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An assessment of two wave prediction models: Hindwave and Bristwave

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An assessment of two wave prediction models: HINDWAVE and BRISTWAVE

Summary

An assessment is made of two deep water wave models which have been developed for a range of applications in coastal and offshore engineering. The model HINDWAVE was modified to account for shallow water effects using the concept of a self-similar spectrum. Model results are compared with wave measurements at three positions in the southern North Sea. The model BRISTWAVE was evaluated and compared with wave measurements at a deep water and a shallow water location and also against HINDWAVE.

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1 INTRODUCTION

Wave prediction models have a wide range of applications in coastal and offshore engineering, as wave measurements are only available at a limited number of locations and are also of limited duration. Hindcast techniques can be used both for the estimation of the average wave conditions, or wave climate, and also for the estimation of extreme wave conditions expected in a period of 20 years or more.

Hydraulics Research Ltd have developed two deep water wave models, HINDWAVE and BRISTWAVE, with the capability of hindcasting the wave climate and also extremes based on predictions for specific storms.

The first model, HINDWAVE, was developed to meet the needs of coastal engineers requiring large wave data sets at specific sites both quickly and economically. The model uses information on the shape of the generation area, together with hourly wind data from a nearby land station, to predict the hourly sequence of wave height, wave period and direction. The method (Hawkes, 1987) is based on using a JONSWAP spectrum in terms of fetch lengths and wind speed and follows the theory of Seymour (1977).

The second model, BRISTWAVE, was developed by Hydraulics Research in connection with the proposed Severn Estuary Tidal Barrage. The method of wave modelling adopted in BRISTWAVE is, like HINDWAVE, an extension of Seymour's (1977) scheme for wave prediction and includes swell - wind sea interactions, based on ideas first developed during the North Sea Wave Model project (NORSWAM). The main advantage of BRISTWAVE over Seymour's method is in the ability of the model to deal with rapidly time-varying wind fields.

This report is in two parts. Part 1 contains an assessment of HINDWAVE together with methods for specifying the offshore wind field. An adaptation of HINDWAVE to predict waves in shallow water is made based on the concept of a self-similar spectrum. Both HINDWAVE and its shallow water version are compared with wave measurements in the southern North Sea. Part 2 of this report evaluates BRISTWAVE against wave measurements and the results from HINDWAVE. The comparisons are carried out against wave measurements at Cromer in the southern North Sea and at Perranporth, Cornwall. These two locations are representative of shallow water and deep water locations, respectively. Conclusions are given at the end of each part of this report.

PART 1

2 ASSESSMENT OF THE HINDWAVE MODEL

The deep-water numerical wave model, HINDWAVE, has been successfully used for a number of years in numerous applications around the British Isles. The model has been developed by Hawkes (1987) from the forecasting method of Seymour (1977).

In essence, the model uses information about the shape of the wave generation area as provided by a table of fetch lengths, drawn radially from the point of interest, at a set of equal directions, usually every 10 degrees. With this information and assuming a JONSWAP spectrum (Hasselmann et al 1973), Seymour's method estimates the spectrum at the point of interest by a weighted average of contributions from all directions. The significant wave height, wave period and direction are obtained by numerical integration of the spectrum. However, before hindcasts can be carried out, a set of site specific offshore wave forecasting tables are produced. Each table gives the predicted wave height, period and wave direction for a wide range of wind speeds and directions, assuming several particular wind durations. Then, the hourly wind records for the site are used in conjunction with the forecasting tables. For each duration, the corresponding wave height is obtained and the largest of all these these values is selected together with the appropriate wave period and direction. This procedure is repeated for the next hour until the end of the set of wind data. A description of the model is given in Appendix 1.

All wave models, including HINDWAVE, are limited in the accuracy of their output by the quality of the input wind information. HINDWAVE requires as input a long series of good quality, hourly wind speed and direction data - it being assumed that these are constant over the generating area. The model does not take into account any swell and may not therefore be suitable for use in certain exposed areas, nor does it consider bottom influences such as refraction, shoaling and dissipation.

The following sections of this chapter will consider the wind input and then the physics of the model.

2.1 The wind input

Land-based wind data are available at hourly intervals around the British Isles for most coastal sites from 1970 and are a consistent and reliable data source for the use of hindcast methods. Wind speeds measured over the land are however lower than those over the sea and adjustments have to be made to accommodate these differences. Comparison of land wind data with ship observations (VOS) can often be used to infer the "mark-up" in wind speed necessary for accurate predictions using HINDWAVE. The ratio of wind speed over the sea to that over the land, R = U(sea)/U(land), has been found to be dependent on both wind speed and direction. These two factors are incorporated into HINDWAVE (see, for example, Hydraulics Research Report EX 1665, January 1988: chapter 3.3).

The Shore Protection Manual (1984) advocates the use of an adjusted wind speed, U_A, from the empirical formula

$$U_A = 0.71\ U^{1.23} \qquad \text{(U in m/s)}$$

in the absence of any intercomparisons of land/sea winds, as noted above. The following table shows particular values from this formula:

U (m/s)	U_A (m/s)	R
5	5.1	1.03
10	12.1	1.21
15	19.9	1.32
20	28.3	1.41

However, the relation given in the Shore Protection Manual does not agree with results from a study made by Resio and Vincent (1977) over the Great Lakes. In this study, R was found to be nonlinearly dependent on wind speed and atmospheric stability (see Figs 1 and 2). Furthermore, R decreased with increasing wind speed such that for wind speeds greater than 10m/s, R = 1.2.

Another important result obtained by Resio and Vincent (1977) concerned the adjustment distance for the wind profile to become fully acclimatised to its marine condition. This distance was found to be approximately 20 miles. Thus an additional factor

$$R_1 = \begin{cases} 0.41\, F^{0.297} & F < 20 \text{ miles} \\ 1 & F > 20 \text{ miles} \end{cases}$$

should be incorporated with the value of R.

The present procedure, used for example in the study of wave climate in the Anglian region (Hydraulics Research Report EX 1665, January 1988), of using carefully calibrated land winds in comparison with observed wind distributions over the sea gives consistent results and is preferable to using the empirical formula advocated in the Shore Protection Manual (1984). In the absence of information on wind data over the sea, the use of results given by Resio and Vincent (1977), possibly coupled with a wind speed dependent factor at short fetches, is recommended.

2.2 Model physics

The merit of HINDWAVE is its simplicity. The use of Seymour's method is warranted under stationary wind conditions with a defined fetch but runs into difficulties in dealing with spatially varying changing wind fields, both in speed and direction.

