Wave Climatology and Extreme Value Analysis for the Baltic Sea Area off the Warnemünde Harbour Entrance

Gerhard Gayer, Heinz Günther and Norbert Winkel

UDC 551.466.326; Baltic Sea

Summary

A numerical wave model was used to determine the wave climate in the southern Baltic Sea. The basic data derived from wave hindcasts were evaluated statistically. Climate graphs were developed on the basis of continuous computations for the years 1988 through 1993. Extreme value statistics were derived from the results of hindcast computations for 40 storms in the years 1956–1993. The evaluation was made primarily with a view to redesigning the Warnemünde harbour entrance, but the data are also useful with respect to other areas of the Baltic Sea.

The paper describes the methods and models used in preparing the wind and wave fields. The model data are presented and compared with measurement data. On the example of a grid point off Warnemünde, the method of developing wave climatology and extreme value statistics on the basis of the model data is presented, and the results are discussed.

Seegangsklimatologie und Extremwertanalyse für das Seegebiet vor der Hafeneinfahrt von Warnemünde (Zusammenfassung)

Es wurde ein numerisches Seegangsmodell angewandt, um die Seegangsverhältnisse in der südlichen Ostsee zu ermitteln. Die durch Nachhersage des Seegangs erstellten Basisdaten wurden statistisch ausgewertet. Aus kontinuierlichen Berechnungen für die Jahre 1988 bis 1993 wurden Klimadiagramme erstellt. Extremwertstatistiken wurden aus den Ergebnissen der Hindcastrechnungen für 40 Stürme aus den Jahren 1956–1993 abgeleitet. Dabei stand die Auswertung für die Neugestaltung der Hafeneinfahrt von Warnemünde im Vordergrund, jedoch sind die Daten auch in anderen Gebieten der Ostsee entsprechend auswertbar.

Beschrieben werden die benutzten Methoden und Modelle zur Erstellung der Wind- und Seegangsfelder. Die mit den Modellen erstellten Daten werden vorgestellt und mit Naturmessungen verglichen. Am Beispiel eines Gitterpunktes vor Warnemünde wird die Aufbereitung der Modelldaten zu einer Seegangsklimatologie und einer Extremwertstatistik vorgestellt, und die Ergebnisse werden diskutiert.

1 Introduction

Detailed knowledge on local wave conditions is an essential prerequisite for designing marine structures. Apart from extreme events which constitute an immediate risk for such structures, it is important to know the wave climatology to prevent damage due to permanent stress.

Since long-term wave measurements, which are required for developing a wave climatology and an extreme value analysis, are not available in most cases, wave conditions are determined on the basis of the wind data recorded by weather services. Numerical wave models are suitable tools in performing such calculations.

Within the framework of a marine reconstruction project at the Warnemünde harbour entrance, GKSS Forschungszentrum Geesthacht (GKSS) on behalf of Bundesanstalt für Wasserbau (BAW), represented by Außenstelle Küste, investigated wave conditions off the Warnemünde harbour entrance by means of the HYPAS wave model (Gayer et al. [1993]).

For that purpose, wind and wave fields from the entire Baltic Sea were computed, and the results of 100 model grid points off the German coast were stored. On the basis of continuous computations for the years 1988 through 1993, climate graphs were established for selected points. Extreme value statistics were derived from the results of hindcast computations for 40 storms in the years 1956–1993.

2 Methods used

While the development of wave climatology requires a long, continuous time series of data, only the most extreme events in previous years are required for establishing extreme value statistics. To obtain significant statements, time series of at least five years are required for climatology. Typical input data used in developing extreme value statistics are the 20 maximum wave events (largest significant wave height) recorded in the past 50 years. Since wave measurements generally cover only very short periods of time at few locations, with data on extreme events missing completely in most cases, the data needed for establishing statistics were produced by hindcast computations using a numerical wave model.

2.1 Generation of wind input data

In order to carry out wave computations, it was necessary to obtain wind data for the period investigated covering the entire Baltic Sea. Since such fields are not available continuously for the past 50 years, two methods of wind data production have been used. With both methods, wind fields were produced at a reference height of 10 m (Bijvoet [1957]; Timmermann [1977]). Wind fields for the 5-year hindcast, required for the development of climatology, were derived from the atmospheric model of Amt für Wehrgeophysik (Geophysical Office of the Armed Forces) at Traben-Trarbach. The wind fields for the storm hindcast required for the extreme value statistics were computed at GKSS using surface pressure weather charts provided by Seewetteramt Hamburg (Office for marine meteorology).

2.1.1 5-year hindcast wind data

The wind fields obtained from Amt für Wehrgeophysik had a temporal resolution of 6 hours, and a spatial resolution of 127 km (01.01.1988–05.12.1988) or 63.5 km (05.12.1988–01.04.1993). For wave computations, these fields were interpolated onto the grid and time step of the wave model of 15.875 km and 15 minutes, with bilinear interpolation in space and nonlinear Fast Fourier transformations in time. Contrary to linear interpolation in time, this method takes into account the cyclone migration.

2.1.2 Wind data for storm hindcast

Basic data for the selection of storms were wind measurements carried out by Deutscher Wetterdienst (DWD, German Weather Service) at the meteorological station Rostock-Warnemünde. The hourly wind direction and speed data considered cover the period from 01.01.1954 through 21.04.1993 (approx. 40 years). The number of storms investigated was increased to make sure that the 20 maximum wave events were included in the extreme value analysis. The Rostock-Warnemünde measuring station is a landbased station with measurement data transferable only to a limited extent to conditions at sea. The data were suitable, however, for identifying storms.

The most severe wave events to which the Warnemünde harbour entrance is exposed arrive from northerly directions. Therefore, a period of gale-force winds was defined as a storm event if the wind came from one of the sectors indicated in Table 1 for more than 1 hour and had a wind speed greater than 15 m/s.

The wind time series comprised 402 storms. They were sorted and numbered in descending sequence according to wind speed maximum, mean wind speed, and duration. The storm number determined in this way was retained in all investigations that followed.

The next step was to compute the maximum wind speed, mean wind speed, and wind duration of the individual storm events for each directional sector, sorting the sectors as shown above. Table 1 shows the number of active storms for each directional sector, with some of the 402 storms represented in several sectors.

Since storms from the west and east sectors do not constitute a risk for the harbour, only the ten storms with maximum wind speeds from each of the directions WNW, NNW, N, NNE, and ENE were selected for the storm hindcast. Some of the storms were active in several sectors, and only 3 storms were found in the sector ENE, which explains the total number of 39 storms. They are represented in Table 2, together with the period to be computed, which was determined subjectively on the basis of the wind time series. At least one day preceding the storm event was considered, and the gradual wave decay was included as well. In cases where it was found, while determining the computation period, that the time series contained another gale occurrence prior to the active period, it was included in the computation period in order to allow for swell that may have been generated. The last columns of Table 2 show the results of the wave hindcast at the station "Warnemünde harbour" (cf. Table 6), which are discussed in chapter 6.

For producing the input wind fields of the storm hindcast, GKSS obtained the corresponding surface pressure charts (3 different chart types, scales 1:10 million, 1:15 million, and 1:20 million, for 0:00, 6:00, 12:00, and 18:00 hours) from the marine meteorological office.

The isobars were digitized with an accuracy of 1 mm onto a grid with a 1 mm resolution. Depending on the chart type, this corresponds to 10, 15, or 20 km in reality. The digitized isobars were interpolated onto a 47.625 km grid taking into account the pressure gradients and a distance weighting function. Fig. 1 shows an example of a contour representation of the pressure field. From the pressure fields, wind fields were generated taking into account the isobar curvature and air/water temperature differences (using the method described in Bijvoet [1957] and Timmermann [1977]).

After quality control, the fields were interpolated onto the wave model grid, as in the 5-year hindcast. Fig. 2 shows the wind field as a contour and vector representation superimposed on the wave model grid. To keep the illustration legible, only every 3rd vector is shown.

Table 1

Definition of wind directional sectors and number of storms active in the individual sectors

Sector	from (degree)	to (degree)	number
W	255	285	212
WNW	285	315	251
NNW	315	345	73
N	345	15	33
NNE	15	45	19
ENE	45	75	3
E	75	105	1

Table 2

Events selected for the storm hindcast. Storm number, period to be modelled, and active period (*M* = month, *T* = day, *S* = hour) are indicated. For the directional sector selected and each partial 30° sector, the duration (*D*) is indicated in hours, the maximum (*UP*) and mean (*UQ*) wind speed in m/s, and the direction (*R*) of maximum speed (in degrees). The last columns show, for the station "Warnemünde harbour", the hindcast based maximum significant wave height (H_s) in metres, the corresponding peak period (T_p) in seconds, and the wave direction (R_s) in degrees, together with the maximum wind speed (*UP*) in m/s reached during the storm and the direction (R_w) of maximum speed (in degrees). Two storms were not modelled because weather charts were not available

