Wave analysis at Lubiatowo and in the Pomeranian Bay based on measurements from 1997/1998 – comparison with modelled data (WAM4 model)

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Barbara Paplińska
Institute of Hydro-Engineering,
Polish Academy of Sciences,
Kościerska 7, 80–953 Gdańsk, Poland;
e-mail: bep@ibwpan.gda.pl

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Abstract

The third generation WAM4 wave model was applied to the Baltic Sea. The computed significant wave height was compared with wave measurements for the periods October–November 1997 and February–May 1998. The calculations were conducted with wind fields obtained from the numerical weather prediction system at present in use as a quasi-operational system at ICM. Statistical analysis indicates good agreement between the modelled and measured significant wave height. Finally, a visualisation of wave fields is presented in the form in which it could be published in a daily meteorological forecast.

1. Introduction

Studies of sea waves in the Baltic Sea have a long history in Poland. The results of numerous projects have found application in many fields, such as maritime construction design, shore protection, coastal zone ecology and exploitation of underwater resources. Nevertheless, progress in these fields requires more and more precise information concerning the marine environment. Increasing shipping traffic needs reliable operational forecasts of sea waves. Besides atmospheric models, numerical wave models have become an important accessory tool for synoptics in operational services. As regards scientific utility, a validated model provides opportunities for simulating expensive field experiments; moreover, it is becoming a tool for achieving a good understanding of various wave-related phenomena, and can supply input data to hydrodynamical and ecological models.

The WAM4 wave model (WAve Modelling) was worked out by an international group of experts under the supervision of Prof. Hans Hasselmann. The model is in operation in hydrological services, for example, in Great Britain (UKMO), at the European Meteorological Centre (ECMWF), in the United States of America (NOAA) and in Germany for the North Sea area.

The present project was undertaken to evaluate the regional version of the WAM4 model in order to study waves in the Baltic Sea and ascertain its usefulness in forecasting. This model was used to calculate wave fields in the Baltic Sea during a total of 6 months in 1997 and 1998. The calculations for such a long period were performed on the hardware facilities of the Interdisciplinary Centre of Mathematical and Computational Modelling at Warsaw University (ICM). Wind fields are the basic input data for the wave model and in this particular case, the results of the mesoscale atmospheric model, functioning pre-operationally at ICM, were used in WAM4.

The calculations were conducted for the period in which field measurements were carried out at two locations along the Polish coast: in the vicinity of Niechorze and at Lubiatowo. This is the first time that wave measurements have been carried out in the Polish coastal zone for such a long period. They were used to verify the numerical calculations.

2. Materials and methods

2.1. Wave modelling in the Baltic Sea

The WAM4 numerical wave model, described in detail in a publication edited by Komen *et al.* (1994), was applied to the Baltic Sea. The principle on which this model is based involves the solution of the transport equation within spherical co-ordinates. The following physical processes are incorporated in the model: wave generation by wind, non-linear wave-wave interaction and whitecapping dissipation, bottom friction dissipation and wave-current interaction. The wind input and dissipation terms are based on Janssen's quasi-linear theory of wind-wave generation (Janssen 1989, 1991). He took into account the effect of the stage of wave development on the magnitude of exchanged energy. Parametrisation of the source function describing non-linear interaction of wave components was done after Hasselmann *et al.* (1981, 1985). Even though the basic form of the non-linear expression remained unchanged, the five-dimensional continuum of all resonance quadruplets was reduced to a two-dimensional one.

2.1.1. Calculation grid

The rotated equidistant projection was applied in the model. The central point in this projection was assigned the following geographical co-ordinates in the primary grid: 56°N and 19.3°E. The rotation is 0° and the grid step is 0.15° (*ca* 16.7 km) in both the latitudinal and the longitudinal directions. The calculation grid is shown in Fig. 1.

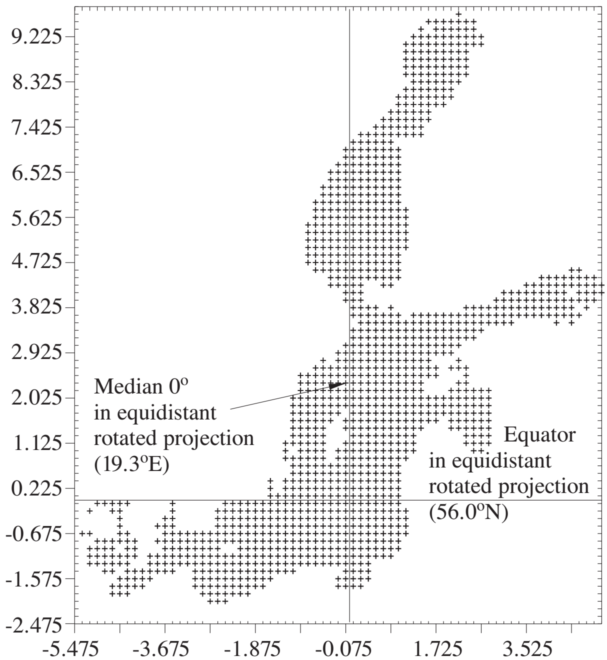


Fig. 1. Calculation grid for the Baltic Sea in equidistant rotated projection. The geographical co-ordinates of the primary projection are shown in parentheses