Hawkes (1987) notes that a $\cos^6\Theta$ directional distribution gives better results than the $\cos^2\Theta$ distribution proposed by Seymour (1977) in some circumstance. According to the JONSWAP group (Hasselmann et al, 1980), the directional spread at the peak of the wave spectrum behaves like $\cos^{2s}\frac{1}{2}\Theta$ where s = 10. The $\cos^6\Theta$ distribution translated to a half-angle form gives s = 12: close to the value accepted by oceanographers. It seems doubtful if the refinement of a frequency - dependent spread, s - as observed in nature - would improve the model results.

The model is unable to take into account any swell wave energy which could be generated by distant wind fields. This is not a serious limitation for storm seas where the contribution from swell is usually very small, but could be important in hindcasting the wave climate on a daily basis.

3 ADAPTATION OF HINDWAVE TO PREDICT WAVES IN SHALLOW WATER

HINDWAVE is restricted in its use to deep-water wave prediction. Previous studies carried out in the southern North Sea have indicated that the model may be unsuitable for wave prediction in shallow water. (See, for example, comparisons of the model with wave measurements off Cromer shown in Hydraulics Research Report EX 1665, January 1988.) In some situations, the highest wave heights in storms are about 50% higher than the measured values. A method for shallow water wave prediction has therefore been incorporated into HINDWAVE as discussed below.

3.1 Use of the TMA spectrum

Shallow water effects may be represented in wave prediction models through the concept of a self-similar spectrum, called the TMA spectrum (Bouws et al. 1985, Bouws et al. 1987), in a manner comparable to using the JONSWAP self-similar spectrum in deep water. The second-generation wave model, HYPAS, was the first model to employ these ideas.

The method is based on the work of Kitaigorodskii et al (1975). These authors showed that the concept of a saturation spectrum (or Phillips range) could be extended to water of finite depth by means of a function Φ where

$$\Phi = \frac{\tanh^2 kh}{(1 + 2kh / \sinh 2kh)}$$

where k is the wave number and h the water depth. k satisfies the dispersion relation $(2\pi f)^2 = gk \tanh kh$. Figure 3 shows Φ as a function of $\omega_H \equiv 2\pi f\sqrt{h/g}$.

The TMA spectrum is then defined as

$$E_{TMA}(f,h) = E_J(f) \, . \, \Phi(f,h) \qquad (1)$$

where E_J is the JONSWAP spectrum. [The abbreviation

TMA is obtained from the Texel-Marsen-Arsloe experiments, in which the above ideas were first tested and validated.]

3.2 Estimation of parameters

The TMA spectrum can be estimated from equation (1) if we know the water depth and the three parameters α, f_m and γ describing the JONSWAP spectrum.

Bouws et al (1987) show that α and γ are functions of the nondimensional wave number $K = U^2 k_m/g$, where U is the wind speed at the 10m level. From their Table 3 we obtain

$$\alpha = 0.0086\ (K/1.23)^{0.49} \tag{2}$$

$$\gamma = 2.68\ (K/1.23)^{0.39} \tag{3}$$

For f_m, we use the usual JONSWAP relation in terms of fetch and wind speed, namely

$Uf_m/g = 3.5\ \tilde{x}^{-0.33}$ where the nondimensional fetch is defined as $\tilde{x} = gx/U^2$.

3.3 Bounds for f_m and H_s in shallow water

Vincent and Hughes (1985) suggest that a lower bound for f_m in shallow water can be taken as

$$f_m > \frac{0.9}{2\pi}\ (g/h)^{0.5} \tag{4}$$

An upper bound for the significant wave height, H_s, has been given by Chen and Wang (1983), namely

$$H_s/L_m = 0.12 \tanh k_m h \tag{5}$$

where the subscript m denotes the spectral peak. L is the wavelength. Both these limits are incorporated into the modified version of HINDWAVE used in shallow water.

4 PREDICTION OF WAVE HEIGHTS IN THE SOUTHERN NORTH SEA

The shallow water version of HINDWAVE was run for three positions in the southern North Sea. These positions were Cromer, Dowsing and Galloper (see Fig 4). A full report on the hindcasts using HINDWAVE and the shallow water form of HINDWAVE has been made in an internal report (M W Morris, 1989). This report shows some of the principal results.

4.1 Hindcasts at Cromer

The water depth to be associated with each fetch-direction line was obtained from an average value up to 100km along each line. A total depth of average chart value plus 3m was then used to give values at the mean water level. For fetches less than 100km, only the first two-thirds of each fetch length was used. (The hindcasts were not found to be sensitive to small changes in the water depth). Table 1 gives the fetch lengths and depths used in the calculations.

The analysis period chosen for the hindcasts was from 1 December 1985 to 31 March 1986. Wave measurements from a WAVEC buoy of the Institute of Oceanographic Sciences were used for validation purposes (Clayson and Ewing, 1988). This buoy provides information on wave direction as well as wave height and period.

Figures 5 and 6 show the results from the hindcast using HINDWAVE and its shallow water version. The shallow water model clearly gives improved estimates of storm wave heights. Table 2 compares the results from the two models against storm peaks exceeding a thresholds of 3m and 4m. HINDWAVE overpredicts storm maxima exceeding 3m and 4m by 14% and 20% respectively. The shallow water model underpredicts storm peaks by 2% and 5% for the same levels.

Both HINDWAVE and its shallow water version predict storm peaks which are delayed with respect to measured storm peaks. The average delay being about 6 hours. It is not known if this is due to timing errors in the wind field or due to the simplified physics of the model which does not include any growth rate terms.

A comparison of the wave height exceedence curves shown in Figures 7 and 8 confirms the good agreement between the shallow water version of HINDWAVE and the wave measurements.

4.2 Hindcasts at Dowsing Light Vessel

Average depth data for each fetch-direction line are given in Table 3. The hindcast period selected for this site was from 1 January 1984 to 31 December 1985. The full set of results are given in an internal report (M W Morris, 1989). In this report, we show a limited period of hindcasts from 1 January 1984 to 31 August 1984. Figures 9a and 9b for HINDWAVE are to be compared with Figures 10a and 10b for the shallow water model.

Figures 9a and 9b show that HINDWAVE both under and overpredicts the wave heights. There is a tendency for HINDWAVE to underpredict the lower wave heights and to overpredict the higher wave heights. For storm peaks exceeding 4m, Table 4 shows that HINDWAVE underpredicts wave heights by about 12%.

The shallow water model overpredicts the highest storm peak in the hindcast period (on 2 March 1984) by 7% compared with a 31% overprediction by HINDWAVE, but the overall tendency is to underpredict storm peaks by about 19%. This general underprediction is not related to wave height or wind direction.

4.3 Hindcasts at Galloper Light Vessel

Fetch and averaged depth data are given in Table 5. The full set of results for hindcasts from 1 March 1981 to 29 February 1972 is given in an internal report (M W Morris, 1989). We show a limited set of results from 1 March 1971 to 30 June 1971.