		Computation from			Computation to		Active period from		Active period to		255 < R < 105			
No	Year	M	T	S	T	S	T	S	T	S	D	UP	R	UQ
1	1969	11	9	0	12	0	10	5	10	7	3	29,5	300	24,5
2	1972	11	12	0	15	0	13	13	13	20	8	29,0	280	23,6
3	1968	1	9	0	17	0	11	5	12	10	30	27,6	330	20,1
4	1971	3	10	0	13	0	10	23	11	16	18	27,0	290	22,3
7	1962	2	14	0	19	0	16	12	17	11	24	25,2	270	20,1
8	1964	11	16	0	20	0	17	2	17	9	8	25,2	293	19,4
10	1992	11	25	12	27	12	26	10	26	12	3	24,8	300	20,9
11	1955	1	16	0	18	0	17	4	17	12	9	24,7	338	20,3
12	1961	3	30	12	1	12	31	16	31	20	5	24,5	293	20,6
14	1986	1	18	0	21	0	20	2	20	5	4	24,0	310	21,3
15	1973	11	22	12	27	0	24	21	25	6	10	24,0	290	20,8
16	1986	10	19	12	22	0	21	0	21	6	7	24,0	350	20,6
17	1971	11	15	0	19	0	17	0	17	23	24	24,0	300	19,4
33	1964	2	3	0	8	0	5	6	5	22	17	22,5	293	18,3
43	1964	11	16	0	20	0	18	4	18	17	14	22,0	315	18,2
45	1965	2	26	0	28	12	27	2	27	13	12	21,8	338	18,8
47	1969	10	26	0	2	12	29	7	31	0	42	21,6	300	17,9
56	1975	3	27	0	30	0	28	17	28	21	5	21,0	340	18,6
61	1986	12	18	0	21	0	19	12	19	19	8	21,0	360	17,7
62	1967	12	2	12	8	12	3	19	4	10	16	20,8	330	18,9
63	1969	9	30	0	3	12	1	10	2	12	27	20,8	330	18,1
67	1970	12	2	12	4	12	3	12	3	13	2	20,4	360	18,8
74	1987	1	9	12	14	0	12	15	12	22	8	20,0	40	18,9
79	1976	12	24	0	27	0	25	23	26	9	11	20,0	320	18,0
81	1979	8	9	12	11	0	10	10	10	13	4	20,0	360	18,0
86	1989	8	27	12	30	0	28	17	28	22	6	20,0	360	17,8
97	1969	2	14	0	17	0	15	22	16	7	10	19,9	30	17,3
110	1960	1	12	0	15	0	13	18	14	5	12	19,2	23	17,6
122	1973	12	3	0	10	12	8	18	8	20	3	19,0	20	17,7
130	1954	1	1	0	6	0	4	9	4	15	7	19,0	360	17,4
158	1954	11	7	0	9	0	8	7	8	10	4	18,3	23	17,0
162	1965	11	20	0	23	0	21	17	21	21	5	18,1	23	17,2
165	1980	12	2	12	4	12	3	16	3	19	4	18,0	340	17,7
180	1957	12	12	12	16	0	14	3	14	8	6	18,0	45	17,1
186	1988	2	24	12	26	12	25	21	25	22	2	18,0	40	17,0
193	1987	1	9	12	14	0	12	6	12	9	4	18,0	50	16,8
196	1971	12	27	0	30	12	29	14	29	16	3	18,0	20	16,7
201	1986	11	1	0	7	0	2	0	2	2	3	18,0	40	16,7
224	1969	11	25	0	30	12	26	7	26	9	3	17,4	60	17,1

	WNW				NNW				N			
No	D	UP	R	UQ	D	UP	R	UQ	D	UP	R	UQ
1	1	29,5	300	29,5	0				0			
2	2	28,0	290	27,0	0				0			
3	3	20,4	300	18,3	9	27,6	330	23,4	18	21,6	360	18,8
4	12	27,0	290	23,3	4	23,0	320	20,0	0			
7	12	24,3	293	20,0	0				0			
8	6	25,2	293	20,4	0				0			
10	3	24,8	300	20,9	0				0			
11	3	23,1	315	21,0	5	24,7	338	20,4	1	17,8	360	17,8
12	4	24,5	293	20,1	0				0			
14	2	24,0	310	24,0	2	20,0	320	18,5	0			
15	6	24,0	290	20,8	0				0			
16	0				4	24,0	340	19,0	3	24,0	350	22,7
17	10	24,0	300	20,7	0				0			
33	14	22,5	293	18,2	2	21,6	338	18,7	0			
43	8	22,0	315	18,2	6	21,5	338	18,3	0			
45	2	20,5	315	19,6	10	21,8	338	18,6	0			
47	14	21,6	300	18,2	28	21,6	330	17,7	0			
56	0				2	21,0	340	20,0	3	19,0	350	17,7
61	0				0				8	21,0	360	17,7
62	10	20,6	300	19,1	6	20,8	330	18,6	0			
63	14	19,5	300	18,0	13	20,8	330	18,2	0			
67	0				0				2	20,4	360	18,8
74	0				0				0			
79	1	16,0	290	16,0	8	20,0	320	18,2	2	19,0	350	18,0
81	0				0				4	20,0	360	18,0
86	0				0				6	20,0	360	17,8
97	0				0				0			
110	0				0				0			
122	0				0				0			
130	0				0				7	19,0	360	17,4
158	0				0				2	16,4	360	15,9
162	0				0				0			
165	0				3	18,0	340	17,7	1	18,0	350	18,0
180	0				0				0			
186	0				0				0			
193	0				0				0			
196	0				0				0			
201	0				0				0			
224	0				0				0			

	NNE				ENE				Warnemünde harbour Hindcast				
No	D	UP	R	UQ	D	UP	R	UQ	Hs	Tp	Rs	UP	Rw
1	0				0				2,9	7,9	282	22,0	276
2	0				0				2,7	6,8	303	25,6	299
3	0				0				3,6	9,0	3	30,2	356
4	0				0				3,3	8,2	332	23,0	346
7	0				0				No weather charts.				
8	0				0				2,6	7,4	296	21,6	289
10	0				0				2,7	7,1	273	18,8	279
11	0				0				2,6	7,0	315	24,0	323
12	0				0				2,9	7,5	296	26,6	286
14	0				0				2,9	7,5	297	25,8	293
15	0				0				2,9	7,9	275	22,8	256
16	0				0				3,1	7,6	303	28,2	309
17	0				0				2,9	7,8	287	26,8	270
33	0				0				2,8	7,6	310	20,4	320
43	0				0				2,5	7,5	309	17,6	300
45	0				0				3,1	7,4	352	25,8	345
47	0				0				2,5	8,0	297	17,0	293
56	0				0				1,6	5,5	49	14,2	45
61	0				0				2,3	6,3	315	21,0	315
62	0				0				No weather charts.				
63	0				0				3,1	8,1	289	24,4	267
67	0				0				2,1	6,0	350	15,0	356
74	5	20,0	40	19,2	3	19,0	50	18,3	3,3	9,9	35	18,4	38
79	0				0				2,3	6,5	358	16,0	355
81	0				0				1,5	5,5	358	9,6	336
86	0				0				1,9	5,9	329	14,0	340
97	10	19,9	30	17,3	0				2,9	8,5	39	19,0	35
110	12	19,2	23	17,6	0				3,1	9,0	42	17,4	51
122	3	19,0	20	17,7	0				2,1	6,7	9	15,8	9
130	0				0				3,5	8,2	269	30,2	263
158	2	18,3	23	18,0	0				1,6	5,4	3	11,6	12
162	5	18,1	23	17,2	0				2,8	8,2	48	15,2	62
165	0				0				1,9	5,9	342	14,4	345
180	6	18,0	45	17,1	0				3,6	10,1	33	20,8	45
186	2	18,0	40	17,0	0				2,8	8,2	56	15,4	42
193	0				4	18,0	50	16,8	Maximum in storm 74				
196	3	18,0	20	16,7	0				2,6	8,1	52	13,6	61
201	3	18,0	40	16,7	0				1,7	5,5	356	14,0	338
224	0				3	17,4	60	17,1	2,0	6,7	18	12,8	9

