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Operational wave prediction of extreme storms in Northern Europe

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Abstract The disastrous effects of numerous winter storms on the marine environment in the North Sea and the Baltic Sea during the last decade show that wind waves generated by strong winds actually represent natural hazards and require high quality wave forecast systems as warning tools to avoid losses due to the impact of rough seas. Hence, the operational wave forecast system running at the German Weather Service including a regional wave model for the North Sea and the Baltic Sea is checked extensively whether it provides reasonable wave forecasts, especially for periods of extraordinary high sea states during winter storms. For two selected extreme storm events that induced serious damage in the area of interest, comprehensive comparisons between wave measurements and wave model forecast data are accomplished. Spectral data as well as integrated parameters are considered and the final outcome of the corresponding comparisons and statistical analysis is encouraging. Over and above the capability to provide good short term forecast results, the regional wave model is able to predict extreme events as severe winter storms connected with extraordinary high waves already about two days in advance. Therefore it represents an appropriate warning tool for offshore activities and coastal environment.

Keywords Wind waves • Operational wave forecasting • WAM • North Sea • Baltic Sea • Destructive winter storms

1 Introduction

During the last decade, Northern Europe was afflicted by quiet a few destructive winter storms that caused serious damage to the marine environment in the North Sea and the Baltic Sea area. Table 1 includes 10 major extratropical cyclones that reached the power of a hurricane according to the Saffir-Simpson hurricane scale. Wind gusts of more than 200 km/h have been measured in particular cases and various losses have been reported. Beside the effects on land with disastrous construction and forest damage and a number of people killed in Europe (e.g. 53 during Kyrill and more than 100 during Lothar), numerous ship accidents, damage to offshore platforms, harbours and coastal settlements and substantial beach destruction occurred in the marine environment due to the combination of extraordinary rough seas and unusual high water levels. Taking this into account, it becomes obvious that the waves forced by strong winds are definitely natural hazards for coastal areas and all kinds of offshore activities. Therefore, it is very important to have appropriate warning tools that are able to predict dangerous sea states early enough to avoid or at least to reduce losses as mentioned above. A convenient source for wave forecast data are numerical wave forecast systems that are running in an operational mode at many weather centres worldwide in connection with the numerical weather prediction. One of those is the wave forecast system of the German Weather Service DWD (Deutscher Wetterdienst) including a global model and two regional models, one for the North and the Baltic Sea, another for the Mediterranean. For this investigation the wave forecast results of the LSM (Local Sea wave Model) applied to the North Sea and Baltic Sea are considered.

In order to answer the question whether extreme sea states generated by severe winter storms (Table 1) can successfully be predicted by the LSM, extensive comparisons of the wave forecasts with measurements are done for the two extratropical cyclones Britta and Kyrill. These are selected because their tracks across North Sea and Baltic Sea are representative for two different classes of cyclones generating remarkable different sea states. For the development of the wind waves in the North Sea, it is of great importance whether the tracks of the cyclones crosses the area more like the Britta trajectory or rather uniformly in the central part like the Kyrill trajectory (see Fig. 1). A detailed investigation about the effects of wind waves generated by the winter storm Gudrun in the Baltic Sea area has been done in Soomere et al. (2008). Section 2 gives a short overview about the operational wave forecast system running at the DWD. The comparisons between measurements and model forecast results for Britta and Kyrill including a statistical analysis are discussed in Sect. 3, followed finally by some concluding remarks.

Table 1 Major winter storms during the last decade in the North/ Baltic Sea area

operative date	name of winter storm	operative date	name of winter storm
03.12.1999	Anatol	30.12.2006	Karla
26.12.1999	Lothar	18.01.2007	Kyrill
27.12.2002	Janette	09.11.2007	Tilo
08.01.2005	Gudrun	26.01.2008	Paula
01.11.2006	Britta	29.02.2008	Emma

2 The operational wave forecast system

The numerical wave forecast system at the German Weather Service DWD includes a global (GSM: Global Sea wave Model) and two regional wave models, one for North Sea and Baltic Sea (LSM: Local Sea wave Model) and another one for the Mediterranean (MSM: Mediterranean Sea wave Model). These models are running operationally twice a day in shallow water mode and provide 7 days forecasts on the global and 3 days forecasts on the regional scale. The wave model used since 1999 by the DWD as the appropriate tool for their numerical wave predictions is the third-generation wave model WAM that runs successfully at many institutions worldwide. It describes the evolution of two-dimensional (2D) ocean wave spectra, and in contrast to first and second-generation models it includes no ad hoc assumption on the spectral shape. WAM computes the 2D-wave variance spectrum through integration of the transport equation:

$$\frac{\partial \mathrm{F}}{\partial \mathrm{t}} + \frac{\partial}{\partial \phi}(\dot{\phi}\mathrm{F}) + \frac{\partial}{\partial \lambda}(\dot{\lambda}\mathrm{F}) + \frac{\partial}{\partial \theta}(\dot{\theta}\mathrm{F}) = \mathrm{S} \qquad (1)$$

Where F represents the spectral density with respect to (f,θ,ϕ,λ) and f, θ, ϕ, λ denotes frequencies, directions, latitudes, longitudes, respectively, and $\dot{\phi}, \dot{\lambda}, \text{and}\ \dot{\theta}$ are the rates of change of the position and propagation direction of a wave packet in physical and spectral space.