2.1.2. Description of input data for the model

The input data for the model are wind fields. The calculations are performed with wind fields obtained from the numerical weather prediction system at present in use as a quasi-operational system at ICM. The atmospheric model is a mesoscale version of the Unified Model of the United Kingdom and the system makes use of observational data and lateral boundary files prepared in the supporting meteorological centre, UKMO. The field data are verified and assimilated for calculations every 3 h.

The WAM4 wave model and the atmospheric model operate within the same calculation grid. This was found helpful in order to avoid errors due to the spatial interpolation of wind data. The atmospheric model produces wind fields of two types: predicted and analysed. The forecast is updated twice a day. Wind fields from forecasts are accessible every hour and the analysed ones every three hours. Only the analysed wind fields were applied in wave modelling. If the predicted wind field happened to be applied in the calculations, the difference is clearly indicated in the text.

2.1.3. The calculations

All calculations were performed on an NEC SX–4B/2A vector computer at ICM for the following periods:

- 1 October 1997 – 30 November 1997,
- 4 February 1998 – 31 May 1998.

The series of calculations was interrupted for some short periods when the atmospheric model did not operate and the wind fields were unattainable. The set up of WAM4 in all calculations is shown in Table 1.

Table 1. Set-up of WAM4 model

frequency-direction grid	25 frequencies ($f_{(n+1)} = f_n\,1.1$, $f_1 = 0.0505\,\mathrm{s}^{-1}$)
	24 directions (15°)
propagation time step	300 s
source function time step	150 s
output time step	3 h

2.2. Wave measurement in the Baltic Sea

Wave measurements were done using a Datawell Directional Waverider buoy. The locations and dates of measurements are listed in Table 2.

Table 2. Location of measurement stations

Location of measurements	Buoy co-ordinates in primary system	Buoy co-ordinates in rotated system	Water depth	Date
Pomeranian Bay, near Niechorze	54°08.950′N 15°02.950′E	−1.725° −2.475°	18 m	Oct., Nov. 1997
Lubiatowo	54°51.234′N 17°48.352′E	−1.137° −0.849°	20 m	Feb.–May 1998

3. Results and discussion

3.1. Comparison of wave model results with measurements

Calculations by the wave model yield a number of parameters at the nodes of the calculation grid: significant wave height, mean wave direction, mean wave period, peak period, wave-dependent drag coefficient, wave-induced stress, wave height of swell, mean direction of swell, mean wind sea direction and mean swell period. Additionally, a two-dimensional wave spectrum can be obtained at the assumed points of the time-space grid. In this project only the significant wave height was analysed.

The modelled significant wave height H_{m_0} (WAM4) was compared with the values of H_{m_0} (DWR) measured in the Pomeranian Bay (Niechorze) and in the coastal area at Lubiatowo. The location of the measurement points within the calculation grid is described in Table 3 and shown in Fig. 2.

Table 3. Location of measurement stations within the calculation grid

	Lubiatowo		Niechorze	
	latitude	longitude	latitude	longitude
co-ordinates of measurement station	−1.137°	−0.849°	−1.775°	−2.478°
co-ordinates of model point	−1.125°	−0.825°	−1.725°	−2.475°

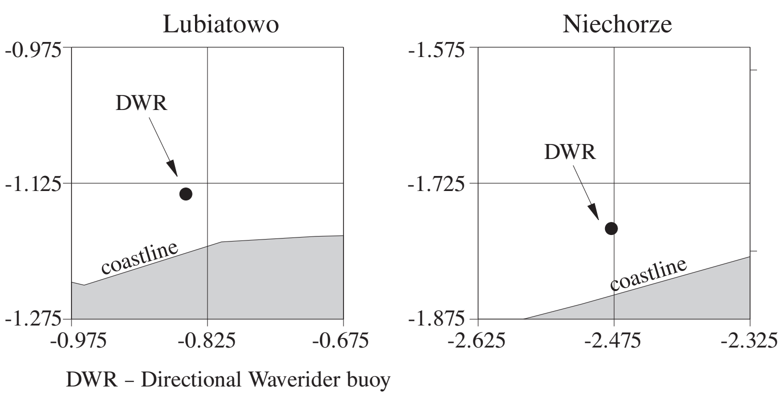


Fig. 2. Location of measurement stations within the calculation grid

Graphical illustrations of H_{m_0} (WAM4) and H_{m_0} (DWR) time series are presented in Figs. 3 and 4 for Niechorze and Lubiatowo respectively.