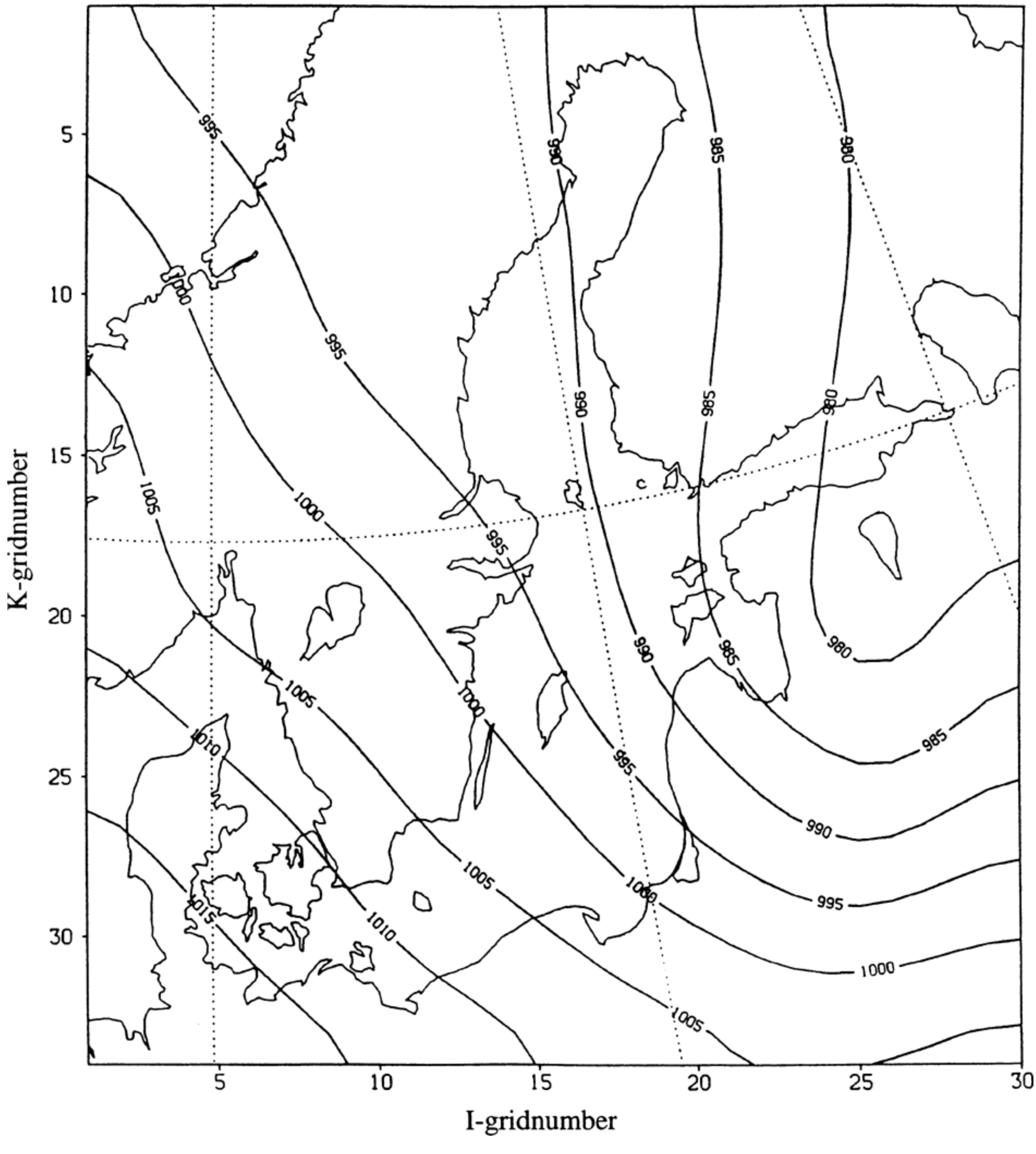

Fig. 1 Contour lines of the pressure field of 23. 11. 1973 12:00 hours interpolated onto the 47.625 km grid (3-fold wave grid spacing)

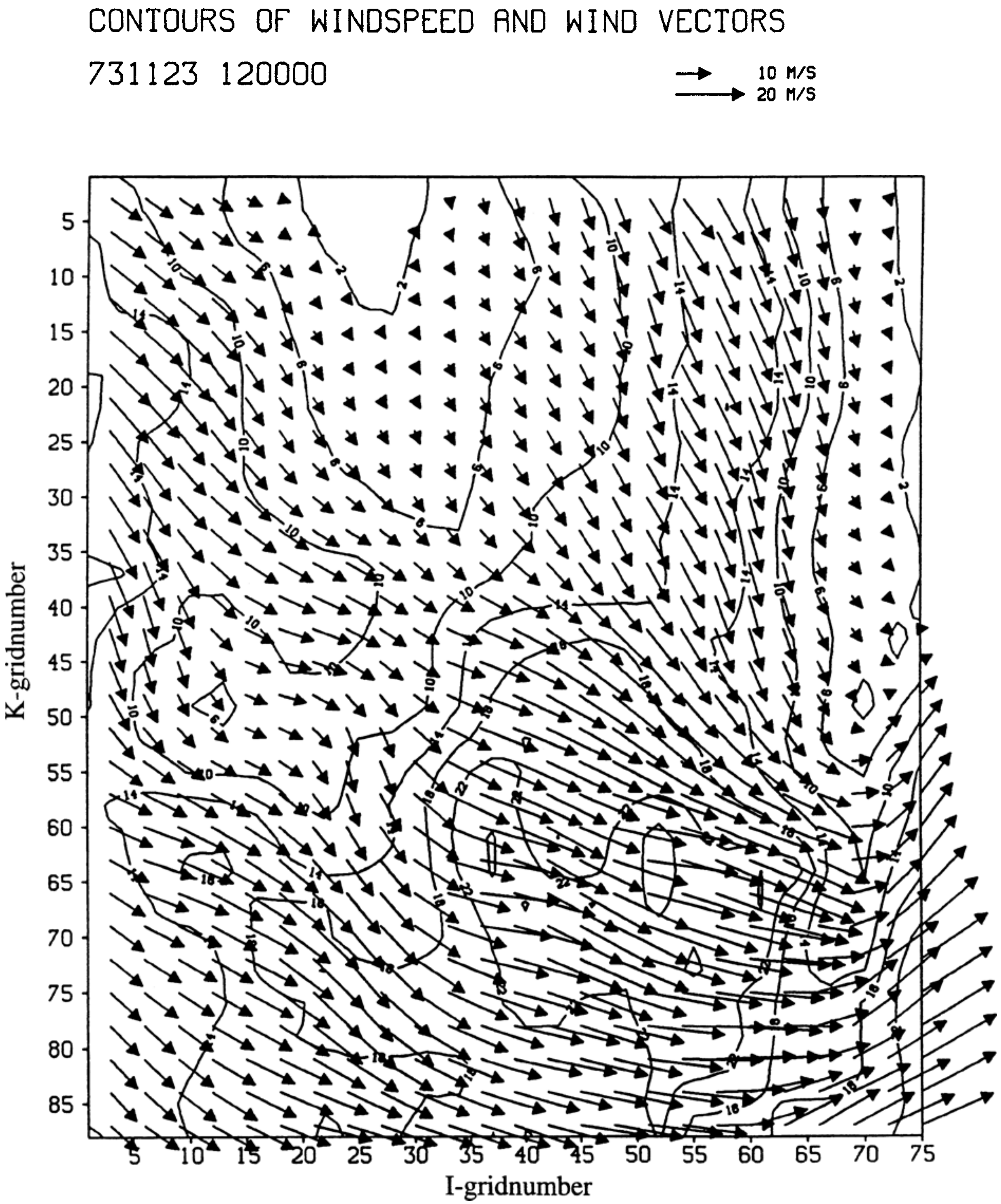

Fig. 2 Contour lines and vectors of the wind field of 23.11.1973 12:00 hours computed from the interpolated pressure field. For reasons of legibility, only every 3rd vector is shown on the wave model grid.

2.2 Wave model

The wave model installed on the Cray2 computer of Klimarechenzentrum (climate computation centre) Hamburg both for the 5-year and the storm hindcast is the shallow water version HYPAS (HYbrid PArametrical Shallow Water Wave Model, G ü n t h e r et al. [1983; 1984]) of the HYPA wave model (G ü n t h e r et al. [1979; 1981]), which GKSS uses for this type of application.

In the wave model, the development in time and space of the two-dimensional energy density spectrum $F(f,\Theta)$ was computed in frequency and direction space, discretized with 17 frequency and 24 direction intervals. This computation was carried out at each of the 1709 grid points (cf. Fig. 3) of the wave model grid (resolution 15.875 km) and at each computation time step (15 minutes).

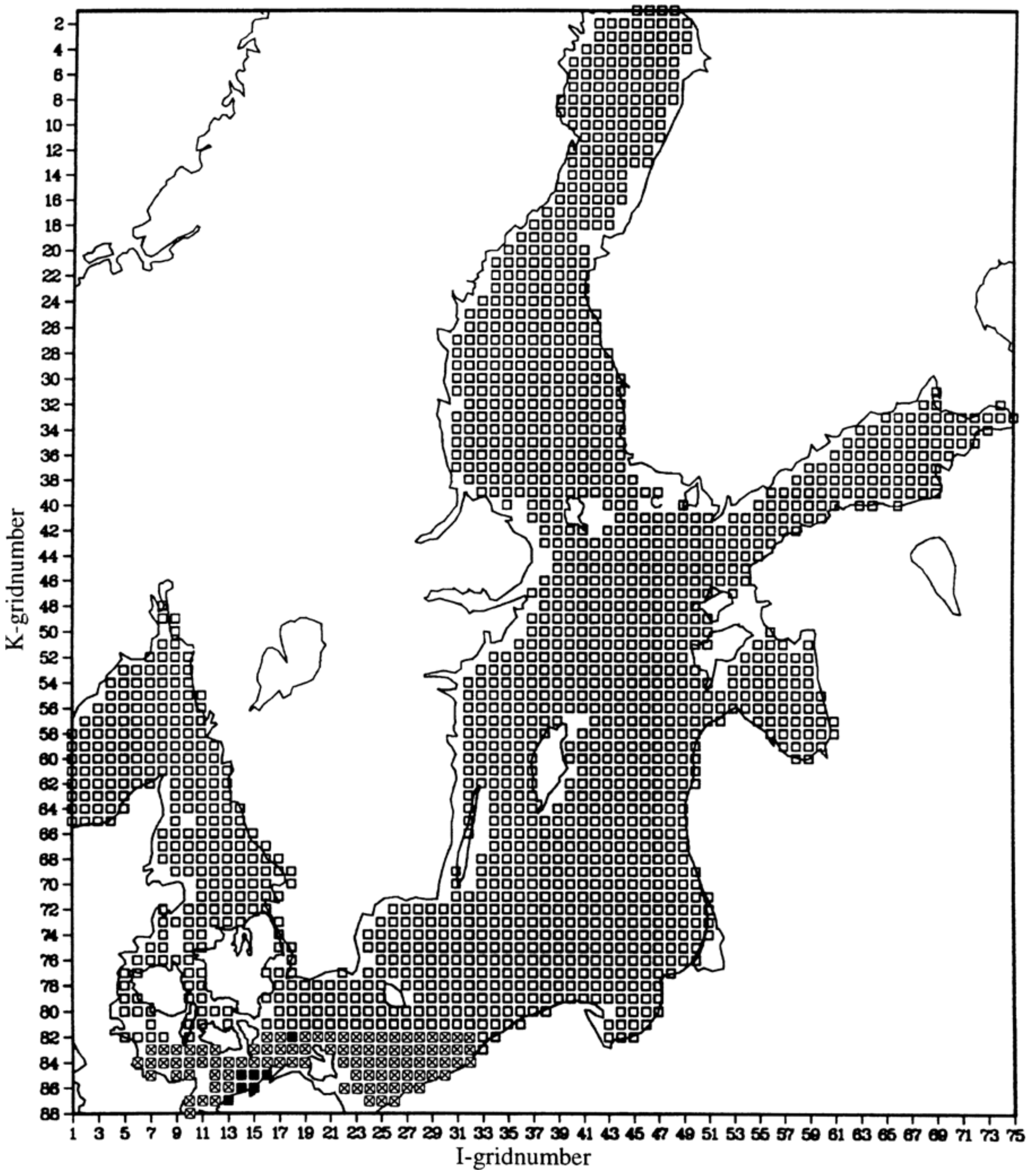

Fig. 3 Grid of HYPAS wave model. The squares indicate the computation points of the model. At the points marked by full squares (cf. Table 6), a statistical evaluation was made. The area of the southern Baltic Sea for which the 100-point model data sets are available is marked by squares filled with crosses.