The source function S is represented as a superposition of the wind input S_{in}, white capping dissipation S_{dis}, nonlinear transfer S_{nl} and bottom friction S_{bf} :

$$S = S_{in} + S_{dis} + S_{nl} + S_{bf} \tag{2}$$

Detailed information about the physics of the wave model is available in literature (WAMDI group: Hasselmann et al. 1988; Komen et al. 1994).
Since the area of interest for this investigation is the northern part of Europe, the forecast results obtained by the wave model LSM are used to check whether the extreme storm events in the North Sea and in the Baltic Sea are predicted satisfactorily. The LSM runs on a model grid situated between 40.55° N to 66.05° N and 3.75° W to 30.75° E, with a spatial resolution of $\Delta\varphi * \Delta\lambda = 0.1° * 0.167°$ (~ 10 km). It calculates the 2D energy density spectrum at each of the 14114 active model grid points in the frequency/direction space. The solution of Eq. 1 is provided for 24 directional bands at 15° each, starting at 7.5° and measured clockwise with respect to true north, and 25 frequencies logarithmically spaced from 0.042 Hz to 0.41 Hz at intervals of $\Delta f/f = 0.1$. At the open boundaries the LSM uses the full 2D spectral information provided by the global model GSM (spatial resolution 0.75° * 0.75°). The driving forces are the U_{10} forecast wind fields delivered by the regional atmosphere model of the DWD that runs on a 0.0625° (7 km) grid. Results of the LSM are stored every 3 h for the entire forecast period of 78 h.

3 Wave measurements in comparison with numerical forecast results

The wave measurements used for comparison with the computed wave forecast results are continuously provided via the GTS (Global Telecommunication System) net. The parameters recorded by buoys or at offshore platforms are usually significant wave height, wind speed and wind direction. For these three parameters an automatic validation system is running at the DWD that performs an extensive statistical analysis at the end of each month for 19 sites in the North Sea. Three of those are selected for a detailed discussion in this section. Figure 1 includes a map of the locations with the values for the corresponding latitudes and longitudes in Table 2.

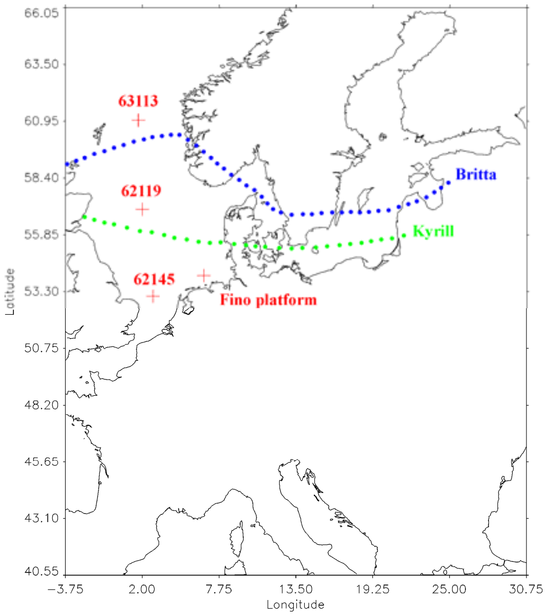


Fig. 1 Geographical position of three selected GTS buoys and the FINO platform in the LSM wave model grid. Measurements recorded at those are used for comparison with wave model forecast results. The dotted lines denote the trajectories of the extratropical cyclones Britta (blue) and Kyrill (green)

Table 2 Geographical positions of locations

location	longitude	latitude
63113	1.70° E	61.00° N
62119	2.00° E	57.00° N
62145	2.80° E	53.10° N
FINO platform	6.58° E	54.00° N