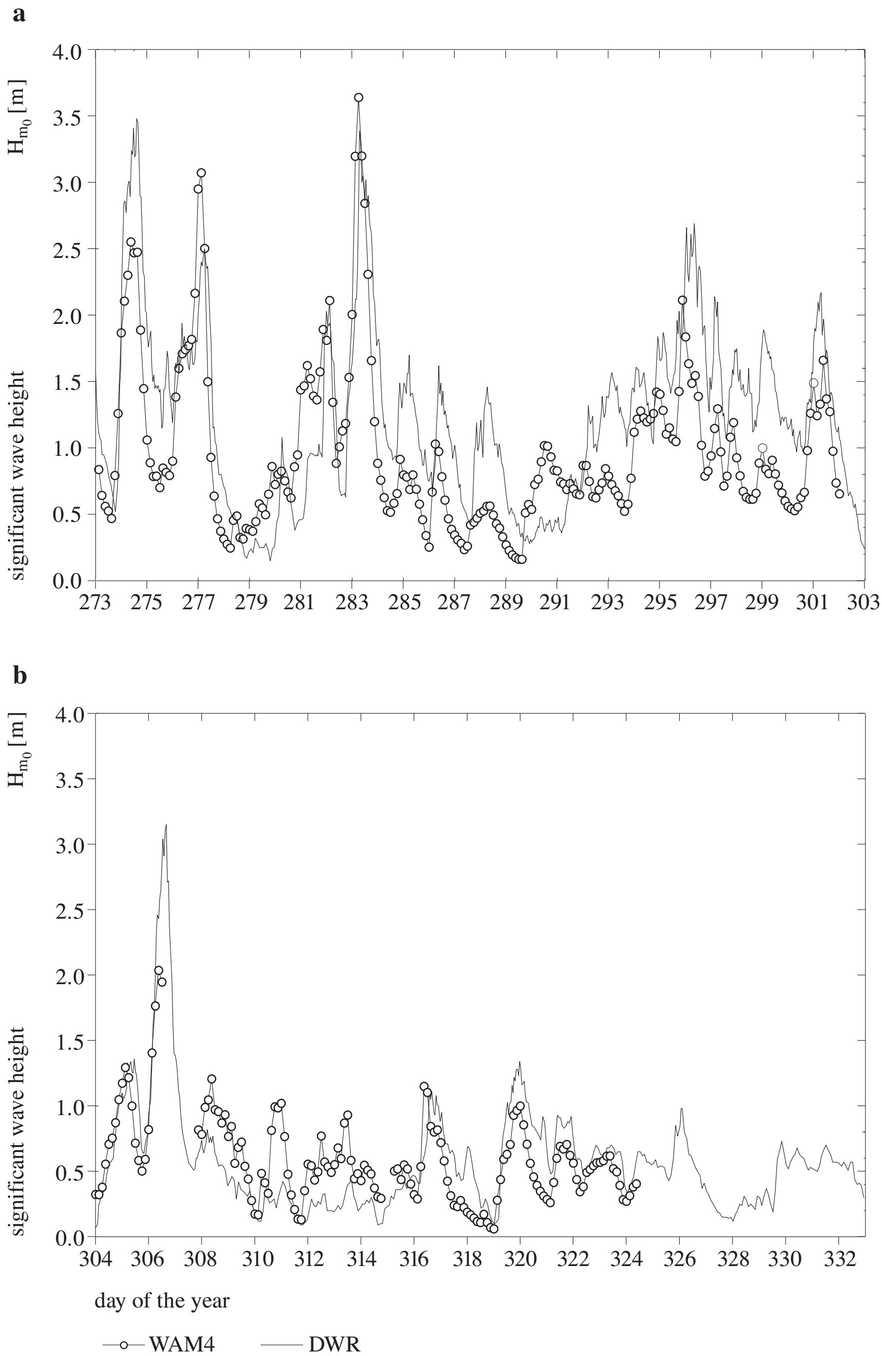


Fig. 3. Time series of significant wave height: experimental results from the Directional Waverider buoy (DWR) at Niechorze station and calculated by the WAM4 model (WAM4) in October 1998 (a) and November 1998 (b)