For that purpose, the energy transport equation was solved for the wind sea part using a parametrical method based on the TMA spectrum (B o u w s et al. [1985]), and for the swell part based on characteristics. The energy transport equation contains the propagation, refraction, and shoaling terms and, on the right side, the source terms divided into energy input due to wind forcing, nonlinear interaction, and energy dissipation.

$$\frac{\partial F}{\partial t} + v_x \frac{\partial F}{\partial x} + v_y \frac{\partial F}{\partial y} + \dot{\Theta} \frac{\partial F}{\partial \Theta} = S_{in} + S_{nl} + S_{dis}$$

This necessitated various input fields:

- The water depth has to be provided for each grid point in order to make allowance for shallow water effects such as refraction, shoaling, and energy dissipation. For that purpose, a depth data set digitized from nautical charts was used.
- A wind vector value (cf. 2.1) had to be provided to force wave generation for each grid point and at each time step.

3 Model output data sets

With the wave model, two data sets were computed and extracted for the 100 grid points in the southern Baltic Sea, for the computation periods concerned. Model output for the 5-year hindcast was in 3-hour time steps, and for the storm computation in 1-hour steps.

The data sets contain the two-dimensional spectra, i.e. the energy density values in each interval of the frequency-direction space, as well as quantities derived from the spectra:

Starting from the two-dimensional energy density spectrum $F(f,\Theta)$, the moments m_i of the order $i = 1, ..., n$ are computed as

$$m_i = \iint F(f, \Theta) f^i \, df \, d\Theta$$

and the one-dimensional energy density spectrum $E(f)$ as

$$E(f) = \int F(f, \Theta) \, d\Theta$$

By means of the 0th moment, the significant wave height is obtained as

$$H_s = 4 \sqrt{m_0}$$

Through the first or second moments, the two following periods are defined:

$$T_{m1} = m_0 / m_1$$

$$T_{m2} = \sqrt{m_0 / m_2}$$

The peak period T_p is defined by

$$T_p = f_{max}^{-1} \text{ at the point } E(f_{max}) = \max \{E(f)\}$$

the maximum of the one-dimensional spectrum $E(f)$ being determined by means of an interpolated parabola.

The mean wave direction is defined as:

$\bar{\Theta} = \text{atan2}\,(s_0, c_0)$, with the integrals

$$c_0 = \iint F(f, \Theta) \cos\Theta \, df \, d\Theta$$
$$s_0 = \iint F(f, \Theta) \sin\Theta \, df \, d\Theta$$

4 Verification

Wave measurement data were available from two stations:

1. Time series of the significant wave height (H_S), obtained from buoy measurements off the Warnemünde harbour entrance: Wave Rider buoy operated by Bundesamt für Seeschiffahrt und Hydrographie (BSH, Federal Maritime and Hydrographic Agency), positioned at 12° 5.2' east and 54° 11.65' north at the 10 meter water depth contour. The model grid point with the coordinates 12° 1.2' east and 54° 13.8' north closest to this position, the station "Warnemünde harbour", had a water depth of 13 m.
2. Time series of the significant wave height (H_S) and peak period (T_p) of buoy measurements off Zingst: The grid point closest to the GKSS wave buoy in the measuring field off Zingst (21 m water depth) is the station "Zingst" with a model water depth of 19 m and a geographical position of 12° 46.2' east and 54° 45.6' north. Time series of the significant wave height and peak period at irregular intervals were available. From these series, in the time from 01. 05. 1992 00:00 hours to 31. 12. 1992 21:00 hours, 1299 points in time were selected for the significant wave height, and 1296 for the peak period, making sure that they were closest to the 3-hourly model output times.

For a statistical comparison (as in Günther et al. [1993]) of the computations (x_i) with the measurements (y_i), the following parameters were computed from the time series: (N shall be the number of values contained in the time series):

– max. model value $x_{\max}$ and max. measured value $y_{\max}$

$$x_{\text{Max}} = \operatorname*{Max}_{i=1}^{N} \{x_i\} \qquad\qquad y_{\text{Max}} = \operatorname*{Max}_{i=1}^{N} \{y_i\}$$

– mean value of computations x_q and mean value of measurements y_q

$$x_q = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad\qquad y_q = \frac{1}{N}\sum_{i=1}^{N} y_i$$

– Scatter of computations S_x and measurements S_y around their mean value

$$S_x = \left(\frac{1}{N-1}\sum_{i=1}^{N} (x_i - x_q)^2\right)^{0.5} \qquad\qquad S_y = \left(\frac{1}{N-1}\sum_{i=1}^{N} (y_i - y_q)^2\right)^{0.5}$$

– Maximum difference between measurement and model

$$d_{\text{Max}} = \operatorname*{Max}_{i=1}^{N} \{|\, y_i - x_i \,|\}$$

– Mean deviation between measurement and model

$$d_q = \frac{1}{N}\sum_{i=1}^{N} (y_i - x_i)$$

– Standard deviation between measurement and model

$$S_d = \left(\frac{1}{N-1} \sum_{i=1}^{N} \{(y_i - y_q) - (x_i - x_q)\}^2 \right)^{0.5}$$

– Correlation between measurement and model

$$Cor = \left[\sum_{i=1}^{N} (y_i - y_q)(x_i - x_q) \right] / \left[\sum_{i=1}^{N} (y_i - y_q)^2 \sum_{i=1}^{N} (x_i - x_q)^2 \right]^{0.5}$$

– Scatter index between measurement and model

$$Scat = 100 \cdot S_d / y_q$$

Table 3 shows the statistics of the comparison between modelled and measured significant wave heights (H_S) off Warnemünde in the months February and March 1993, as well as in the entire period. The maximum measured wave height (y_{Max}) in these two months is 2.11 m, 11 cm higher than the model value (x_{Max}). While the mean values (x_q and y_q) differ by d_q = 10 and d_q = –7 cm in the individual months, the difference over the whole period, at –1 cm, is negligible. The scatter of measurements (S_y) and computations (S_x) around their mean values is about 53 cm. An exception is the measurements in March, with a scatter of 33 cm. The standard deviations between measurement and model of S_d = 29 cm in February, 35 cm in March, and 33 cm in the whole period are smaller than the scatter of the individual data sets. The scatter index (Scat) of 46%, which scales the standard deviation with the inverse mean value of the measurements, and the correlation (Cor) of 0.80 are acceptable for this order of magnitude of wave heights. The fit of model and measurements achieved at "Warnemünde harbour" was very good also by international standards (standard deviation (S_d) smaller than 50 cm with significant wave heights below 5 m, and almost no bias (d_q); cf. for example Cavaleri et al., discussion on page 307).

Table 3

Statistics of comparison of modelled and measured significant wave heights off Warnemünde in February and March 1993, and of the total data

Month 1993	Number	Model x_{Max} (m)	Model x_q (m)	Model S_x (m)	Buoy y_{Max} (m)	Buoy y_q (m)	Buoy S_y (m)	Buoy-Model d_{max} (m)	Buoy-Model d_q (m)	Buoy-Model S_d (m)	Buoy-Model Cor	Buoy-Model Scat %
2	99	2,00	0,69	0,53	2,11	0,79	0,52	0,79	0,10	0,29	0,84	42
3	176	1,90	0,73	0,54	1,71	0,66	0,33	0,79	-0,07	0,35	0,77	49
Total	275	2,00	0,72	0,54	2,11	0,71	0,40	0,79	-0,01	0,33	0,80	46

Table 4 shows the statistics of the comparison of modelled and measured significant wave heights at the buoy off Zingst from May through December 1992. In comparison with the results for the station "Warnemünde harbour", the maximum significant wave heights at the station "Zingst", at 2.60 m, are higher. This is due to the larger water depth of the measuring and model station and to the fact that it is located more toward the open sea. A general trend toward higher maximum values either in the measurements or in the model is not observed. The maximum differences found (d_{max}) vary between 0.80 m in December and 2.10 m in November. The mean deviation values in the individual months are much lower (min. 2 cm in July and max. 40 cm in October). In the total statistics, these differences disappear completely. The mean deviation between model and measurement data is 4 cm, with a mean measured value of 79 cm, and a mean computed value of 75 cm. The model data generally scatter slightly more around the mean value than the buoy measurement data. In the total statistics, the difference reduces to 7 cm (48 cm for the model data, 41 cm for the measurements). The correlation of 0.81 (all data) is comparable to that at the station "Warnemünde harbour", although here the scatter index of 38% is slightly better.