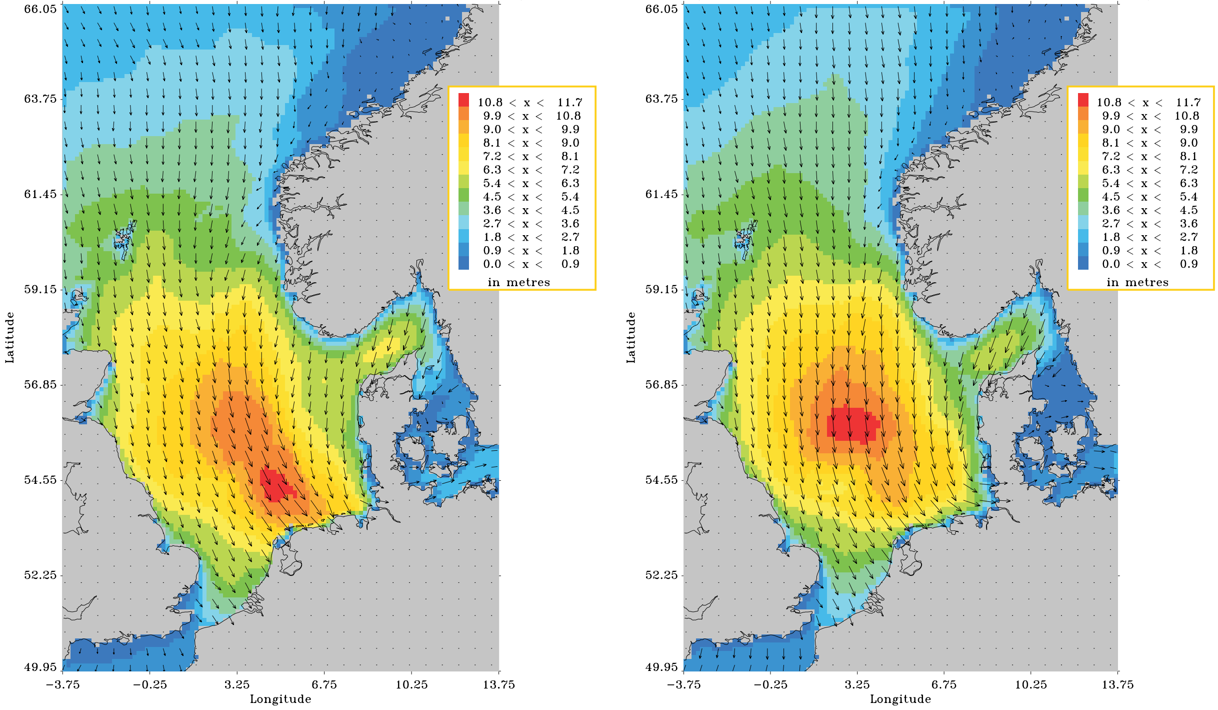
An additional location is the FINO platform in the German Bight. At this site not only data recorded by a Wave Rider buoy, but also measurements of the 2D wave spectra obtained by a

WaMoS II (Wave Monitoring System II) are available for comparison with model data. WaMoS II has been proved during several applications to be a powerful tool to monitor ocean waves from fixed platforms as well as from moving vessels, especially under extreme weather conditions (Young et al. 1985; Ziemer and Günther 1994; Nieto-Borge et al. 1999; Hessner et al. 2001). The Wave Rider measurements have been provided by the BSH (Bundesamt für Seeschifffahrt und Hydrographie, Hamburg) and the WaMoS II data by OceanWaveS, Lüneburg.

The wave model results introduced to the comparisons with measurements are forecast data only. Continuous time series of wave model data have been generated by merging the model results obtained during the first 12 hours of each of the consecutive wave forecasts.

3.1 Winter storm Britta

The severe winter storm Britta afflicted the North Sea during the night from 31 October 2006 to 1 November 2006. Prevailing strong winds from northerly directions with maximum wind speeds of 27 – 29 m/s drove the waves along the longitudinal axis of the North Sea to the south. Due to the long fetch of more than 1500 km, record breaking significant wave heights (H_s) up to 13 m have been generated in the central North Sea at 21:00 UTC on 31 October 2006. This area of maximum wave heights propagated southwards towards the German coast and hit the coast at about 03:00 UTC on 1 November. At that time the significant wave heights were still about 10 m (see Fig. 2a). Figure 2b shows the distribution of H_s at the same time as in Fig. 2a, but computed by the wave forecast released already two days before (30 October 2006, 00:00 UTC). This indicates that the wave forecast model LSM is able to predict such an extreme event already 2 days in advance. The only difference between both forecasts is a small time shift; the highest waves hit the coast a little earlier in reality as predicted two days before.



a) 1.11.2006 03:00 UTC (3 hours forecast)

b) 1.11.2006 03:00 UTC (51 hours forecast)

maximum wind speed: 28.43 m/s

maximum wind speed: 26.40 m/s

Fig. 2 Distribution of significant wave height and driving wind field when the highest waves hit the German coast (a). The forecast results in (b) emanated from a run released already two days before

Figure 3 includes time series for measured and computed H_s at the locations 63113 and 62119 in the northern and central North Sea. The model series are composed from the 3 - 12 h forecasts. The monthly time series for October and November provided by the automatic wave model validation system of the DWD are shown for both locations in the relevant time window between 25 October and 4 November 2006.

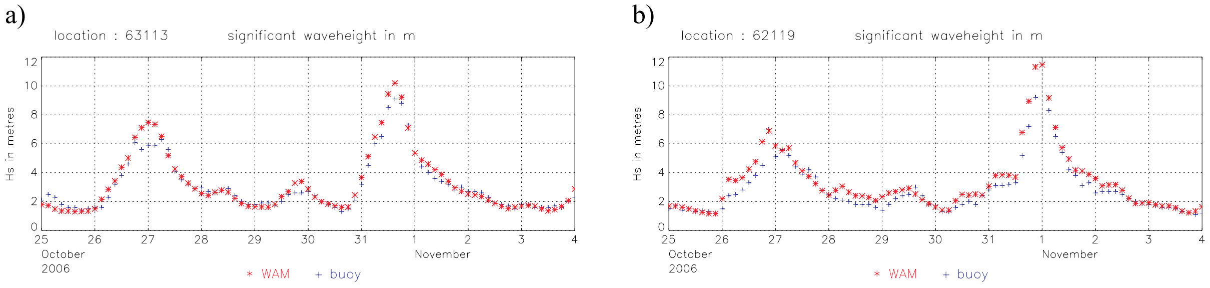


Fig. 3 Time series of measured and computed H_s at the GTS locations 63113 (a) and 62119 (b) for the time period 25 October – 4 November 2006, 0 UTC