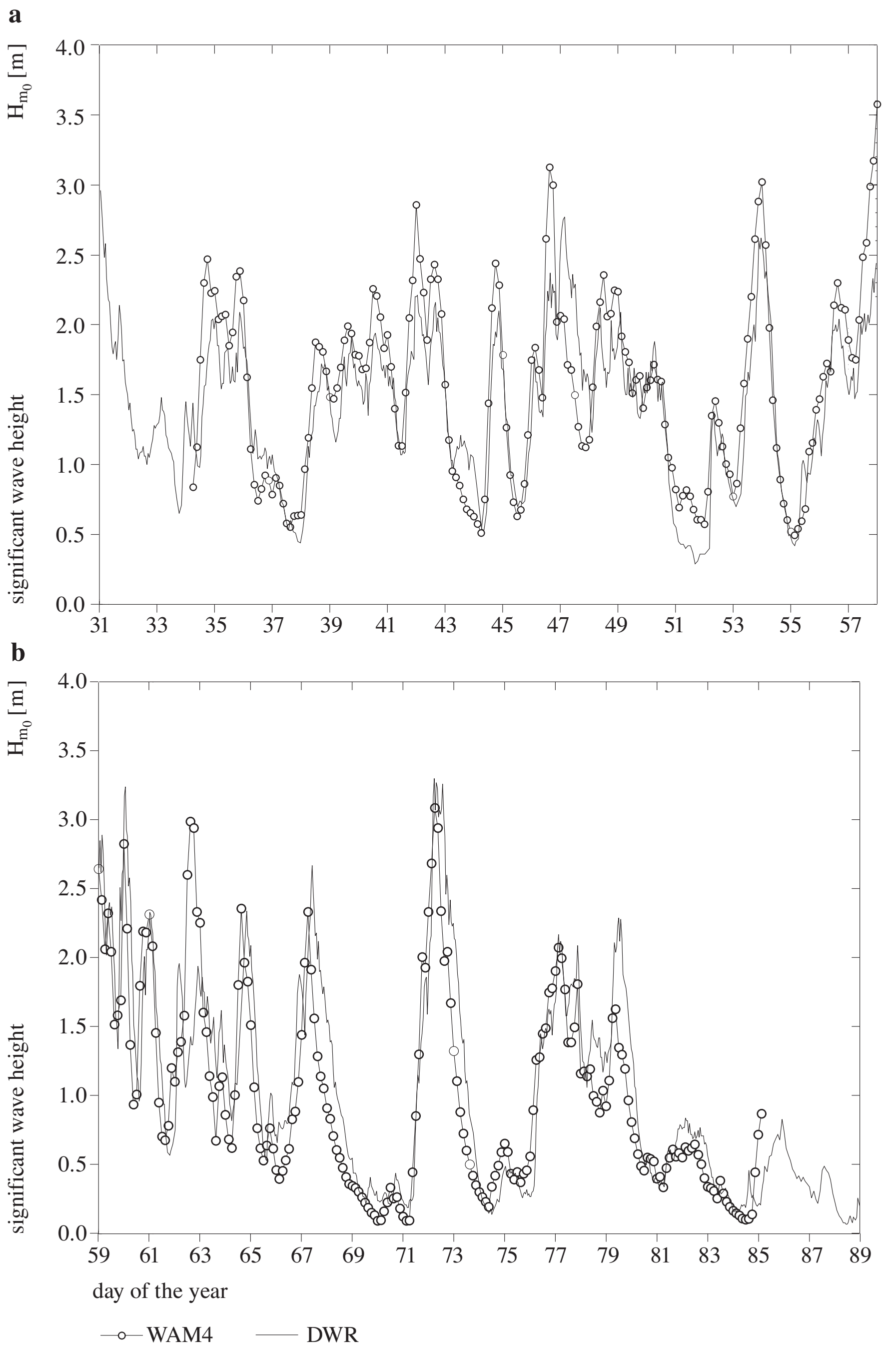
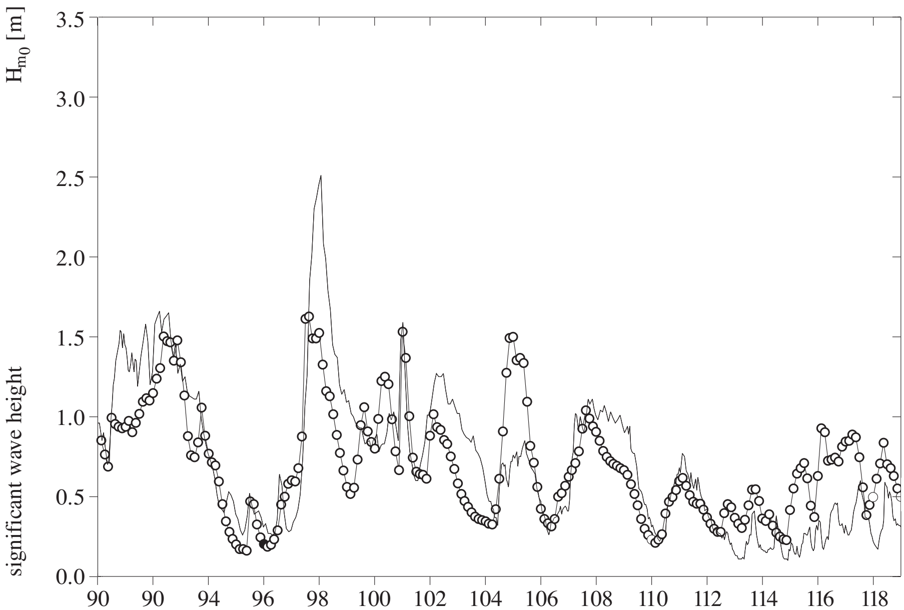