Figure 11 shows that HINDWAVE underpredicts the higher storm peaks, whilst the lower wave heights are in reasonable agreement with the background level of wave measurements. For storm peaks exceeding 3m, Table 6 shows that HINDWAVE underpredicts the peak values by about 21%.

The shallow water model (see Fig 12) underpredicts storm peaks exceeding 3m on average by 33%. As for hindcasts at Dowsing Light Vessel, this underprediction is not correlated with wave height or direction.

4.4 Deep water calculations

A comparison was made between HINDWAVE and its shallow water version by setting the water depth to 2000m in the latter model. Hindcasts were then run for Dowsing Light Vessel for the two-year period January 1984 to December 1985. For wave heights exceeding 3m, the shallow water model gave values 6.8% lower than HINDWAVE. Thus, in future runs of the model it would be desirable to make changes to equation (2) to maintain continuity between the deep and shallow water models at large depths. Since α is proportional to H_s^2, the revised equation becomes

$$\alpha = 0.0098\ (K/1.23)^{0.49} \qquad (2)'$$

5 CONCLUSIONS

HINDWAVE was modified for shallow water wave prediction through the use of self-similarity arguments and the TMA spectrum. In using this method one depth only must be assigned to each fetch-direction ray, but the hindcast results do not appear to be sensitive to this crude assumption.

Hindcasts were made for three locations in the southern North Sea. At the site off Cromer, the shallow water model showed considerable improvement compared with HINDWAVE, with storm peaks exceeding 3m and 4m being underpredicted by 2% and 5% respectively.

The timing of storm peaks in both HINDWAVE and its shallow water version generally lag the same measurements by about 6 hours. The reason for this is not known but could be due to timing errors in the wind field or the simplified physics used in the models.

Hindcasts for Dowsing Light Vessel and Galloper from the shallow water model underestimate storm peaks by 20-30%. However, since HINDWAVE also underpredicts the wave heights at these two stations, it is to be expected that a further underprediction will arise in using the shallow water model.

A hindcast was made for Dowsing Light Vessel with water depths set at 2000m and comparisons carried out with HINDWAVE. The shallow water model was found to give values of storm peak wave heights about 7% lower than HINDWAVE. An adjustment can readily be made for this in the shallow water equations: the effect of this change in future hindcasts will be to reduce the level of underprediction at Dowsing Light Vessel and Galloper Light Vessel.

PART 2

6 ASSESSMENT OF THE BRISTWAVE MODEL

The method of wave modelling adopted in BRISTWAVE is an extension of Seymour's (1977) scheme for wave prediction in limited-fetch regions to include swell-wind sea interactions, based on ideas developed during the North Sea Wave Model (NORSWAM) project (see Ewing, Weare and Worthington, 1979). A detailed description of the model is contained in HRS Report No EX 978, March 1981.

BRISTWAVE separates the wave spectrum into wind-sea and swell. When the wind speed drops, then wave energy in the wind-sea is reduced and the reduction in wave energy is transferred to swell. In the contrary situation, when the wind speed rises, part of the swell spectrum is absorbed into the wind-sea. These situations are handled by energy conservation methods first implemented in NORSWAM.

The decay of swell is represented in an empirical way because the model is based on "fetch-concepts" where it is not possible to represent the propagation of swell correctly.

The main advantage of BRISTWAVE over Seymour's method, and also over HINDWAVE, is in the ability of the model to handle rapidly time varying wind fields. This is achieved by considering energy transfers between wind-sea and swell, as briefly described above. For storm conditions, where swell waves are usually of minor importance, it would be expected that BRISTWAVE and HINDWAVE give comparable results.

The following sections of this chapter contain comparative hindcasts from BRISTWAVE and HINDWAVE at the Cromer site in the southern North Sea and at a deep water location off Perranporth. Swell waves are expected to be important at Perranporth since this location is exposed to the North Atlantic.

6.1 Hindcasts at Cromer

Hindcasts for both BRISTWAVE and HINDWAVE wave carried out for the four-month period December 1985 to March 1986. Although both models are only valid for deep water, it was considered useful to carry out the intercomparison for two reasons. Firstly, to see if wind-sea swell interactions are important in the southern North Sea and, secondly, to compare the computational times required by the two models.

6.1.1 Computations with BRISTWAVE

The program for BRISTWAVE allows up to 18 wind sea and 18 swell frequencies, defined at equal increments of frequency, df. Initial tests showed that although spectra in storm conditions were well-defined at df = 0.01Hz, the general conditions, especially for fetch-limited, west winds, needed wave spectra defined up to 0.50Hz (a wave period of 2 sec). It was therefore decided to make all hindcasts for the four monthly periods, with a bandwidth of 0.03Hz, starting at 0.05Hz and ending at 0.56Hz.

A comparison of computing time on the SUN 3/50 for one month's hindcast in January 1986, for BRISTWAVE and HINDWAVE is shown below:

	User time (sec)
BRISTWAVE	731
HINDWAVE	23

Although BRISTWAVE is more expensive to run than HINDWAVE, it should be noted that the above time for HINDWAVE does not include the time consuming first phase for setting up this model. It would therefore seem that BRISTWAVE may well be suitable for wave hindcasting from long time series of wind fields.

6.2 Comparison of results at Cromer

Figure 5 shows the hindcasts from HINDWAVE for the period December 1985 to March 1986. The comparable results from BRISTWAVE are given in Figure 13. While there is general overall agreement in the two hindcast methods, there are however some notable differences.

For BRISTWAVE, the wave height goes to very low values (see, for example, on 5,8,10 and 11 December 1985) due to the cut-off in wave energy at 0.56Hz in fetch-limited situations. In the case of peak wave heights during storms, BRISTWAVE avoids the flat-topped appearance of HINDWAVE, but still, like HINDWAVE lags behind the measured peak values (see, especially, the storms of 26 December 1985 and 25 January and 6 February 1986).

A detailed analysis of storm maxima is given in Table 7. The storm peaks, regardless of timing, are compared for significant wave heights exceeding a level of 3m for BRISTWAVE. A total of 15 storm events were considered. Table 7 shows that BRISTWAVE gives about 23% greater values than HINDWAVE, with HINDWAVE in turn being about 14% greater than the measured values at Cromer.

Swell wave energy exceeding 60% of the total energy is identified along the time axis of Figure 13 where such levels are exceeded for more than 4 hours. Most of these events are concentrated in decaying sea states after a storm peak has been reached. BRISTWAVE does not appear to give better results than HINDWAVE during these periods.

6.3 Hindcasts at Perranporth

Hindcasts for both models were carried out for the four-month period September 1978 to December 1978. Identical bandwidths to those chosen for the Cromer hindcasts were used, namely df = 0.03Hz starting at 0.05Hz and ending at 0.56Hz.