Looking at the time series for the location 63113 in Fig. 3a it becomes obvious that the agreement between measurements and model results is excellent for that time period. The maximum significant wave height of 9.10 m recorded by the buoy at 15:00 UTC on 31 October 2006 is well predicted by the LSM. Therefore, it is not remarkable that the driving wind, delivered by the atmosphere model of the DWD is in good agreement with the measurements at that time as well. The direction of the wind turns sharply from northwest to north at peak time and reached values of 25 m/s. The time series of the significant wave heights furthermore show the rapid increase from less than 2 m to more than 9 m during the last 24 hours before the storm peak of Britta and its rapid decrease back to values of about 2 m afterwards. These good results are supported by the comparison at the location 62119, located south of buoy 63113 in the central North Sea. Since the area of highest waves propagates to the south, towards the German coast, the storm peak ($H_s = 9.20$ m) is shifted by 6 hours in time and was recorded at 21:00 UTC on 31 October 2006.

Beyond the graphical analysis of the comparisons, a statistical analysis is done continuously for the comparisons between measurements and model forecast data at all the GTS locations available in the LSM model area. Table 3 and 4 include statistical parameters calculated for the three selected sites marked in Figure 1 for October 2006 and November 2006. The mathematical description of the statistical parameters is given in the appendix.

Table 3 LSM October 2006 statistics for significant wave height and wind speed at selected GTS locations

buoy	number	mean	bias	rms	regr.	skill (rv)	scatter
a) significant wave height		(m)	(m)	(m)			(%)
62119	245	1.84	0.20	0.44	1.27	0.86	21
62145	222	1.47	0.14	0.36	1.27	0.73	22
63113	246	2.54	0.04	0.45	1.08	0.88	18
b) wind speed		(m/s)	(m/s)	(m/s)			(%)
62119	237	6.41	1.48	3.20	1.49	0.33	44
62145	214	8.06	1.32	2.03	1.31	0.67	19
63113	242	8.46	0.71	2.10	1.18	0.76	23

Table 4 LSM November 2006 statistics for significant wave height and wind speed at selected GTS locations

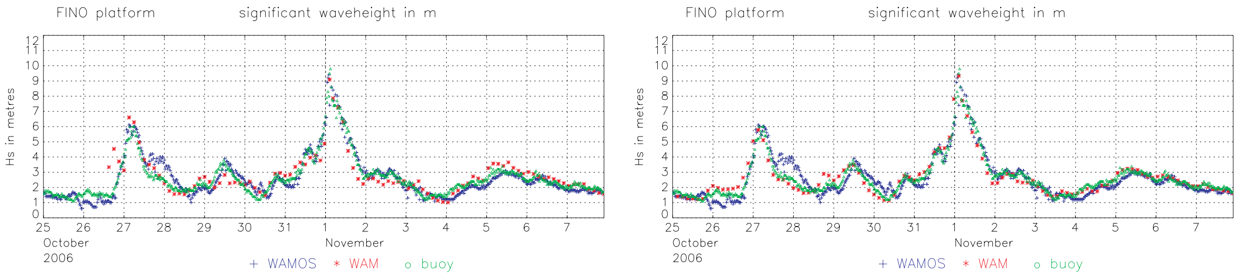
buoy	number	mean	bias	rms	regr.	skill (rv)	scatter
a) significant wave height		(m)	(m)	(m)			(%)
62119	238	2.77	0.50	0.67	1.38	0.62	16
62145	232	2.03	0.22	0.64	1.23	0.38	30
63113	238	3.76	0.21	0.54	1.14	0.75	13
b) wind speed		(m/s)	(m/s)	(m/s)			(%)
62119	219	10.58	1.41	3.32	1.27	0.13	28
62145	236	10.11	1.36	1.95	1.27	0.60	14
63113	237	11.07	0.75	2.10	1.13	0.70	18

The statistics are valid for the whole month. The mean measured significant wave height ranges in October between 1.47 m and 2.54 m at the different stations. During November the waves were higher with mean values between 2.03 m and 3.76 m. The positive bias which denotes the mean of the differences between measured and computed data (model – measurements) indicates that the LSM tends to overestimate the measured wave heights in the North Sea (supported by the values > 1 for the slope of the regression line). This is obviously due to the forecast wind speeds that are slightly too high as well. The skill parameters reduction of variance (rv) and scatter index are a measure for the quality of the wave model forecasts and the values of rv are very satisfactory, especially those obtained for the significant wave heights at 63113 (0.77 – 0.88). The scatter indices with values around 20 % support the good quality of the wave forecasts as well.