Fig. 4. Time series of significant wave height: experimental results from the Directional Waverider buoy (DWR) at Lubiatowo and calculated by WAM4 model (WAM4) in February 1998 (a), March 1998 (b), April 1998 (c) and May 1998 (d)

c



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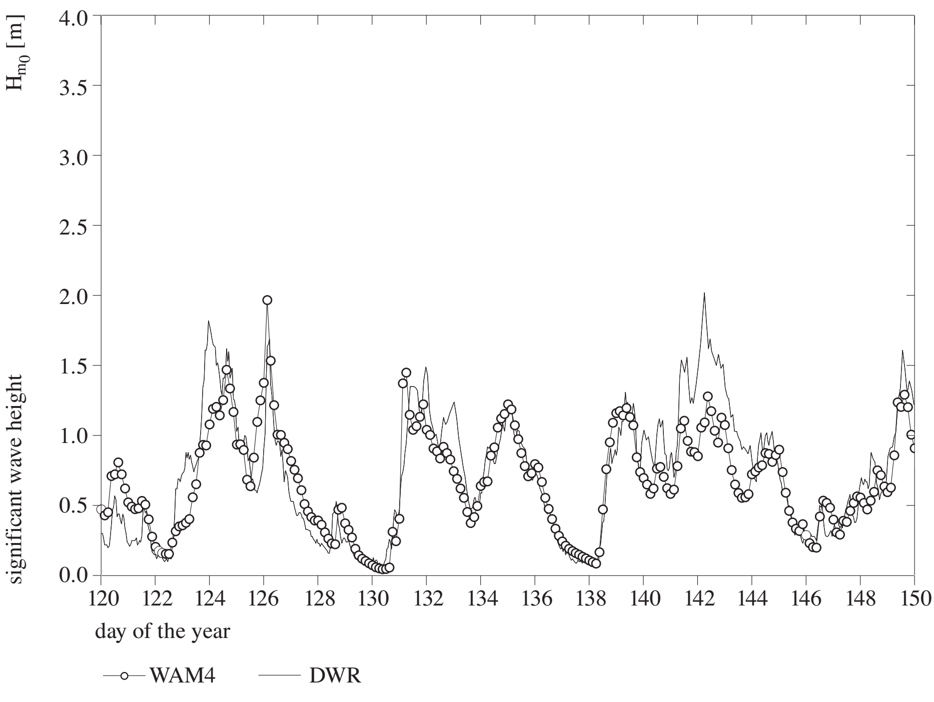

Fig. 4. (continued)

Inspection of the graphs shows that the results of modelling are comparable with the measured values, although greater differences were found in the data from Niechorze than in those from Lubiatowo. There is no explicit trend indicating that the modelled data have been over- or underestimaed with respect to the measured data.

Table 4. Statistics for the significant wave height at Lubiatowo and Niechorze

	Lubiatowo		Niechorze	
	measurements DWR	model results WAM4	measurements DWR	model results WAM4
number of data	875	875	383	383
mean value [m]	0.97	0.95	0.99	0.83
standard deviation [m]	0.63	0.64	0.67	0.55
variance	0.40	0.41	0.45	0.31
maximum value [m]	3.17	3.58	3.52	3.64
confidence level (95.0%)	0.04	0.04	0.07	0.06
	difference (DWR–WAM4)		difference (DWR–WAM4)	
maximum value [m]	1.19		1.13	
minimum value [m]	–1.56		–1.01	
standard deviation [m]	0.328		0.435	
Rms-error [m]	0.108		0.216	
Bias [m]	0.021		0.164	
reduction of variance	0.729		0.520	
correlation coefficient	0.87		0.76	
reliability index	1.47		1.77	