Figures 14 and 15 show the results. Both BRISTWAVE and HINDWAVE give comparable results for storm peak wave heights. For the small sample of eight storms exceeding 3m shown in Table 8, BRISTWAVE is on average 2% higher than the measurements while HINDWAVE is 9% lower than measured scale values. Both models give poor results for the first 10 days of November and December 1978, possibly due to deficiencies in the specification of the wind field.

As for Cromer, swell wave energy exceeding 60% of the total energy is indicated along the time axis of Figure 14. BRISTWAVE does not appear to give better results than HINDWAVE during these periods.

The time lag of both model results compared with measured storm peaks is given in Table 8 to the nearest hour. On average, BRISTWAVE and HINDWAVE lag the measured peaks by 6h and 9h respectively.

7 CONCLUSIONS

An evaluation of BRISTWAVE has been carried out with the new computing facilities at Hydraulics Research Ltd. The computing time for hindcasts using BRISTWAVE was not found to be excessive in comparison with HINDWAVE. The model may well be suitable for wave hindcasting from long series of wind records.

Hindcasts were made for two locations. At Cromer in the southern North Sea, BRISTWAVE gave about 23% greater values for significant wave height the results from HINDWAVE, with HINDWAVE being in turn 14% greater than the measured values at Cromer. At a deep water location, Perranporth, both wave models gave results in fair agreement with measurements.

Swell wave sequences were identified from the BRISTWAVE output, but the model results during such events were not significantly better than those from HINDWAVE.

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TABLES.

TABLE 1 Fetch lengths and average fetch depth data for Cromer

Latitude 53 04' 00" N
Longitude 1 31' 00" E

ANGLE (DEGREES)	FETCH LENGTH (KM)	AVERAGE FETCH DEPTH (M)
0	1000	29
10	1000	31
20	682	28
30	669	27
40	772	27
50	547	28
60	527	29
70	492	29
80	302	31
90	214	33
100	213	33
110	216	30
120	212	34
130	207	32
140	212	30
150	219	32
160	43	27
170	29	25
180	25	25
190	22	25
200	21	25
210	20	25
220	20	25
230	22	25
240	25	25
250	32	25
260	48	24
270	86	20
280	79	20
290	91	20
300	108	20
310	150	20
320	181	24
330	489	25
340	727	26
350	836	27

TABLE 2 **Values of peak significant wave height (m) during storms at Cromer from HINDWAVE, the shallow water version of HINDWAVE and from measurements**

Storm	HINDWAVE	HINDWAVE (shallow water)	Measured
26 Dec 1985	5.4	4.3	4.0
2 Jan 1986	4.0	3.3	3.3
14 Jan 1986	5.0	4.4	4.1
16 Jan 1986	3.0	2.4	3.2
24 Jan 1986	5.4	4.3	4.5
31 Jan 1986	4.0	3.4	4.1
1 Feb 1986	8.2	5.6	4.8
6 Feb 1986	3.3	2.8	3.0
14 Feb 1986	3.3	2.9	3.2
17 Feb 1986	3.2	2.8	3.2
28 Feb 1986	3.3	2.9	3.3
24 Mar 1986	4.0	3.8	4.2

Averaged values of H_s (model)/H_s (measured):

	HINDWAVE	HINDWAVE (shallow water)
Events over 3m	1.20	0.95
Events over 4m	1.14	0.98

TABLE 3 Fetch lengths and average fetch depth data for Dowsing LV

Latitude 53 34' 00" N
Longitude 0 50' 00" E

ANGLE (DEGREES)	FETCH LENGTH (KM)	AVERAGE FETCH DEPTH (M)
0	1000	43
10	1000	41
20	720	38
30	640	39
40	860	36
50	560	35
60	520	37
70	500	30
80	520	26
90	280	24
100	280	21
110	280	21
120	280	21
130	300	22
140	300	21
150	86	18
160	73	18
170	67	17
180	65	16
190	65	18
200	80	20
210	61	25
220	51	25
230	46	23
240	45	23
250	44	27
260	46	25
270	48	18
280	47	19
290	57	19
300	75	23
310	89	29
320	149	41
330	407	46
340	469	47
350	708	48

TABLE 4 Values of peak significant wave height (m) during storms at Dowsing Light Vessel from HINDWAVE, the shallow water version of HINDWAVE and from measurements

Storm	HINDWAVE	HINDWAVE (shallow water)	Measured
4 Jan 1984	3.3	3.2	4.0
7 Jan 1984	3.0	2.8	3.3
13 Jan 1984	3.5	3.7	3.5
14 Jan 1984	3.5	3.8	4.7
15 Jan 1984	2.5	2.8	3.3
16 Jan 1984	3.3	3.6	3.6
22 Jan 1984	3.2	2.8	3.9
23 Jan 1984	3.1	2.7	4.4
26 Jan 1984	3.1	2.6	3.5
8 Feb 1984	3.7	3.6	3.7
2 Mar 1984	7.2	5.9	5.5
24 Mar 1984	3.7	3.0	3.9
3 July 1984	3.4	3.0	3.0
4 Sept 1984	4.6	3.9	3.9
10 Sept 1984	3.0	2.9	3.6
25 Sept 1984	2.8	1.8	3.4
5 Oct 1984	4.0	3.3	4.0
18 Oct 1984	3.1	3.3	3.8
20 Oct 1984	2.9	3.1	3.2
22 Oct 1984	2.3	2.2	3.0
25 Oct 1984	2.5	2.3	3.0
3 Nov 1984	2.3	2.4	3.0
16 Nov 1984	1.8	1.4	3.3
23 Nov 1984	2.4	2.4	3.0
27 Nov 1984	3.0	2.7	3.2
16 Dec 1984	1.4	1.3	3.1
24 Dec 1984	2.4	2.3	3.4
5 Aug 1985	2.8	2.7	3.5
10 Nov 1985	5.2	4.5	4.2
19 Nov 1985	2.8	2.4	3.6
28 Nov 1985	2.1	2.2	3.2
26 Dec 1985	5.5	4.6	4.3

Averaged values of H_s (model)/H_s (measured):

	HINDWAVE	HINDWAVE (Shallow water)
Events over 3m	1.01	0.89
Events over 4m	0.88	0.81

TABLE 5 Fetch lengths and average fetch depth data for Galloper LV

Latitude 51 43' 54" N
Longitude 01 57' 48" E

ANGLE (DEGREES)	FETCH LENGTH (KM)	AVERAGE FETCH DEPTH (M)
0	1000	28
10	866	33
20	844	36
30	710	36
40	599	36
50	254	36
60	204	32
70	175	31
80	139	29
90	114	27
100	101	27
110	105	27
120	90	25
130	83	27
140	80	26
150	79	26
160	78	26
170	78	27
180	80	28
190	86	31
200	236	41
210	293	28
220	55	26
230	58	26
240	79	25
250	89	22
260	70	22
270	68	23
280	51	24
290	51	24
300	48	24
310	47	24
320	47	25
330	50	26
340	64	26
350	83	27