The impact of the high waves on the marine environment during Britta was manifold. In front of the Norwegian coast an offshore platform broke away from its tugs and was drifting disabled in the heavy sea, two ships were in distress near the island Borkum in front of the German coast and a cargo ship capsized and sank between the Swedish islands Öland and Gotland in the Baltic Sea. A stroke of luck for this investigation is the location of the FINO platform (Fig 1; Table 2) in the German Bight. During Britta single waves hit the lower working deck of the platform at 11 m above the actual water level, causing damage, where several floor gratings were tore off their mountings, and parts of the railings were heavily deformed (see Fig. 4).

Fig. 4 Picture of the FINO platform showing the damage due to wave impact (BSH)

A wave rider buoy deployed next to the platform recorded a maximum H_s of 10.54 m at 3:30 UTC on 1 November 2006. The WaMoS II which is installed at the FINO platform to investigate the load and stability of the structure due to surface waves and currents provided wave data during that time as well and enables a comparison not only between buoy data and wave model forecast data, but also with the corresponding data measured by the WaMoS II. Figure 5 includes the 2 weeks time series of the significant wave height measured by the Wave Rider buoy and WaMoS II, compared with the forecast results of the wave model LSM. The difference of Fig. 5a and b is the start time of the wave model forecasts. The forecast in Fig. 5a has been released already two days earlier than that one in Fig. 5b. That supports impressively the capability of the wave forecast system to predict extreme events like Britta already two days before. The peak at 3:00 UTC on 1 November 2006 is excellent estimated by the model and also the general agreement between measured and computed data is very satisfactory for the whole 2 weeks time period in Fig. 5a, although it's slightly better for the short term forecast in Fig. 5b, especially for the first peak around 27 October and the last peak around 5 November 2006.


a) wave forecasts: T_0 + 39 to 48 hours

b) wave forecasts: T_0 + 3 to 12 hours

Fig. 5 Comparison of significant wave height at FINO platform, recorded by a Wave Rider buoy, WaMoS II and computed by the operational wave model WAM for the time period 25 October – 8 November 2006

The comparisons in Fig. 5 are for significant wave heights only, but since H_s is the average height of the third-highest waves in a record of time period, higher single waves can be expected. The analysis of the WaMoS II wave measurements, with the aid of a directional wave finding algorithm (DWFA) developed by OceanWaveS, delivered a time series of maximum wave heights (see Fig. 6) compared with those recorded by the Wave Rider buoy. At 2:25 UTC on 1 November, a record maximum wave height of 20.57 m for a single wave was detected by WaMoS II and provides an explanation for the damage to the FINO platform shown in Fig. 4. The results of the DWFA show a scattering of about 4 m. This scattering is that high because the variation of wave heights within space for a relative short time (80 s) is higher relative to point measurements over a relative long period of 30 min like the buoy measurements.

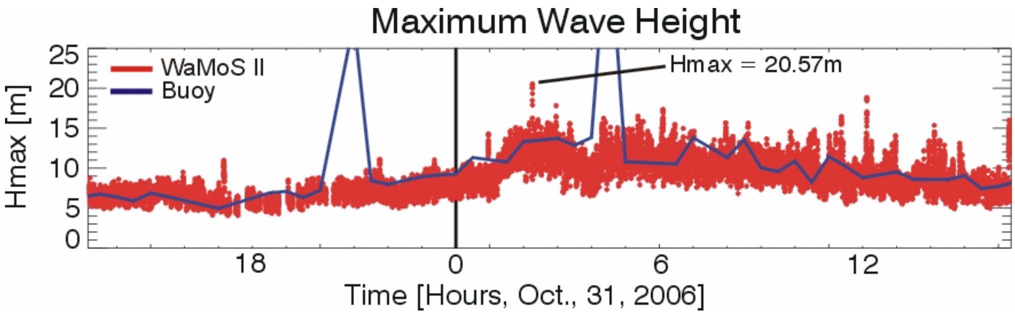
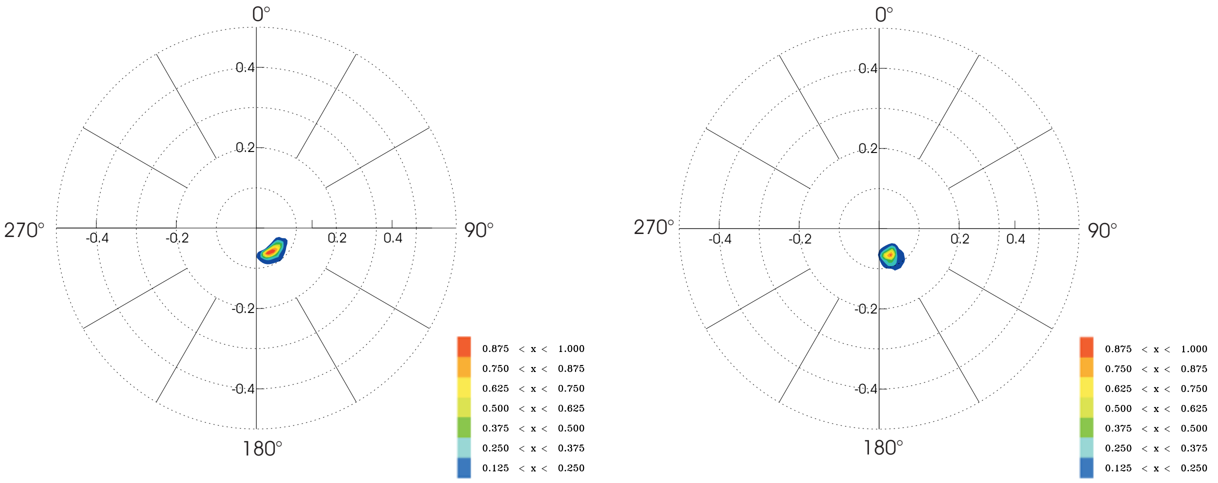


