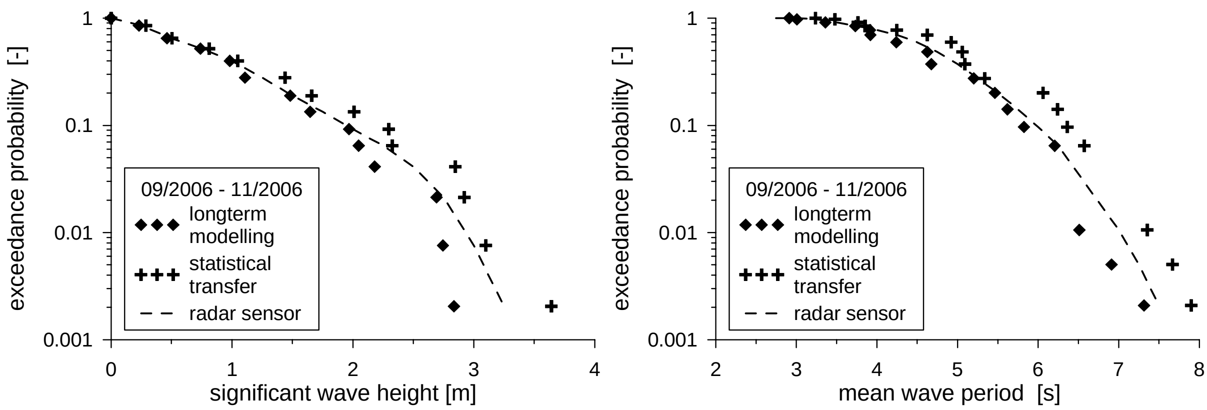


**Figure 13: Wave statistics at the gauge "Leuchtturm Alte Weser" derived by indirect methods (left: wave height, right: wave period)**

Both methods of deriving wave statistics indirectly from wind by means of numerical simulations are used for the calculation of the wave statistics at the gauges “Borkum-Südstrand” and “Leuchtturm Alte Weser”. The analysis is carried out for the same periods as in Chapter 2 for the statistical analysis of wave measurements. The statistics of wave heights and wave periods are given in Fig. 12 for the gauge “Borkum-Südstrand” and in Fig. 13 for the gauge “Leuchtturm Alte-Weser”). It is found that the wave statistics derived by numerical modelling is in rather good agreement with the wave statistics derived directly from measurements. The deviation between both is up to approximately 10 %. As expected, the statistics derived from long-term modelling better fits the statistics derived from measurements. However, it depends on the task whether the extra computational effort of long-term modelling is needed (In the study of the estuary of the River Ems the cpu time of the long-term simulation exceeded the cpu time of all short-term simulations by a factor of 10).

## 4. CONCLUSIONS

The lack of long-term wave records in the direct vicinity of the German coasts can be compensated by numerical modelling using time-series of water level and wind as inputs. The deviation between the statistics derived directly from measurements and those obtained indirectly by numerical modelling is in the order of 10 %. The statistical analysis of long-term simulations revealed only slight advantages compared with the approach of transferring wind statistics into wave statistics on the basis of a set of short-term simulations. In the future, further tests of the proposed methodologies will become possible, since the German gauging stations are more and more equipped with radar sensors, thus opening the possibility of continuous wave recording with very little need for station maintenance.

## 5. REFERENCES

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