In the subsequent statistical analysis, the measurement time series was approximated by a spline function in order to reconstruct the data from the same time points (every 3 hours) as in the wave model. Then the basic statistical parameters were calculated: correlation coefficient, reliability index and reduction of variance. The calculated statistical parameters are listed in Table 4. The reliability index was taken as defined by Lagged & Williams (1981) in the form applied by Keen & Glenn (1997):

$$RI = \frac{1 + \sqrt{\frac{1}{N}\sum\limits_{i=1}^{N}\left(1 - \frac{Y_i}{X_i} \Big/ 1 + \frac{Y_i}{X_i}\right)^2}}{1 - \sqrt{\frac{1}{N}\sum\limits_{i=1}^{N}\left(1 - \frac{Y_i}{X_i} \Big/ 1 + \frac{Y_i}{X_i}\right)^2}}, \tag{1}$$

where
N – number of samples,
Y_i – measured values,
X_i – values calculated by the model.
The reliability index $RI = 1$ when there is an ideal fit between the field and modelled data; its value increases when the discrepancies between the data do so.

The reduction of variance is given by

$$RV = 1 - \frac{\sum\limits_{i=1}^{N} (Y_i - X_i)^2}{\sum\limits_{i=1}^{N} (Y_i - M)^2}, \tag{2}$$

where X_i, Y_i are described above and M is defined here as the mean of the sample. The reduction of variance compares the variance of the modelled value to the estimate M, based on the mean of the sample or on the climatologic mean. RV ranges from $-n$ to $+1$. A negative value implies that the mean (climate or sample) is a better predictor than the modelled value. $RV = 0$ implies that the forecast is no better than the mean and $RV = 1$ implies that there is no error in the modelled value.

The correlation coefficient was high at both Lubiatowo and Niechorze, that is to say the modelled representation of the wave height was very good. In the case of Lubiatowo, the mean and standard deviation were almost equal for the measurement series and for the modelled data. Greater differences appeared in the statistical parameters characterising the data from Niechorze, so the correlation coefficient was lower and the reliability index higher. The RV index is positive for both locations.

Wind fields are the key parameters in wave forecasting. Any inaccuracy introduced with the input wind field data is reflected as an error in the calculated wave fields. Cavaleri discussed in Komen *et al.* (1994) the impact of the input wind field on the modelled wave fields. He pointed out two factors that are important for the wind-wave relationship. Wind waves are sensitive to the slightest changes in the input data. In fully developed conditions $H \propto U^2$. A 10% accuracy in the prognosis rating is acceptable in meteorological forecasting, but an error of 10–20% in the predicted wave height or a 20–50% error in wave energy estimations render the forecast inadmissible in many cases. The spatial distributions of errors in wind and wave prognoses are quite different. The errors in wind forecasting are usually centred within a limited area, the errors being caused by local orographic influences or an atmospheric front. The consequences of these errors in wave forecasting are distributed throughout the modelled area and give rise to over- or underestimated forecasts for the entire basin.

The reliability index RI and correlation coefficient between the measured and modelled heights of significant waves were analysed relative to wind direction (Fig. 5). At Lubiatowo, the reliability coefficient decreased and the correlation coefficient increased with an offshore wind, which means that the representation of wave heights by the model was less precise for these directions. As regards the station at Niechorze, better results were obtained for winds blowing along the coast, both from the west and the east. The correlation coefficient of southerly winds was very small (0.01). The causes of the poorer correlation for offshore winds should be sought 1) in the size of the spatial calculation grid in the wave model (inaccuracies in reproducing the shoreline and bathymetry), and 2) in inaccuracies of the wind forecast due to the problems involved in taking account of the roughness of the substrate at the land-sea boundary.