Fig. 6 Time series of maximum wave height by a Wave Rider buoy and WaMoS II at FINO platform

The WaMoS II was developed for real time measurements of directional ocean wave spectra and therefore offers also the rare possibility to compare the measured spectra at FINO platform with the full spectral information forecasted by the wave model. Figure 7 includes a comparison of the measured and forecasted energy density distribution (normalized to 1) at the Britta storm peak. On the left side (Fig. 7a) the computed and on the right side (Fig. 7b) the measured spectrum is shown. For a better understanding it should be mentioned that the resolution in the frequency/direction domain for the wave model and WaMoS II is not the same. As the resolution for the wave model is 24 directions and 25 frequencies (chapter 2), the WaMoS II energy densities are delivered for 90 direction bands (4°) and 64 frequency bands ($\Delta f = 0.00547$ Hz). Therefore, it is possible to detect more details in the measured spectra. Despite of that, the general agreement between the computed and the measured spectra is fairly well. Since the energies are very high around the peak, a very narrow spectrum is generated. The propagation direction of the wave system towards south-easterly directions and also the frequency of the maximum energy density is very similar for forecast data and measurements. This is a further confirmation that the operational wave forecast model is able to predict the sea-state reasonably during extreme winter storms.



a) WAM: 2006110103 UTC
wind speed: 23,8 m/s, direction: 151.1° (U_{10}),
H_s: 9.33 m, T_p: 13.6 s

b) WaMoS II: 2006110103 UTC
wind speed: 26.89 m/s, direction: 129.21° (U_{33}),
H_s: 9.40 m, T_p: 14.1 s

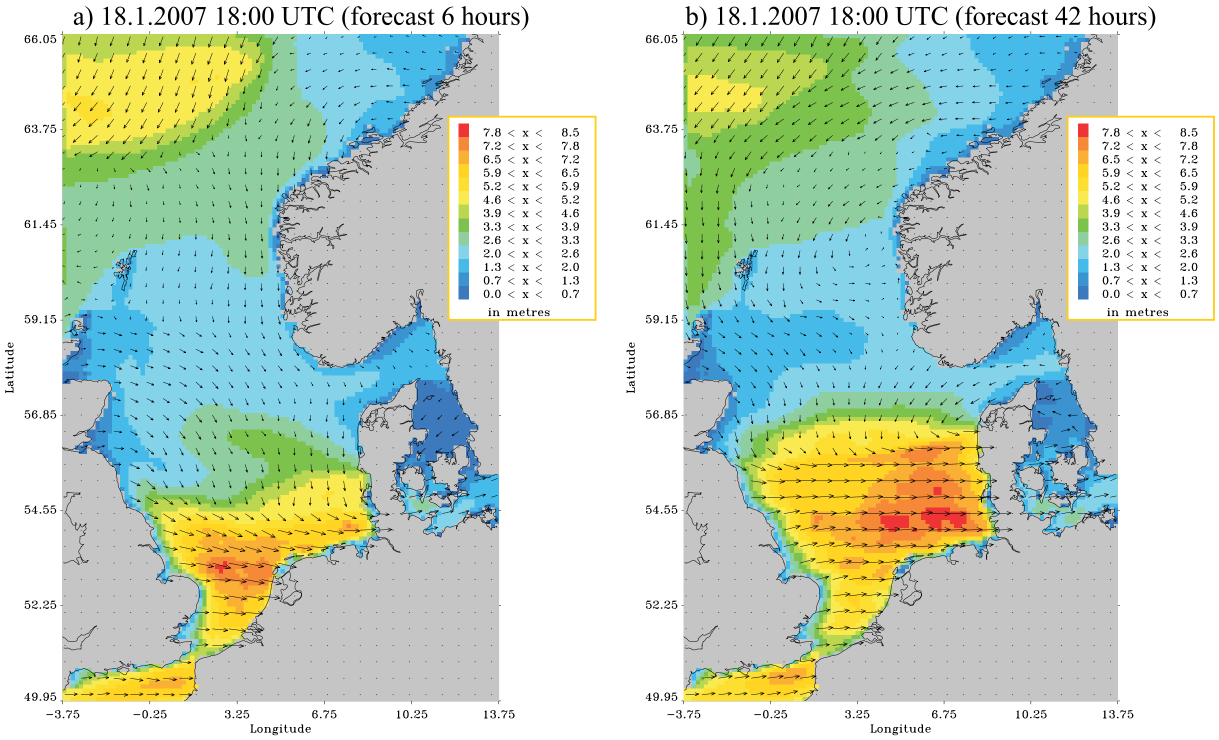
Fig. 7 WaMoS and WAM model forecast spectra (energy densities in m^2*s/rad, normalized to 1) at FINO platform (directions: going to)