Table 4

Statistics of comparison of modelled and measured significant wave heights at the station "Zingst" in May to December 1992, and of the total data

		Model			Buoy			Buoy-Model				
Month 1992	Number	x_{Max} (m)	x_q (m)	S_x (m)	y_{Max} (m)	y_q (m)	S_y (m)	d_{max} (m)	d_q (m)	S_d (m)	Cor	Scat %
5	170	2,60	0,79	0,52	1,90	0,51	0,30	1,20	-0,28	0,31	0,85	39
6	177	1,90	0,78	0,52	2,00	0,66	0,40	1,40	-0,12	0,35	0,74	45
7	196	2,10	0,69	0,53	2,00	0,67	0,44	0,90	-0,02	0,30	0,82	43
8	176	2,20	0,94	0,48	2,10	0,77	0,38	1,30	-0,17	0,31	0,76	33
9	131	1,40	0,54	0,39	1,80	0,74	0,39	0,80	0,21	0,23	0,82	43
10	150	1,90	0,69	0,48	2,60	1,09	0,54	1,40	0,40	0,27	0,87	39
11	116	2,00	0,85	0,45	2,40	1,03	0,40	2,10	0,18	0,31	0,74	37
12	183	1,90	0,69	0,45	2,20	0,94	0,41	0,80	0,24	0,20	0,90	28
Total	1299	2,60	0,75	0,48	2,60	0,79	0,41	2,10	0,04	0,29	0,81	38

The statistics of the comparison of modelled and measured peak periods (T_p) for the station "Zingst" from May through December 1992 and of all data are compiled in Table 5. A comparison of the peak periods shows a substantially higher maximum measured value of 10 s compared to the model value of 7.8 s, while the mean values of 4.30 s and 4.03 s are on the same order of magnitude. The discrepancy between the maximum values is due to a measurement in June 1992. In the other months, too, the maximum measured data generally are higher than the model data, but the differences are smaller. The buoy obviously is moored at a position where it is more exposed to long-period waves than the model point, which is protected by a model coast line with coarser discretization. Scatter and standard deviations of all data range between 0.9 and 1.0 s. The result is a small scatter index of 23%, but also a low correlation of 0.53.

Table 5

Statistics of comparison of modelled and measured peak periods at the station "Zingst" in May to December 1992, and of the total data

		Model			Buoy			Buoy-Model				
Month 1992	Number	x_{Max} (s)	x_q (s)	S_x (s)	y_{Max} (s)	y_q (s)	S_y (s)	d_{max} (s)	d_q (s)	S_d (s)	Cor	Scat %
5	167	7,80	4,11	0,99	6,70	4,02	1,01	4,90	-0,09	1,22	0,25	30
6	177	6,50	4,22	0,95	10,00	4,44	1,27	7,20	0,22	1,23	0,41	29
7	196	6,40	3,93	0,96	7,10	4,07	1,06	3,90	0,14	0,95	0,56	24
8	176	6,70	4,28	0,94	7,70	4,11	0,88	2,80	-0,17	0,82	0,60	19
9	131	5,20	3,73	0,69	6,70	4,05	1,10	2,50	0,32	0,91	0,57	24
10	150	6,00	4,09	0,90	7,70	4,86	1,11	2,80	0,77	0,93	0,59	23
11	116	6,20	4,01	0,89	6,20	4,46	0,83	2,80	0,45	0,66	0,70	17
12	183	6,00	3,84	0,79	6,70	4,47	0,94	3,10	0,62	0,75	0,64	19
Total	1296	7,80	4,03	0,90	10,00	4,30	1,03	7,20	0,27	0,94	0,53	23

Fig. 4 demonstrates the good quality of results at the station "Zingst" for December 1992. It shows, from top to bottom, the time series of the significant wave height, peak period, sea direction, wind speed and direction. The measurements of the GKSS buoy are plotted as well for comparison with the model data. Wind measurements were not available.

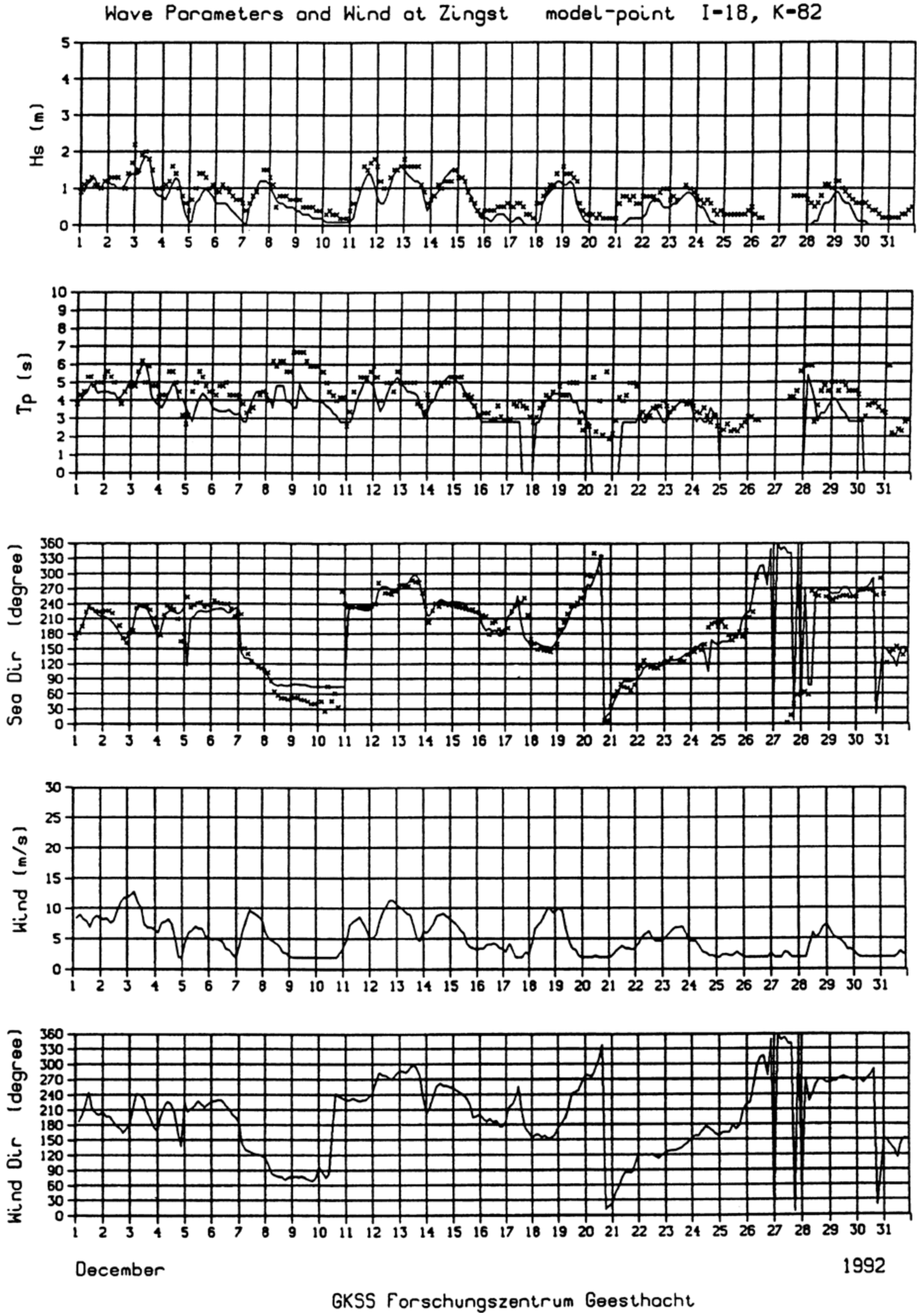

Fig. 4 Time series of the measured (****) and modelled (——) wave heights (H_s), peak periods (T_p), mean sea direction (Sea Dir), and computed wind speed (wind) and wind direction (Wind Dir) at the station "Zingst" for December 1992.

5 Climatology

For the development of a wave climatology, the time series of the 3-hourly model output for the period 01.01.1988 0:00 MEZ through 01.01.1993 00:00 MEZ were processed. Not considered were all periods in which input wind fields were not available for more than 24 hours, where temporal interpolation of the fields thus was not likely to produce reliable results. Of the 14,617 3-hourly output data in the five years considered, 96 data, or 0.66%, were not included in the statistics. This small number is irrelevant for the significance of the statistics, which consequently was based on 14,521 data.

The parameters used in developing the climatology are the significant wave height H_S computed from the model spectra, the period T_{m2} formed through the second moment of the spectrum, the peak period of the one-dimensional spectrum, and the mean wave direction. Wind speed and direction were taken from the input fields interpolated onto the model grid in time and space.

Various climate graphs were generated at 7 evaluation grid points (Tab. 6). Five of these grid points are located in the sea area off Warnemünde. The other evaluation grid points are located closest to the Wismar harbour entrance and at the position of the measuring buoy off Zingst. In Table 6, the positions of the grid points analyzed and the model water depths are indicated.

Table 6

Grid points at which climate graphs were generated

No.	Name	Longitude ° East	Latitude ° North	Grid point I	Grid point K	Depth (m)
1	Warnemünde harbour	12,0	54,2	15	86	13
2	Warnemünde West	11,8	54,2	14	86	20
3	Warnemünde North-West	11,8	54,4	14	85	21
4	Warnemünde North	12,0	54,4	15	85	18
5	Warnemünde Nord-East	12,3	54,4	16	85	15
6	Wismar	11,5	54,1	13	87	11
7	Zingst Buoy	12,8	54,8	18	82	19

At each of the evaluation grid points, climate graphs were generated both from the total data set (annual statistics) and from the seasonal data sub-sets. The correlation graphs were generated for each of the 8 parameter pairs shown in Table 7. Besides the evaluations covering the entire period, separate graphs were prepared for each of the four seasons. These graphs correspond to the North Sea data of ANEP 14 (ANEP [1987]) but representation and discretization reflect the specific Baltic Sea conditions. In addition to the ANEP 14 standard, statistics of the significant wave height plotted against the T_{m2} period were generated.