TABLE 6 Values of peak significant wave height (m) during storms at Galloper from HINDWAVE, the shallow water version of HINDWAVE and from measurements

Storm	HINDWAVE	HINDWAVE (shallow water)	Measured
3 Mar 1971	3.0	2.5	4.1
6 Mar 1971	2.9	2.2	3.9
22 Mar 1971	4.0	3.1	4.4
3 Apr 1971	3.3	2.6	3.2
4 June 1971	3.3	2.5	3.5
10 June 1971	3.3	2.7	3.2
14 June 1971	4.0	3.0	3.4
18 June 1971	1.4	1.2	3.2
13 Oct 1971	4.4	3.4	4.3
18 Oct 1971	2.1	2.0	3.7
19 Oct 1971	2.5	2.4	4.0
7 Nov 1971	2.0	1.8	3.8
9 Nov 1971	3.3	2.7	3.8
19 Nov 1971	2.2	2.2	4.3
20 Nov 1971	2.7	2.7	4.8
22 Nov 1971	4.2	3.6	4.8
24 Nov 1971	2.8	3.2	3.9
19 Dec 1971	2.4	2.2	3.0
20 Dec 1971	2.0	2.0	3.1
28 Dec 1971	2.4	2.0	3.2
30 Dec 1971	4.3	3.4	4.3
17 Jan 1972	2.9	2.6	3.2
19 Jan 1972	2.3	2.2	4.4
28 Jan 1972	5.1	3.9	5.1
1 Feb 1972	2.8	2.6	3.3
15 Feb 1972	2.4	2.4	3.4
18 Feb 1972	3.0	2.4	4.2

Averaged values of H_s (model)/H_s (measured):

	HINDWAVE	HINDWAVE (Shallow water)
Events over 3m	0.77	0.65
Events over 4m	0.79	0.67

TABLE 7 **Values of peak significant wave height (m) during storms at Cromer from BRISTWAVE, HINDWAVE, and from wave measurements**

Storm	BRISTWAVE	HINDWAVE	Measured
26 Dec 1985	6.2	5.5	3.9
3 Jan 1986	4.8	4.0	3.3
8 Jan 1986	3.7	3.2	2.9
14 Jan 1986	4.9	5.0	4.1
19 Jan 1986	3.3	3.3	2.7
24 Jan 1986	5.9	5.5	5.6
29 Jan 1986	3.5	3.2	2.2
31 Jan 1986	6.8	3.9	4.2
2 Feb 1986	10.0	8.0	4.8
6 Feb 1986	4.6	3.3	3.1
14 Feb 1986	4.8	3.3	3.2
17 Feb 1986	4.7	3.3	3.6
28 Feb 1986	5.5	3.3	4.0
1 Mar 1986	3.5	3.8	3.2
24 Mar 1986	3.8	4.0	4.3

Averaged values of H_s (model)/H_s (measured):

	BRISTWAVE	HINDWAVE
Events over 3m	1.40	1.14

TABLE 8 Values of peak significant wave height (m) during storms at Perranporth from BRISTWAVE, HINDWAVE, and from wave measurements

Storm	BRISTWAVE H_s (lag:hr)	HINDWAVE H_s (lag:hr)	Measured
11 Sept 1978	3.9(7)	3.9(1)	3.7
29 Sept 1978	6.3(9)	5.2(17)	4.4
17 Oct 1978	4.4(-4)	3.8(-4)	3.6
15 Nov 1978	3.9(7)	4.0(18)	4.1
25 Nov 1978	3.3(-2)	3.1(1)	3.3
8 Dec 1978	1.9(14)	1.9(15)	3.4
12 Dec 1978	5.4(10)	5.6(25)	6.3
31 Dec 1978	2.0(5)	2.0(5)	3.2

Averaged values of H_s (model)/H_s (measured):

	BRISTWAVE	HINDWAVE
Events over 3m	1.02	0.91

FIGURES.

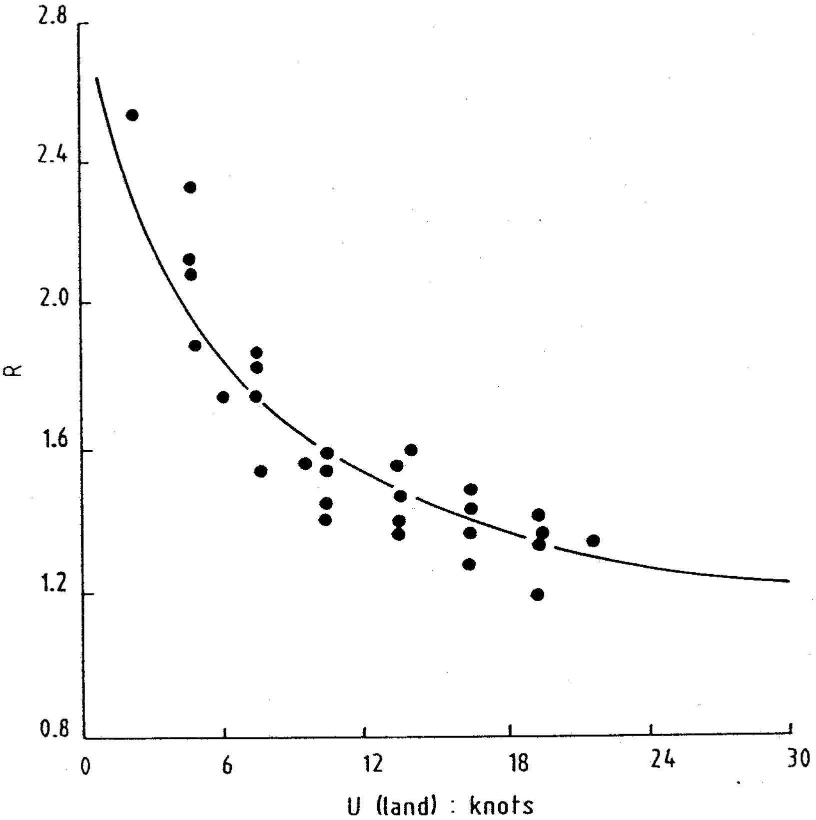

Fig 1 Ratio, R, of wind speed over the sea to that over the land (after Resio and Vincent, 1977).