3.2 Winter storm Kyrill

The second severe winter storm Kyrill which is selected for this investigation as a representative one for the cyclones crossing the central North Sea more southerly and uniformly than those comparable to Britta, caused heavy damage in the European countries during the afternoon on 18 January 2007. Kyrill was more destructive on land than Britta. Europe-wide 44 people were killed, thousands of hectares forest were damaged, hundred thousands of homes were without electricity and phone lines, airports were closed and ferry services and railway traffic were suspended. Although the wind speeds recorded during cyclone Kyrill were comparable to those observed during Britta, this winter storm was less devastating offshore in the North Sea and in the Baltic Sea due to the wind direction connected with its trajectory. The prevailing strong westerly winds during Kyrill drove the waves along the transverse axis of the North Sea with a maximum fetch of about 500 km.

Therefore, the generated wind waves were smaller and shorter (peak periods up to 11.2 s) than those during Britta (T_p up to 14.3 s).

Figure 8a shows the H_s distribution in the North Sea section of the LSM at the Kyrill storm peak (18 January 2007, 18:00 UTC) with wave heights of about 8 m propagating exactly to the east forced by westerly winds of about 26 – 28 m/s speed. Although these strong winds were blowing continuously from west to east for many hours, the generated wind waves did not exceed a significant wave height of 8 m due to the short fetch. Therefore, the damage to offshore platforms, ships or coastal facilities due to wind waves were considerably smaller than those reported for Britta. That the wave model predicted the Kyrill peak already in the forecast released at 12 UTC on 16 January 2007 (42 h earlier) is shown in Fig. 8b which gives the distribution of H_s. Figure 8a shows the distribution at the same time but from the 6 hour forecast. Since the atmosphere model of the DWD provided stronger westerly winds for this earlier forecast, the area of higher significant wave heights around 8 m is more extended as predicted by the short term forecast shown in Fig. 8a. Nevertheless, the main feature has been predicted by the LSM already 42 hours in advance and shows therefore again the capability of the wave forecast system as an appropriate warning tool for all kinds of offshore and coastal activities.



maximum wind speed: 28.64 m/s

maximum wind speed: 28.02 m/s

Fig. 8 Distribution of significant wave height and driving wind field at the Kyrill peak in the German Bight (in comparison to (a) the forecast results in (b) emanated from a run released already two days before)

For an analysis of comparisons between measured and computed data, the GTS location 62145 (see Fig. 1) is a representative one for cyclone Kyrill because of its geographical position in the area of the highest sea states in the southern North Sea. The time series plot in Fig. 9 shows the comparison between measured and computed significant wave heights for the relevant time period in January 2007 at the buoy location 62145.

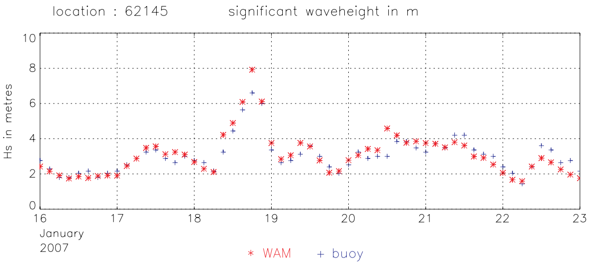
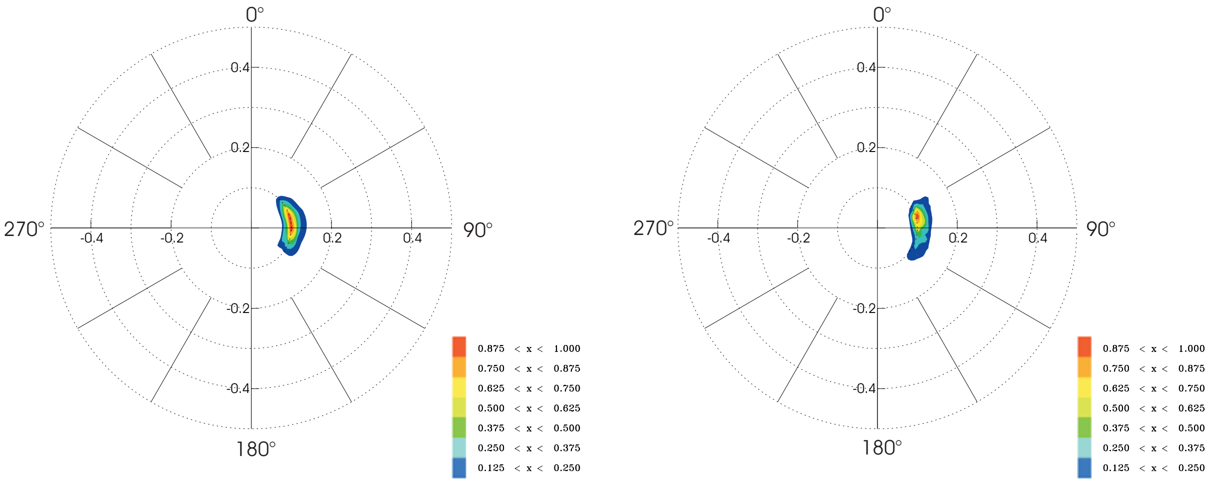