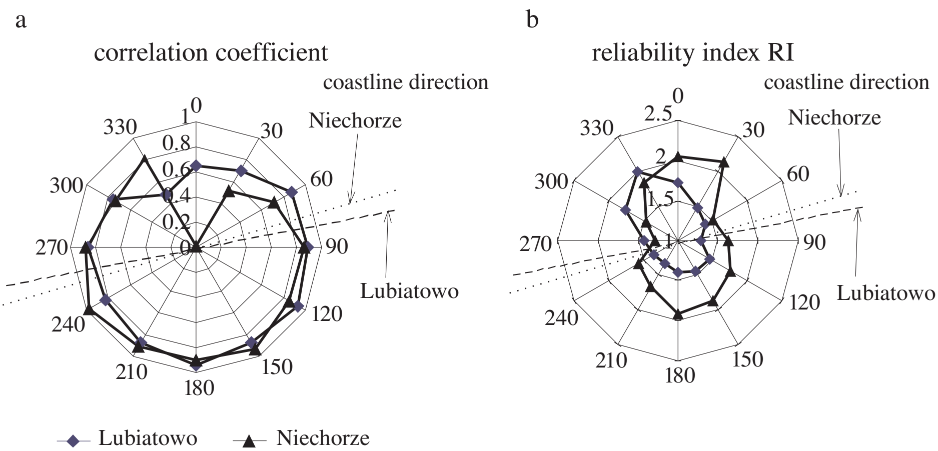

Fig. 5. Radar charts illustrating variations in correlation coefficient (a) and reliability index RI (b) in relation to wind direction. The direction of wind is defined as 'wind blowing to' (*e.g.* the direction of a southerly wind is 0°)

3.2. Application of model WAM4 in forecasting

The WAM4 wave model is applied in a number of countries in operational hydrological services. The regional version of the model presented in this paper can be used to predict wave height. Visualised information about predicted (24-hour forecast) waves is exemplified in Fig. 6 in the form in which it could be published in a daily meteorological forecast. A 24-hour wave forecast was prepared for a given period in February 1998 using the

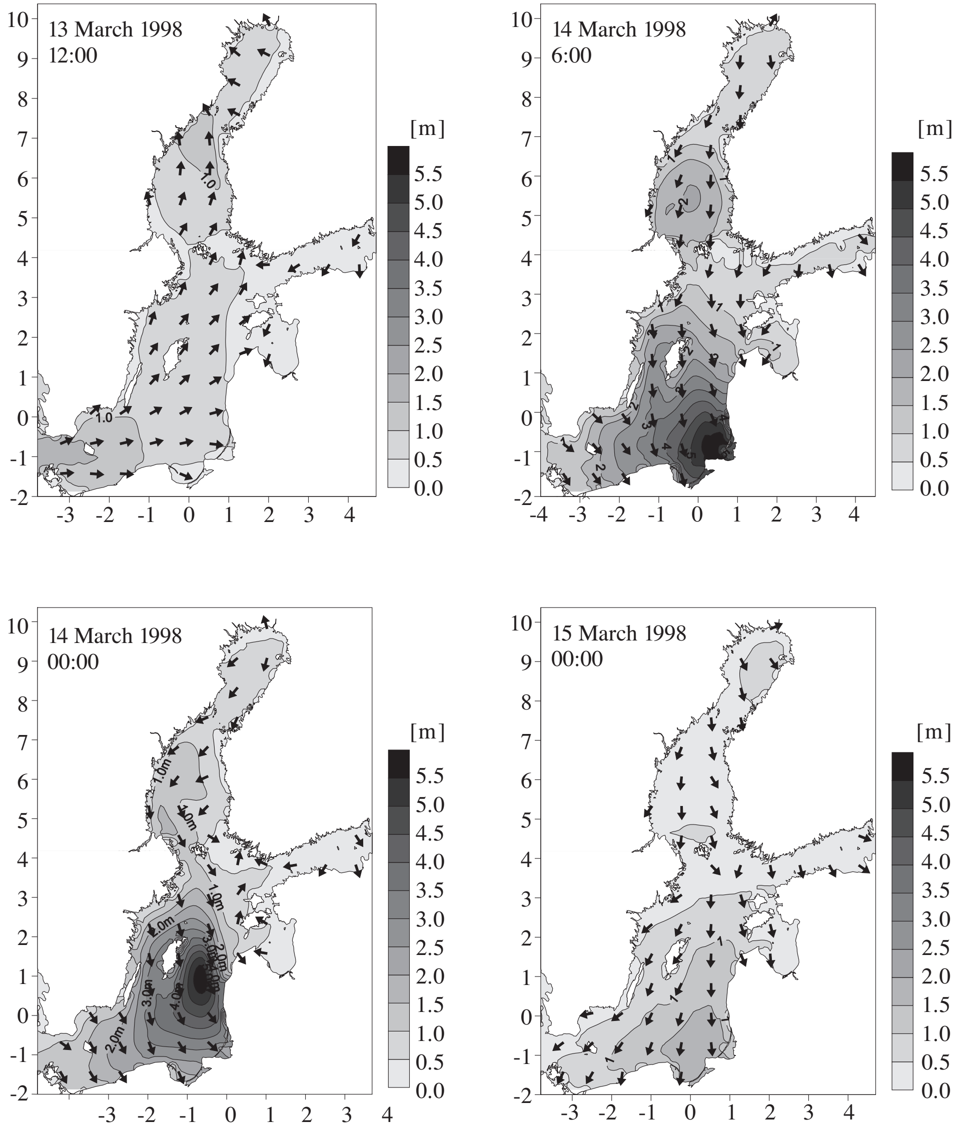

Fig. 6. Spatial distribution of significant wave height in the Baltic Sea in various development phases of the storm on 13–14 March 1998. The arrows indicate the mean wave direction

predicted wind fields (see Section 1). The measured significant wave heights were compared with those modelled using WAM4 to analyse the winds (Fig. 7). The preliminary results were positive – the predicted significant wave heights did not differ considerably from the values modelled from wind analysis.