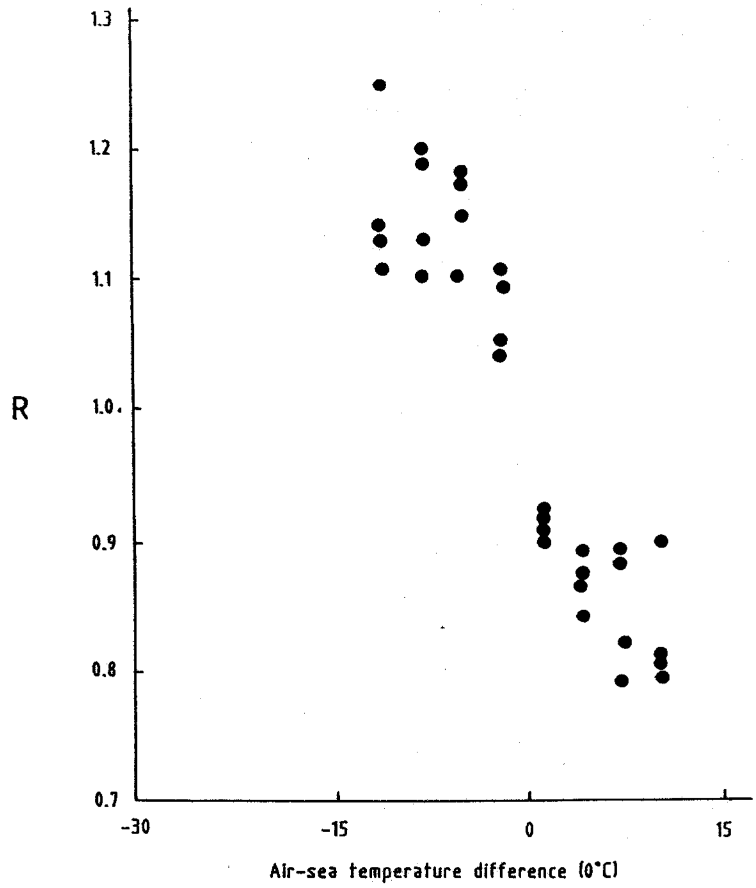

Fig 2 Normalized function, R, as related to air-sea temperature difference, (after Resio and Vincent, 1977).

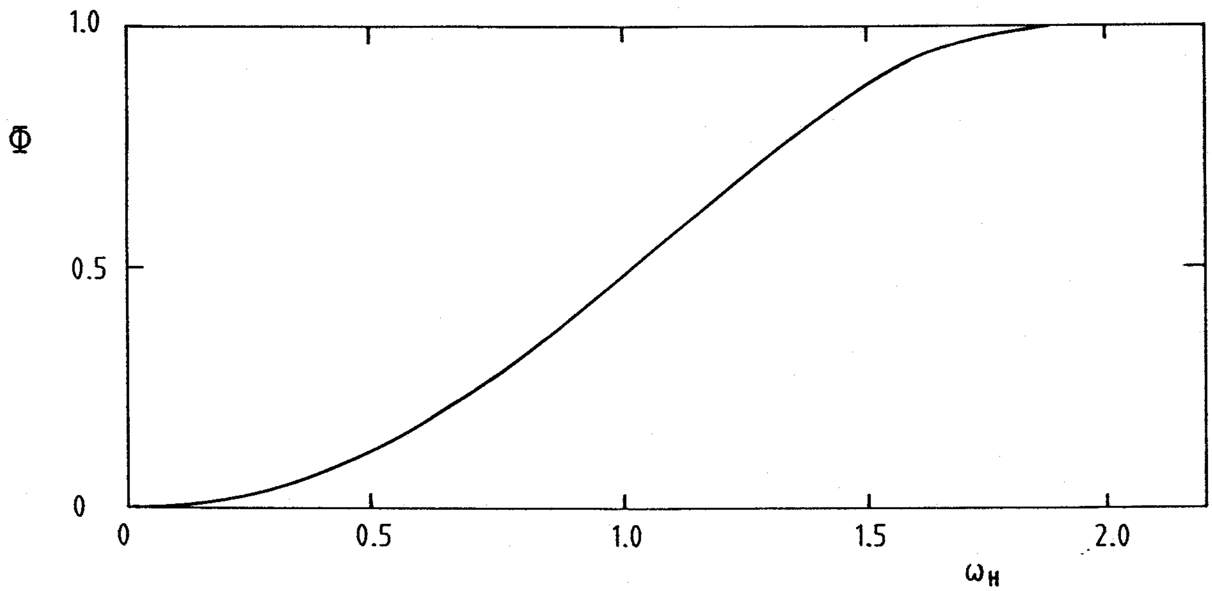

Fig 3 Shallow water function, Φ (See page 7 in text)