Table 7

Graphs generated

No.	*y*-axis	*x*-axis
1	sig. wave height	peak period
2	sig. wave height	T_{m2} period
3	sig. wave height	wind speed
4	sig. wave height	wave direction
5	wind speed	wind direction
6	sig. wave height (WMO)	wind speed (WMO)
7	sig. wave height	duration
8	wind speed	duration

Some of the graphs will be discussed in the following. Graphs that will not be discussed are "Significant wave height versus wind speed (WMO)" because it differs from graph 3 only in the class subdivision, "Significant wave height versus T_{m2} period" and "Wind speed versus duration", because these graphs have the same structure as graphs 1 and 7, respectively. The discussion will only deal with the annual statistics at the grid point "Warnemünde harbour".

5.1 Significant wave height versus peak period

Table 8 shows the joint distribution of the significant wave height (H_s) and peak period (T_p). The maximum wave height was 3.8 m to 4.0 m, with a period between 8.8 s and 9.2 s. The longest period was between 9.2 s and 9.6 s corresponding to a wave height of 3.0 m to 3.2 m. Each of the two events occurred exactly once. With 3681 events, periods between 2.8 s and 3.2 s occurred most frequently. They corresponded to wave heights smaller than 0.8 m, in most cases smaller than 0.4 m. Periods smaller than 2.8 s and wave heights below 0.1 m were not dissolved by the model. This occurred in 1195 cases, which are shown in the class with the smallest wave height and period.

The Table shows two groups of data. One group is characterized by increasing wave heights with longer periods. This is a typical property of waves subject to wind forcing. The second group comprises low wave heights with long periods. This group reflects swell events.

Disregarding wave heights below 0.2 m, the largest figure in column Σ, which shows the distribution of wave heights, is 2169 for wave heights between 0.6 m and 0.8 m. That is 15% of all wave heights compiled in Table 8. All other wave heights below 1.8 m are represented about equally. This contrasts with the distribution of peak periods in the row marked Σ. 25% (3681 events) of all periods occurred in the range from 2.8 s to 3.2 s.

5.2 Significant wave height versus wind speed

The graph in Table 9 shows the distribution of significant wave heights (H_s) versus wind speed. The general correlation between high wind speeds and high waves is evident. A remarkable feature is the number of wave height classes belonging to a particular wind speed class. For example, a wind speed between 11.0 m/s and 14.0 m/s generates wave heights between 1.0 m and 3.0 m. This scatter is attributable not only to the wind direction but also to fetch and duration of the wind events. Wind speeds between 5.5 m/s and 8.5 m/s, with 4081 entries (28%), occurred most frequently. At this wind speed, wave heights up to 1.8 m were observed, the prevailing heights ranging between 0.6 m and 0.8 m (1309 entries, corresponding to 32% in this wind class).

5.3 Significant wave height versus wave direction

The distribution of the significant wave height (H_s) versus the wave direction at the grid point "Warnemünde harbour" is shown in Table 10. The waves propagate mainly in directional sectors around 300°, in 2755 cases (19%), 270° in 2532 cases (17%), and 240° in 1923 cases (13%). Also the highest waves come from those directions. A second preferred direction for high waves is the sectors around 30°. While southerly (offshore) directions around 150° are more frequent than those around 30°, the wave heights reached are lower.

Table 8

Distribution of significant wave height versus peak period. The number of events per class at the grid point "Warnemünde harbour" is shown which occurred in the 5 years modelled

sig. wave height (m)	peak period (s) 2,0	2,4	2,8	3,2	3,6	4,0	4,4	4,8	5,2	5,6	6,0	6,4	6,8	7,2	7,6	8,0	8,4	8,8	9,2	9,6	10,0	≥	Σ	sig. wave height (m)
≥																								≥
5,0																								5,0
4,8																								4,8
4,6																								4,6
4,4																								4,4
4,2																								4,2
4,0																			1				1	4,0
3,8																								3,8
3,6																	6	1	1				8	3,6
3,4																1	5		1				7	3,4
3,2															1	5	10	1	1	1			19	3,2
3,0															37	13	9	5					64	3,0
2,8														7	35	5	7						54	2,8
2,6													41	108	64	23	17						253	2,6
2,4											1	5	192	52	28	4							282	2,4
2,2										2	7	194	157	46	6								412	2,2
2,0									1	4	19	170	50	11									255	2,0
1,8								1	20	304	357	285	58	1									1026	1,8
1,6								26	210	465	75	13	1										790	1,6
1,4							31	176	654	65	3												929	1,4
1,2						60	283	561	134	2													1040	1,2
1,0					76	627	565	103	9	2													1382	1,0
0,8				535	1023	476	105	25	3	1					1								2169	0,8
0,6				811	330	118	25	26	2			2											1314	0,6
0,4				1268	49	63	76	70	18	7	4	9		3		1							1568	0,4
0,2	1195			1067	180	267	89	76	26	8	8	12	7	4	5	2	1	1					2948	0,2
Σ	1195			3681	1658	1611	1174	1064	1077	860	474	690	506	232	177	54	55	8	4	1			14521	Σ
	2,0	2,4	2,8	3,2	3,6	4,0	4,4	4,8	5,2	5,6	6,0	6,4	6,8	7,2	7,6	8,0	8,4	8,8	9,2	9,6	10,0	≥	Σ	
	peak period (s)																							

Table 9

Distribution of significant wave height versus wind speed. The number of events per class at the grid point "Warnemünde harbour" is shown which occurred in the 5 years modelled.

	wind speed (m/s)												
sig. wave height (m)	2,0	3,5	5,5	8,5	11,0	14,0	17,0	20,5	24,0	27,5	≥	Σ	sig. wave height (m)
≥													≥
5,0													5,0
4,8													4,8
4,6													4,6
4,4													4,4
4,2													4,2
4,0											1	1	4,0
3,8													3,8
3,6										3	5	8	3,6
3,4										7		7	3,4
3,2								1	12	6		19	3,2
3,0						1	3	30	30			64	3,0
2,8						2		38	13	1		54	2,8
2,6						10	83	154	6			253	2,6
2,4						34	217	29	2			282	2,4
2,2					10	215	176	10	1			412	2,2
2,0					13	212	27	2		1		255	2,0
1,8				6	492	493	27	8				1026	1,8
1,6				99	585	82	22	2				790	1,6
1,4				555	291	72	9	2				929	1,4
1,2				772	190	65	13					1040	1,2
1,0			46	993	270	73						1382	1,0
0,8	1	2	705	1309	152							2169	0,8
0,6	3	35	993	283								1314	0,6
0,4	64	419	1025	60								1568	0,4
0,2	1139	1378	427	4								2948	0,2
Σ	1207	1834	3196	4081	2003	1259	577	276	64	18	6	14521	Σ
	2,0	3,5	5,5	8,5	11,0	14,0	17,0	20,5	24,0	27,5	≥	Σ	
	wind speed (m/s)												

Table 10

Distribution of significant wave height versus wave direction. The number of events per class at the grid point "Warnemünde harbour" is shown which occurred in the 5 years modelled.

	wave direction (coming from degrees north)												
sig. wave height (m)	0	30	60	90	120	150	180	210	240	270	300	330	Σ	sig. wave height (m)
≥														≥
5,0														5,0
4,8														4,8
4,6														4,6
4,4														4,4
4,2														4,2
4,0										1			1	4,0
3,8														3,8
3,6										8			8	3,6
3,4									2	3	2		7	3,4
3,2									2	10	7		19	3,2
3,0		4							7	37	14	2	64	3,0
2,8		2							10	28	14		54	2,8
2,6	2	7	3	5				10	47	97	81	1	253	2,6
2,4	1	3	5	3				11	56	113	90		282	2,4
2,2	1	5	6	6				16	88	141	146	3	412	2,2
2,0	4	2	1	3				12	56	83	89	5	255	2,0
1,8	16	15	31	21	2	2	3	36	244	340	305	11	1026	1,8
1,6	22	14	28	28	2	4	10	35	178	245	199	25	790	1,6
1,4	19	20	33	37	14	6	18	59	195	263	234	31	929	1,4
1,2	31	19	35	54	40	28	36	84	182	201	279	51	1040	1,2
1,0	40	38	43	70	109	111	107	155	185	211	241	72	1382	1,0
0,8	64	50	57	90	263	297	268	319	214	221	229	97	2169	0,8
0,6	45	72	48	51	101	121	116	123	117	185	227	108	1314	0,6
0,4	37	181	104	61	126	116	149	164	120	156	238	116	1568	0,4
0,2	147	231	308	255	267	275	303	225	220	189	360	168	2948	0,2
Σ	429	663	702	684	924	960	1010	1249	1923	2532	2755	690	14521	Σ
	0	30	60	90	120	150	180	210	240	270	300	330	Σ	
	wave direction (coming from degrees north)													

5.4 Wind speed versus wind direction

While the directions from which high waves are to be expected are west, north-west, and north-east, the distribution of wind speeds against wind directions (Table 11) indicates predominantly westerly directions at wind speeds greater than 20.5 m/s. The preferred wind direction sectors are 270°, with 2648 entries (18%), and 240°, with 2247 entries (15%).