Fig. 9 Time series of measured and computed significant wave heights at GTS buoy location 62145 in the southern North Sea for the time period 16 January – 23 January 2007, 0 UTC (including the Kyrill peak at 18:00 UTC on 18 January 2007)

Up to the storm peak at 18:00 UTC on 18 January 2007, westerly winds have been observed at 62145 all the time with a sharp peak in the wind speed when the cyclone crosses the location. The atmosphere model of the DWD overestimated the measured peak of 22.6 m/s by 4 m/s and therefore the wave model calculated a maximum value of 7.92 m for H_s. This corresponds to an overestimation of 1.32 m at the peak. The increase of the significant wave height before and the decrease afterwards is well predicted by the wave model. The general agreement of the compared measured and computed wave heights for this location is good, especially taking into account that the modelled values are composed of forecasts only. This is also supported by the final results of the statistical analysis.

In order to complete the analysis of the comparisons between measured and computed data for Kyrill, a final check of the corresponding spectral information is done at the FINO platform. Figure 10 shows the spectral energy densities predicted by the wave model LSM on the left side (Fig. 10a) in comparison with those measured by WaMoS II on the right side (Fig. 10b).


a) WAM: 18.1.2007 18:00 UTC
wind speed: 22.8 m/s, direction: 103.7° (U_{10}),
H_s: 6.10 m, T_p: 9.4 s

b) WaMoS II: 18.1.2007 17:48 UTC
wind speed: 24.47 m/s, direction: 91.3° (U_{33}),
H_s: 5.20 m, T_p: 9.6 s

Fig. 10 WaMoS II and WAM model forecast spectra (energy densities in m^2*s/rad, normalized to 1) at FINO platform (direction: going to)

The energy distribution around the Kyrill peak time at 18:00 UTC for measured and computed energy densities with regard to intensity and position in the direction/frequency space agrees fairly well. According to the driving wind fields from westerly directions, the waves propagate to the east and the corresponding energy densities are therefore located around the 90° axis with maximum intensities at the 0.1 Hz line. This indicates that the waves during Britta were not only higher but also longer than those generated by the Kyrill wind fields.

4 Conclusions

Wind waves are natural hazards for ships, offshore platforms and the coastal environment. The operational wave forecast system of the DWD with its regional wave model for North Sea and Baltic Sea represents an appropriate warning tool for northern Europe to avoid losses due to rough seas with extraordinary high wind waves during extreme storm events. Extensive comparisons between measured and computed data for two selected winter storms show the capability of the regional wave model LSM to provide wave forecasts of reasonable quality for those. The sea states during both are representative for two different classes of extratropical cyclones in that area. With prevailing winds from northerly directions with a very long fetch along the longitudinal axes of the North Sea, serious damage to the marine environment can be expected. Winds of the same magnitude, but prevailing westerly directions are more dangerous on land. In this case, the fetch is short and the waves generated along the transverse axis of the North Sea are smaller and shorter. Although the results of this investigation show that the current status of the operational wave forecast model is already satisfactory, there is definitely room for improvements. The monthly statistical analysis of the comparisons between measured and computed data suggests urgently a revision of the atmosphere model, especially for wind above sea. If it would be possible to improve the driving force for the wind waves, a decrease for the bias in wind speed would directly reduce the positive bias in significant wave height. Furthermore, the wave model itself sometimes has problems during storm events to predict reasonable wave heights in shallow water near to the coasts due to insufficient dissipation. Therefore, a further source term will soon be added to the energy density balance equation of the operational wave model LSM that introduces the process of wave breaking (Battjes and Janssen 1978), so that this problem can be solved.

Acknowledgements The authors would like to thank Ocean WaveS in Lüneburg (www.oceanwaves.de) for the measured data recorded by WaMoS II at the FINO platform and for the permission to use their time series plot of the maximum wave height (Fig. 6) in this paper. Furthermore the authors grateful acknowledge the support by the BSH (Bundesamt für Seeschifffahrt und Hydrographie in Hamburg, www.bsh.de) for the permission to use their photo of the damage to the FINO platform during winter storm Britta (Fig. 4) and for the wave data recorded by their Wave Rider buoy at the FINO platform.

Appendix Mathematical description of statistical parameters

Mean of measurements and model values: $\bar{x} = \frac{1}{n}\sum x_i \ , \ \bar{y} = \frac{1}{n}\sum y_i$

Bias: $BIAS = \bar{y} - \bar{x}$

Root mean square error: $RMSE = \left[\frac{1}{n}\sum (y_i - x_i)^2\right]^{0.5}$

Slope of regression line: $SR = \left[\frac{\sum y_i^2}{\sum x_i^2}\right]$

Reduction of Variance (Skill): $RV = 1 - \frac{\sum (x_i - y_i)^2}{\sum (x_i - \bar{x})^2}$

Standard deviation:

$$\mathrm{STD} = \sqrt{\frac{1}{n-1}\sum\left(x_i - y_i - BIAS\right)^2}$$

Scatter-Index:

$$SI = \frac{STD}{\bar{x}} * 100$$

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