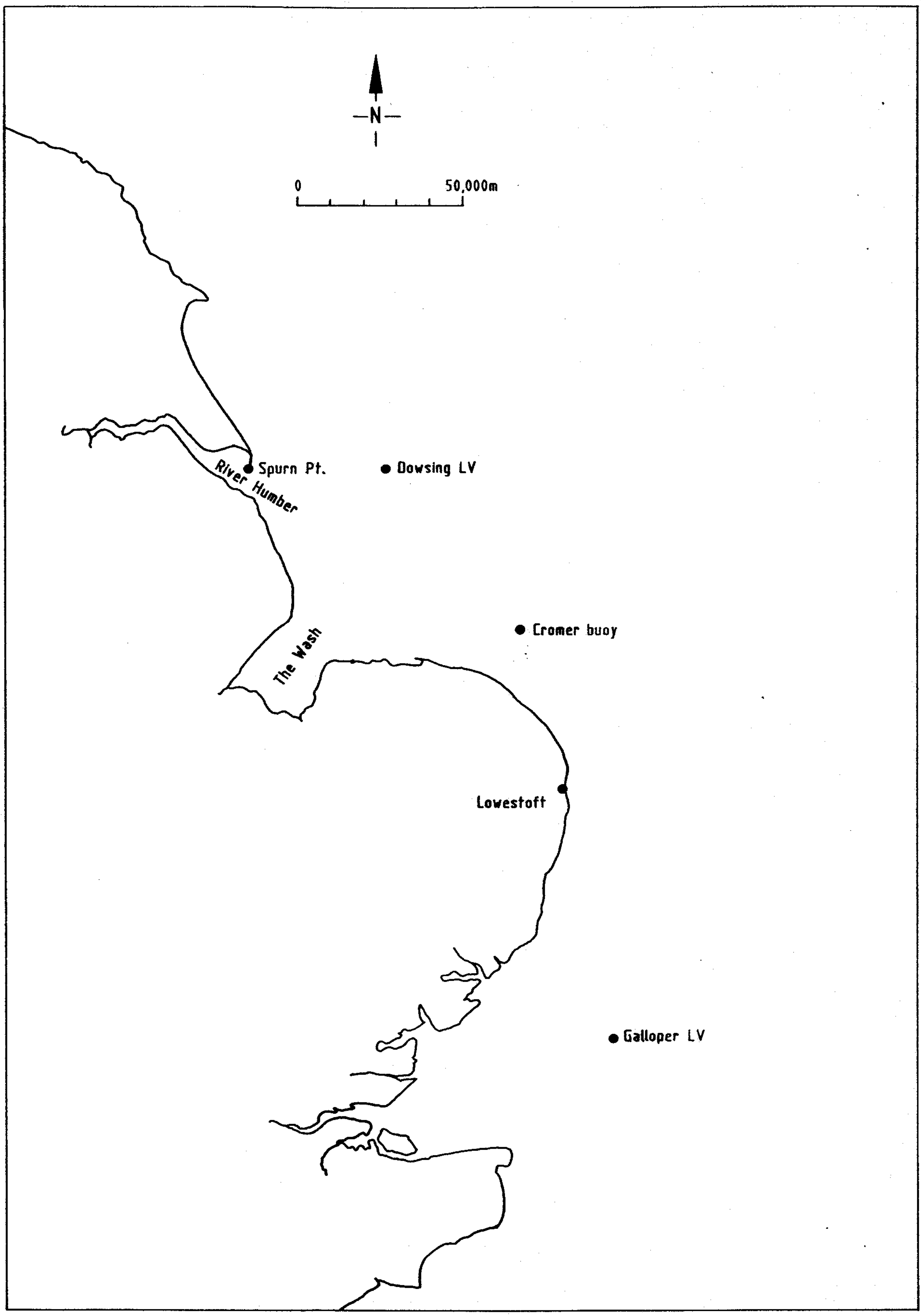

Fig 4 Map showing location of wave measurement stations and hindcast points

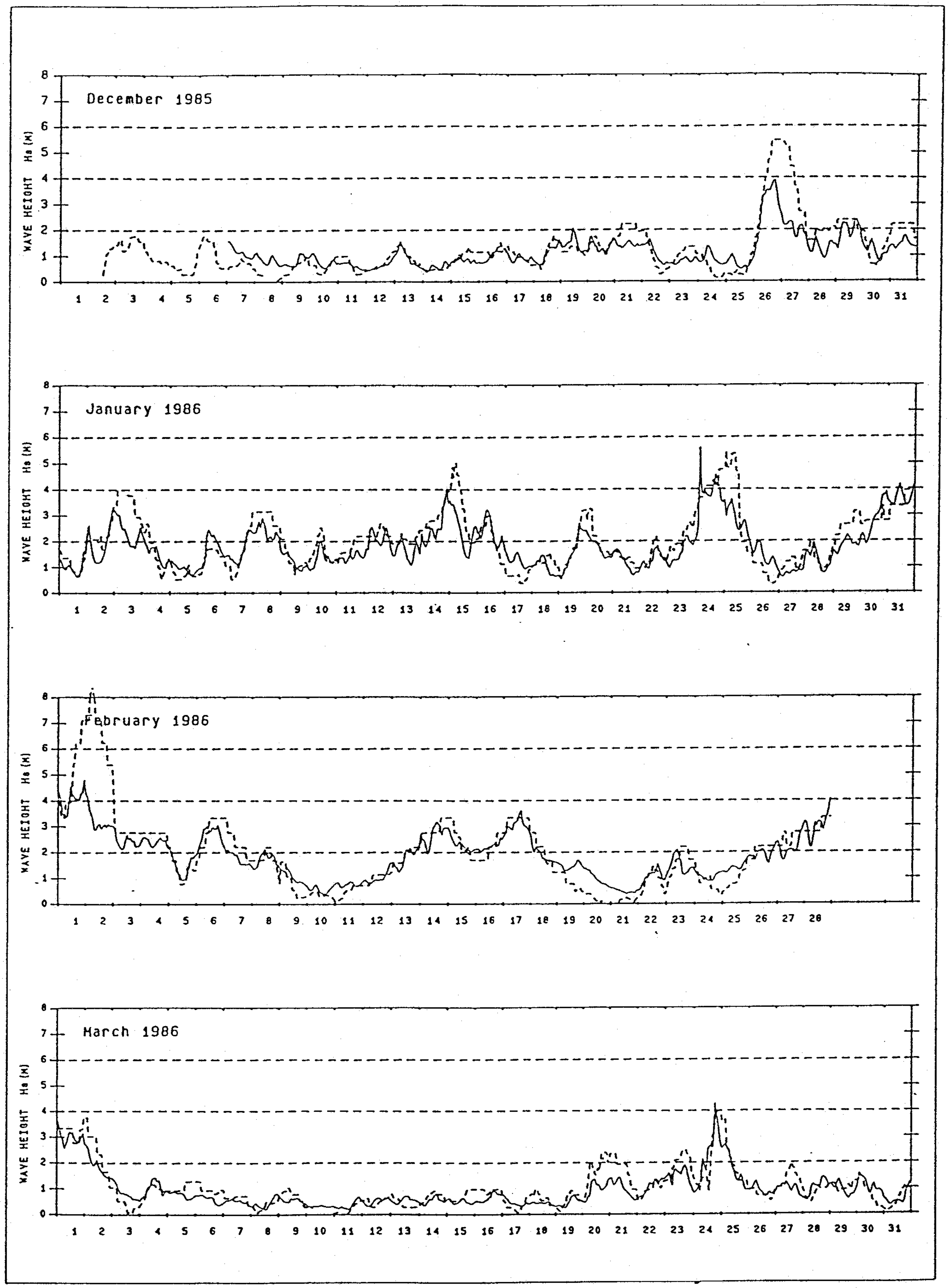

Fig 5 Comparison of HINDWAVE with wave heights at Cromer

model ------- : measured ———