Table 11

Distribution of wind speed versus wind direction. The number of events per class at the grid point "Warnemünde harbour" is shown which occurred in the 5 years modelled.

	wind direction (coming from degrees north)													
wind speed (m/s)	0	30	60	90	120	150	180	210	240	270	300	330	Σ	wind speed (m/s)
≥									3	3			6	≥
27,5								2	6	6	4		18	27,5
24,0							1	6	23	23	10	1	64	24,0
20,5				2	1	4	5	39	64	115	43	3	276	20,5
17,0	4	2	5	15	7	4	17	60	147	209	96	11	577	17,0
14,0	17	10	10	16	50	31	67	135	315	348	220	40	1259	14,0
11,0	39	23	35	96	163	114	119	193	401	467	269	84	2003	11,0
8,5	116	81	133	199	275	352	373	462	599	733	558	200	4081	8,5
5,5	113	99	143	202	246	233	288	346	381	461	411	273	3196	5,5
3,5	127	88	112	156	167	144	140	172	187	182	203	156	1834	3,5
2,0	94	83	96	108	125	113	95	82	121	101	99	90	1207	2,0
Σ	510	386	534	794	1034	995	1105	1497	2247	2648	1913	858	14521	Σ
	0	30	60	90	120	150	180	210	240	270	300	330	Σ	
	wind direction (coming from degrees north)													

5.5 Significant wave height versus duration

Table 12 provides data on the duration or persistency of significant wave heights (H_s). The number of time intervals is entered in which the wave height was constant, i. e. in one wave height class, as well as the duration of the interval. A total of 7724 time intervals was reached, 4919 of which were shorter than 3 hours. Sea states with wave heights above 2.0 m almost always were brief events which rarely lasted longer than 12 hours. In the period of 5 years investigated, 30 intervals occurred in which the wave height was below 0.2 m for over 57 hours.

6 Extreme value analysis

Since the selection of storms was made for the sea area off Warnemünde, the evaluation covered only the grid points 1 to 5 in Table 6. From the time series of the hourly model output,the maximum significant wave height (H_s) computed for each storm was extracted. These data are listed in Table 2, together with the corresponding peak periods (T_p) and wave directions (R_s). Additionally, the maximum wind speed (UP) is indicated, with the corresponding wind direction (R_w).

In order to compile only the extreme significant wave heights, the 20 highest events were selected for the analyses. They are represented in Fig. 5 at the grid point "Warnemünde harbour", together with the peak period, directional sector from which the waves were coming and storm number. The Figure shows that significant wave heights up to 3.6 m were reached. They occurred in storm 180 (December 1957) from NNE, with a peak period of 10.1 s, and in storm 3 (January 1968), with a peak period of 9.0 s from north.

Table 12

Distribution of significant wave height versus duration. The number of events per class at the grid point "Warnemünde harbour" is shown which occurred in the 5 years modelled.

sig. wave height (m)	duration (h)																					sig. wave height (m)
	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	≥	Σ	
≥																						≥
5,0																						5,0
4,8																						4,8
4,6																						4,6
4,4																						4,4
4,2																						4,2
4,0	1																				1	4,0
3,8																						3,8
3,6	2	1		1																	4	3,6
3,4	2	1	1																		4	3,4
3,2	13	3																			16	3,2
3,0	19	11	3	2		1															36	3,0
2,8	31	6			1	1															39	2,8
2,6	58	33	15	13	4	2															125	2,6
2,4	105	30	16	10	2	2	1														166	2,4
2,2	149	57	14	16	5	3															244	2,2
2,0	151	29	9	1	3																193	2,0
1,8	199	107	59	36	17	8	4	5	4		2					1	1				443	1,8
1,6	294	102	36	19	7	8	1	1		1											469	1,6
1,4	386	117	42	26	7	5	2														585	1,4
1,2	523	117	52	12	6	3	1	3													717	1,2
1,0	734	160	52	21	8		4		1		1										981	1,0
0,8	847	304	83	39	19	9	13	4	1				1		1						1321	0,8
0,6	659	176	46	21	7	1	3	1			1										915	0,6
0,4	584	224	67	31	14	5	6	4	1		1						1				938	0,4
0,2	162	48	65	37	44	25	29	15	18	8	13	4	6	9	8	3			3	30	527	0,2
Σ	4919	1526	560	285	144	73	64	33	25	9	18	4	7	9	9	4	2		3	30	7724	Σ
	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	≥	Σ	
	duration (h)																					

The extreme value analysis was only prepared for waves propagating from the sectors WNW to ENE because these are the only directions that may be critical for the harbour entrance. Four events from westerly direction (Fig. 5) were considered as well because in the course of the storm they had a strong north component.

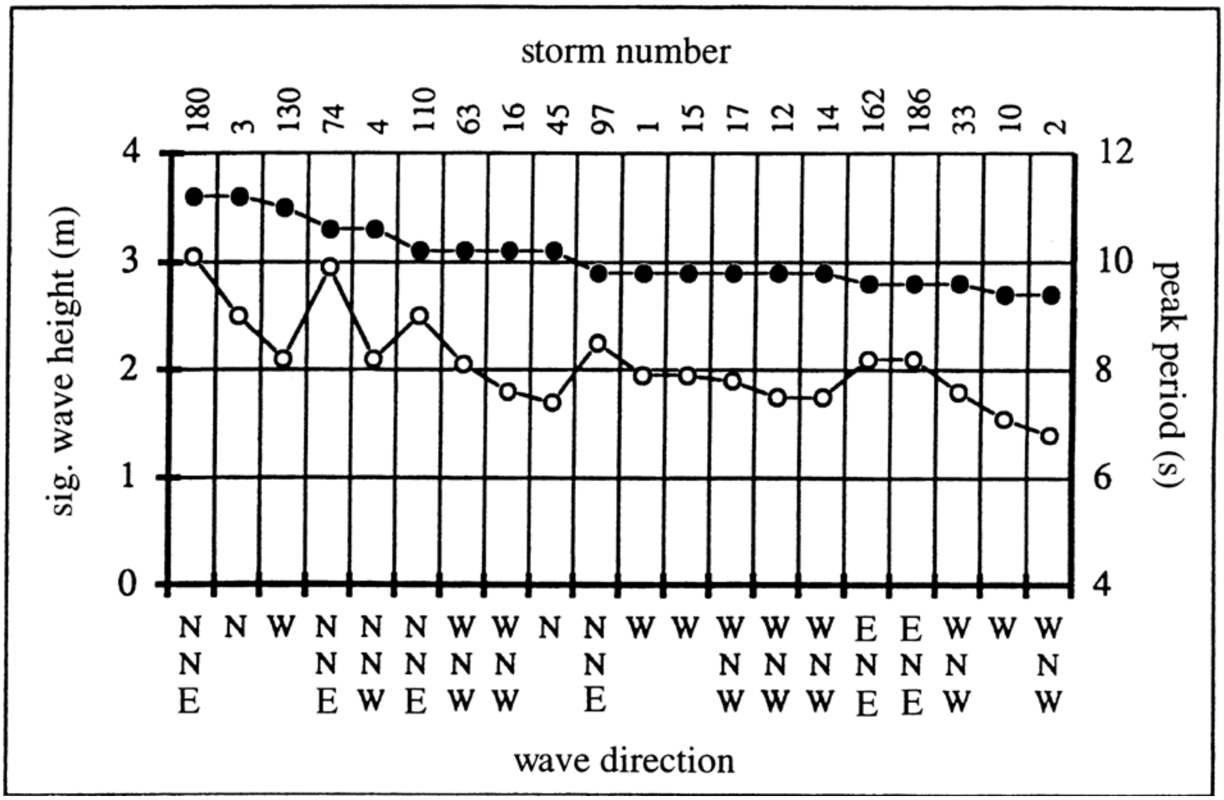

Fig. 5 Max. significant storm wave heights (•) at the grid point "Warnemünde harbour", with the corresponding peak period (o) and wave direction. The 20 highest wave events are shown in descending sequence.

The evaluation was carried out with five different extreme value distributions (Table 13) (Haring [1979]). The free parameters a and b of these probability distribution functions were determined by fitting them to the computed data by the method of least square error. For that purpose, the distribution function was transformed in such a way that a linear equation $y = c + d * x$ with the transformed parameters c and d could be fitted. As independent variable y, the transformed "probability of non-exceedance" was used. With a correlation of 0.97, a very good fit of the data for the Frechet and Gumbel distributions was achieved. The log normal and normal distribution with correlations of 0.96 and 0.95, respectively, also showed a good fit with the data, while slightly poorer results were obtained with the Weibull function, with a correlation of 0.91. Analogous results were obtained at the other grid points.

Table 13

Distributions used, a and b being the parameters to be determined, PHI the probability function, and corr the correlation of linear regression fitted to the data at the grid point "Warnemünde harbour"

Nr.	Name	*P(x<X)*	corr
1	FRECHET	exp (–(*a*/*x*)***b*)	0,97
2	GUMBEL	exp (–exp(*a**(*x*–*b*)))	0,97
3	LOG-NORMAL	PHI (*a**(ln(*x*)–*b*))	0,96
4	NORMAL	PHI (*a**(*x*–*b*))	0,95
5	WEIBULL	1–exp (–(*a***x*)***b*)	0,91

To carry out the fit, a histogram of the cumulative probabilities from the list of extreme waves has to be developed. As in Figure 5, the wave heights were sorted in descending sequence and related to the cumulative probabilities of non-exceedance $n/(n+1)$, ..., $2/(n+1)$, $1/(n+1)$, with $n = 20$ the number of events considered. That corresponds to the left vertical axis of Figure 6 which shows the Frechet distribution as a solid line at the grid point "Warnemünde harbour". The crosses indicate the data used, and the curves to the right and left of the distribution function mark the boundaries of the 90% confidence interval. On the right axis of the Figure, the return probabilities

$$P_j = j * n_m / (j * n_m + 1)$$

of the j = 10-, 25-, 50-, and 100-year waves are marked, with $n_m = 0.51$ the average storm rate per year determined from the period covered of 39.16 years and the 20 storms modelled.