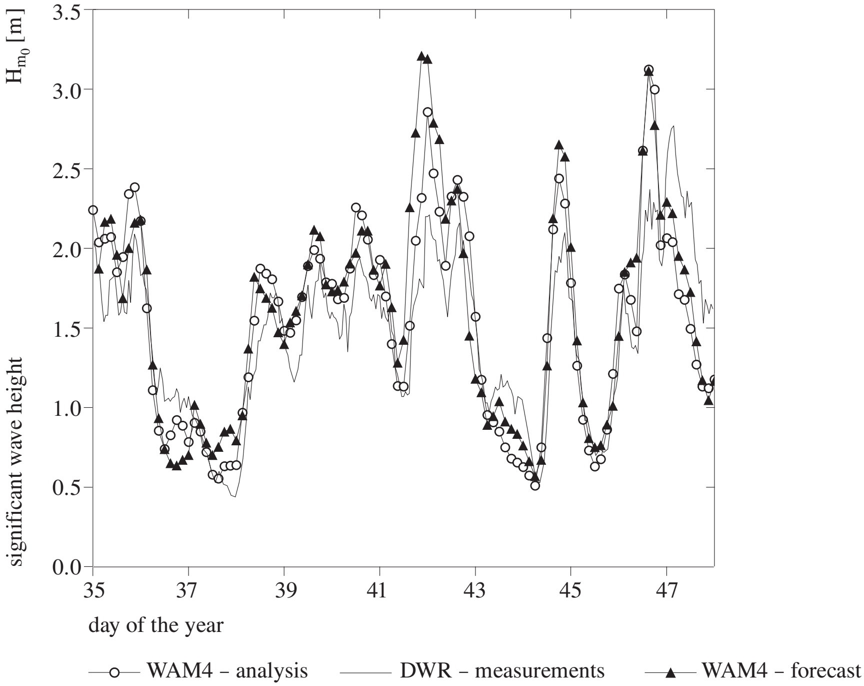

Fig. 7. Comparison of the significant wave height calculated by the WAM4 model using analysed winds (line with circles), calculated by the WAM4 model using winds predicted for 24-hours (line with triangles) and measured (line)

4. Conclusions

Wave measurements were carried out continuously for several months at two locations on the Polish coast of the Baltic Sea. The waves were also calculated using the WAM4 wave model for the same periods. The modelled results presented here are in very good agreement with the measured waves, even when the predicted winds were used in calculations. Applicable to a hindcast study of wave climate, the model also makes it possible to issue wave forecasts for the entire Baltic Sea area.

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References

Hasselmann S., Hasselmann K., 1981, *A symmetrical method of computing the non-linear transfer in a gravity-wave spectrum*, Hamb. Geophys. Einzelschr, Serie A, 52, 138 p.

Hasselmann S., Hasselmann K., 1985, *Computations and parametrizations of the non-linear energy transfer in a gravity-wave spectrum. Part 1. A new method for efficient computations of the exact non-linear transfer integral*, J. Phys. Oceanogr., 15, 1369–1377.

Jakubiak B., 1997, *Simulation of the frontal system evolution by NWP model*, Proc. INM/WMO Int. Symp. Cyclones and Hazardous Weather in the Mediterranean, Palma de Mallorca (Spain), 669–674.

Janssen P. A. E. M., 1991, *Quasi-linear theory of wind wave generation applied to wave forecasting*, J. Phys. Oceanogr., 21, 1631–1642.

Kenn T. R., Glenn S. M., 1997, *A quantitative skill assessment of numerical hydrodynamic models of coastal currents*, Proc. 4th Int. Conf. Estuarine and Coastal Modelling, October 1995, ASCE, New York, 26–24.

Komen G. J., Hasselmann K., Hasselmann S., 1984, *On the existence of a fully developed wind-sea spectrum*, J. Phys. Oceanogr., 14, 1271–1285.

Komen G. J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S., Janssenn P. A. E. M., 1994, *Dynamics and modelling of ocean waves*, Cambridge Univ. Press, Cambridge, 532 pp.

WAMDI group, 1988, *The WAM model – a third-generation ocean wave prediction model*, J. Phys. Oceanogr., 18, 1775–1810.