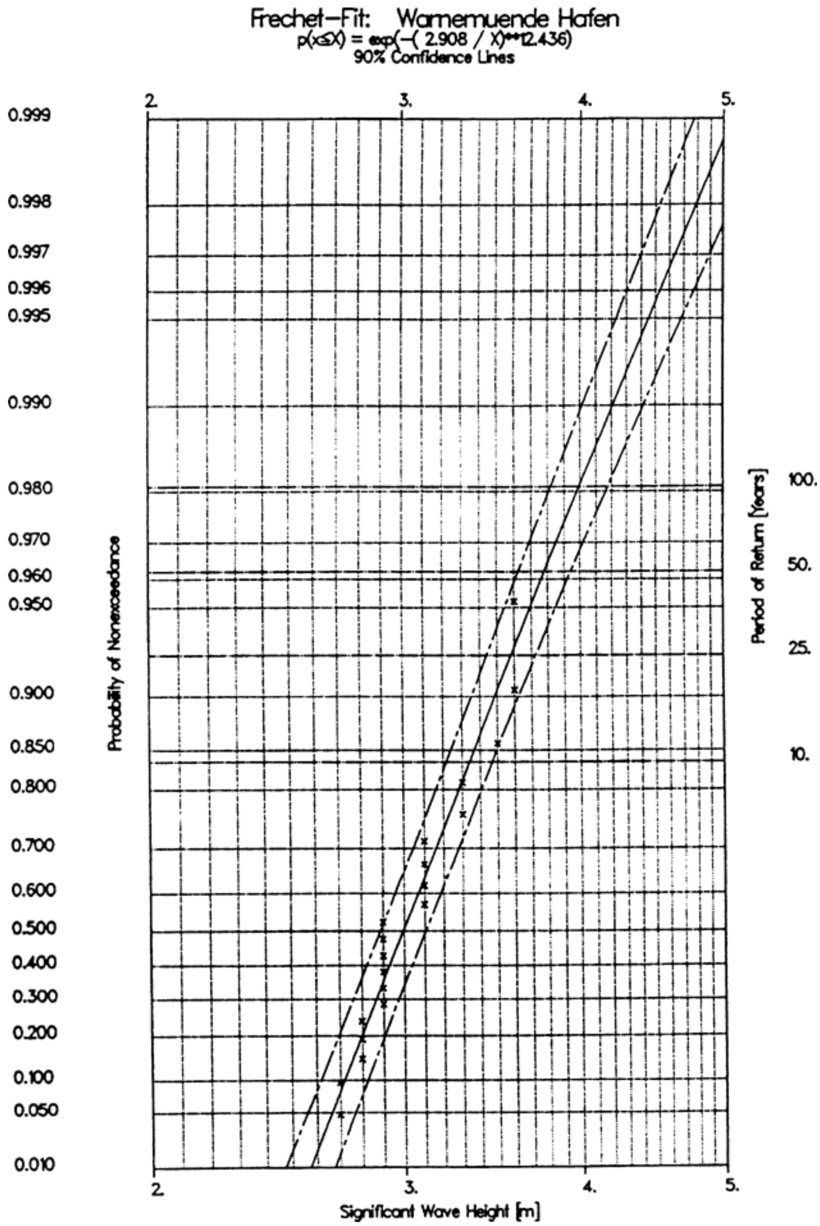

Fig. 6 Frechet extreme value distribution at the grid point "Warnemünde harbour" (solid line). The crosses indicate the data used, and the curves to the right and left of the distribution function mark the boundaries of the 90% confidence interval. On the right axis of the Figure, the return probabilities of the 10-, 25-, 50-, and 100-year waves are marked.

Table 14 summarizes the results for the grid point "Warnemünde harbour". The parameters a and b of the different distributions, the different maximum waves, and the uncertainty intervals are indicated. As in the correlation, the Weibull distribution shows the largest uncertainty intervals (0.52 m for the 100-year wave of 3.49 m). The Gumbel distribution furnishes the smallest error limits of 0.29 m, with a 100-year wave of 3.90 m. The maximum estimate (3.99 m) for the 100-year wave is derived from the Frechet distribution, with an error interval of 0.39 m.

Table 14

Parameters a and b determined for the extreme value distributions at the grid point "Warnemünde harbour" and extrapolated 10, 25, 50, and 100-year waves (H_s). H_l is the lower value, and H_r the upper value of the uncertainty interval. Δ is the width of the interval.

Distribution			10-year wave				25-year wave				50-year wave				100-year wave			
Name	Parameter		H_s	H_l	H_r	Δ	H_s	H_l	H_r	Δ	H_s	H_l	H_r	Δ	H_s	H_l	H_r	Δ
	a	b	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)
FRECHET	2,9081	12,4363	3,34	3,22	3,47	0,25	3,58	3,44	3,72	0,28	3,78	3,62	3,94	0,32	3,99	3,82	4,18	0,36
GUMBEL	3,9774	2,9134	3,35	3,22	3,47	0,25	3,56	3,43	3,69	0,26	3,73	3,60	3,87	0,27	3,90	3,76	4,05	0,29
LOG-NORMAL	10,3760	1,1096	3,33	3,17	3,50	0,33	3,49	3,31	3,68	0,36	3,60	3,41	3,80	0,38	3,70	3,51	3,91	0,41
NORMAL	3,3409	3,0450	3,34	3,17	3,51	0,34	3,48	3,30	3,66	0,35	3,58	3,40	3,76	0,36	3,66	3,48	3,85	0,37
WEIBULL	0,3171	13,3937	3,30	3,07	3,54	0,47	3,39	3,15	3,65	0,49	3,45	3,20	3,71	0,51	3,49	3,24	3,77	0,52

7 Conclusions

GKSS-Forschungszentrum Geesthacht, on behalf of Bundesanstalt für Wasserbau, Außenstelle Küste, developed a wave climatology and an extreme value analysis for the sea area off Rostock-Warnemünde.

For that purpose, a continuous hindcast for the years 1988–1993 was performed for the entire Baltic Sea by means of the numerical wave model HYPAS, and the 36 most extreme storm events in the past 40 years were modelled. The wave model data for 100 grid points off the German Baltic coast were stored and verified against buoy measurements carried out by GKSS off Zingst, and by Bundesamt für Seeschifffahrt und Hydrographie off Warnemünde. The result showed a very good agreement. The data were analyzed statistically at several selected points.

For the 5-year hindcast, the model was driven by wind fields stored at Amt für Wehrgeophysik and generated routinely within the framework of daily meteorological analyses. Climate graphs were developed from the modelled wind and wave data.

The most severe storm events were determined on the basis of wind time series recorded at the Warnemünde station of the German Weather Service. Since digital data sets covering the period investigated were not available, the wind fields required for the storm hindcast were developed at GKSS on the basis of surface weather charts provided by Seewetteramt Hamburg. From the 20 storm events with the highest modelled waves, the probable 10-, 25-, 50-, and 100-year waves were computed by extrapolation.

References

ANEP 14, 1987: Seasonal Climatology of the North Sea (16-year-statistics). Allied Naval Engineering Publication ANEP 14 Edition 1.

Bijvoet, H. C., 1957: A new overlay for the determination of the surface wind over sea from surface weather charts. KNMI, Mededelingen en Verhandelingen, Nr. 71.

Bouws, E., H. Günther, W. Rosenthal and C. L. Vincent, 1985: Similarity of the wind wave spectrum for finite depth water. Part I: Spectral form. J. Geophys. Res., Vol 90, No. C1, pp. 975–986.

Cavaleri, L., G. Burgers, H. Günther, V. Makin and L. Zambresky, 1994: Analysis. Chapter IV.4.1, pp. 300–308. In: Komen et al.: Dynamics and modelling of ocean waves, Cambridge University Press.

Gayer, G., H. Günther, W. Rosenthal, 1993: Seegangsstatistik für die Hafeneinfahrt Warnemünde-Rostock. Abschlußbericht für den Auftrag der Bundesanstalt für Wasserbau, Außenstelle Küste, Hamburg. 3 Bände. GKSS Vorhaben Nr. 819936.

Günther, H., W. Rosenthal, T. J. Weare, B. A. Worthington, K. Hasselmann and J. A. Ewing, 1979a: A hybrid parametrical wave prediction model. J. Geophys. Res. 84, 5727–5738.

Günther, H., W. Rosenthal and M. Dunckel, 1981: The response of surface gravity waves to changing wind directions. J. Phys. Oceanogr. 11, 718–728.

Günther, H. and W. Rosenthal, 1983: Shallow water surface wave model based on the Texel-Marsen-Arsloe (TMA) wave spectrum. In: Proceedings of the 20th Congress of the Internat. Association of Hydraulic Research (IAHR), Moscow/SU 1983.

Günther, H., G. J. Komen and W. Rosenthal, 1984: A Semi-Operational Comparison of Two Parametrical Wave Prediction Models, Dt. Hydrogr. Z. 37, pp. 89–106.

Günther, H., P. Lionello, B. Hansen, 1993: The Impact of ERS-1 Altimeter on the Wave Analysis and Forecast. Bericht des GKSS-Forschungszentrum Geesthacht, Deutschland GKSS 93/E/44, 56 pages.

Haring, R. E., 1979: Extreme wave statistics based on NORSWAM hindcast results. In: Climatologie de la Mer, Sea Climatology, ARAE Collection 34, Editions Technique Paris 1980. ISBN 2-7108-0396-8. pp. 313–362.

Timmermann, H., 1977: Meteorological effects on tidal heights in the North Sea. KNMI, Mededelingen en Verhandelingen, Nr. 99.

Submitted: July 3rd, 1995

Accepted: August 30th, 1995

Addresses of Authors:

Gerhard Gayer
Dr. Heinz Günther
GKSS Forschungszentrum Geesthacht
Postfach 11 60
21494 Geesthacht

Norbert Winkel
Bundesanstalt für Wasserbau
Außenstelle Küste
Wedeler Landstraße 157
22559 Hamburg