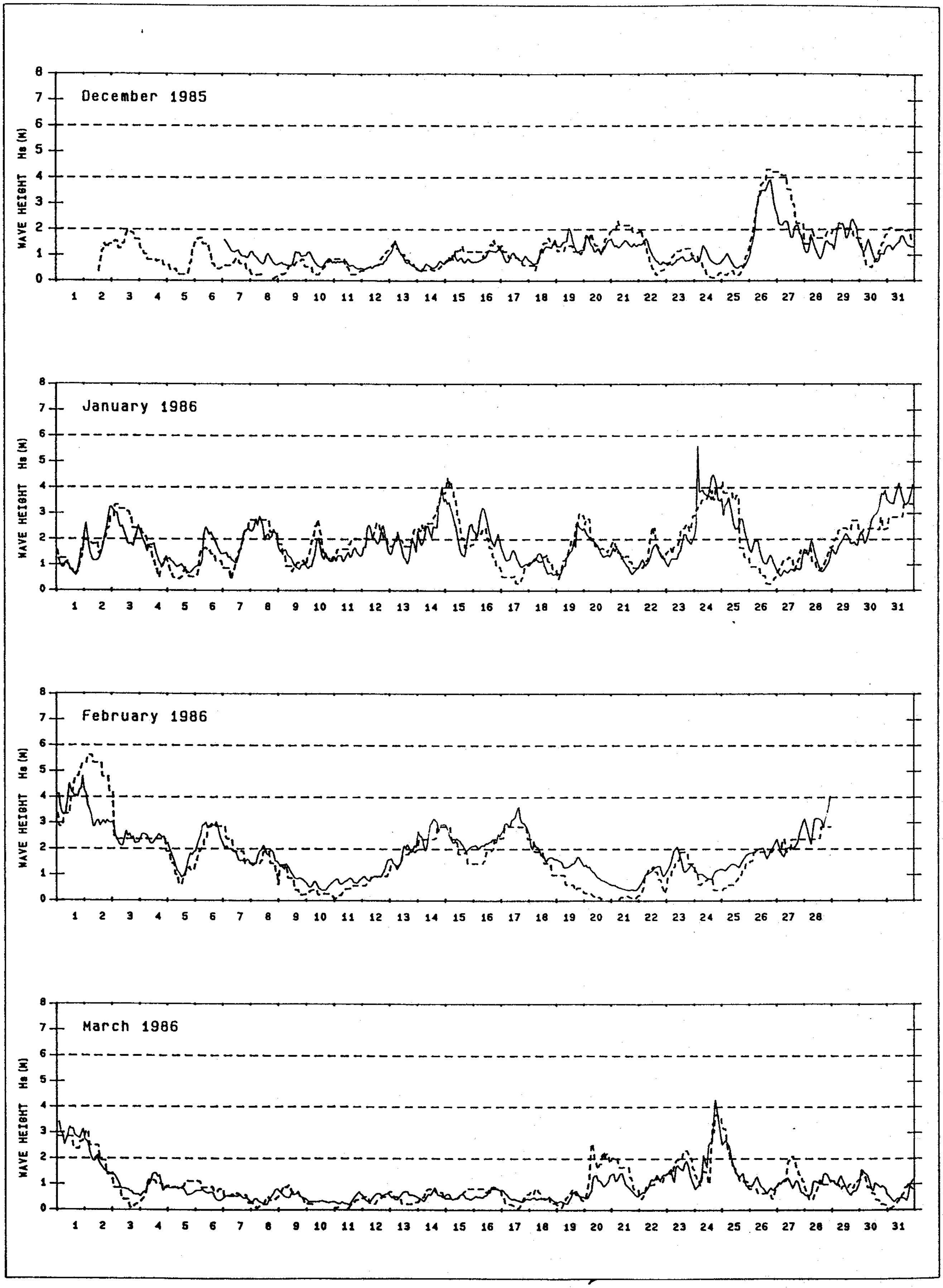

Fig 6 Comparison of shallow water version of HINDWAVE with wave heights at Cromer

model ------ : measured ———

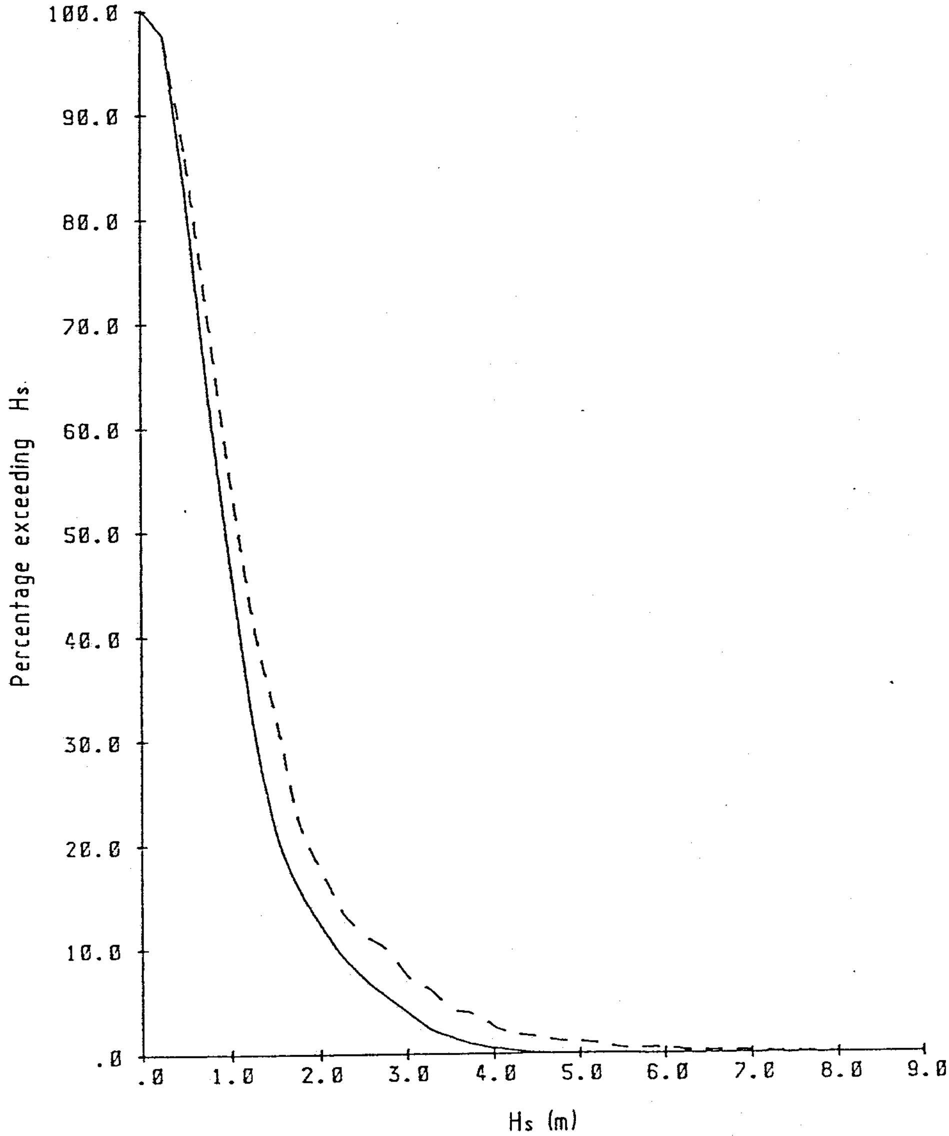

Fig 7 Wave height exceedence curve for Cromer

HINDWAVE ------- : measured ———

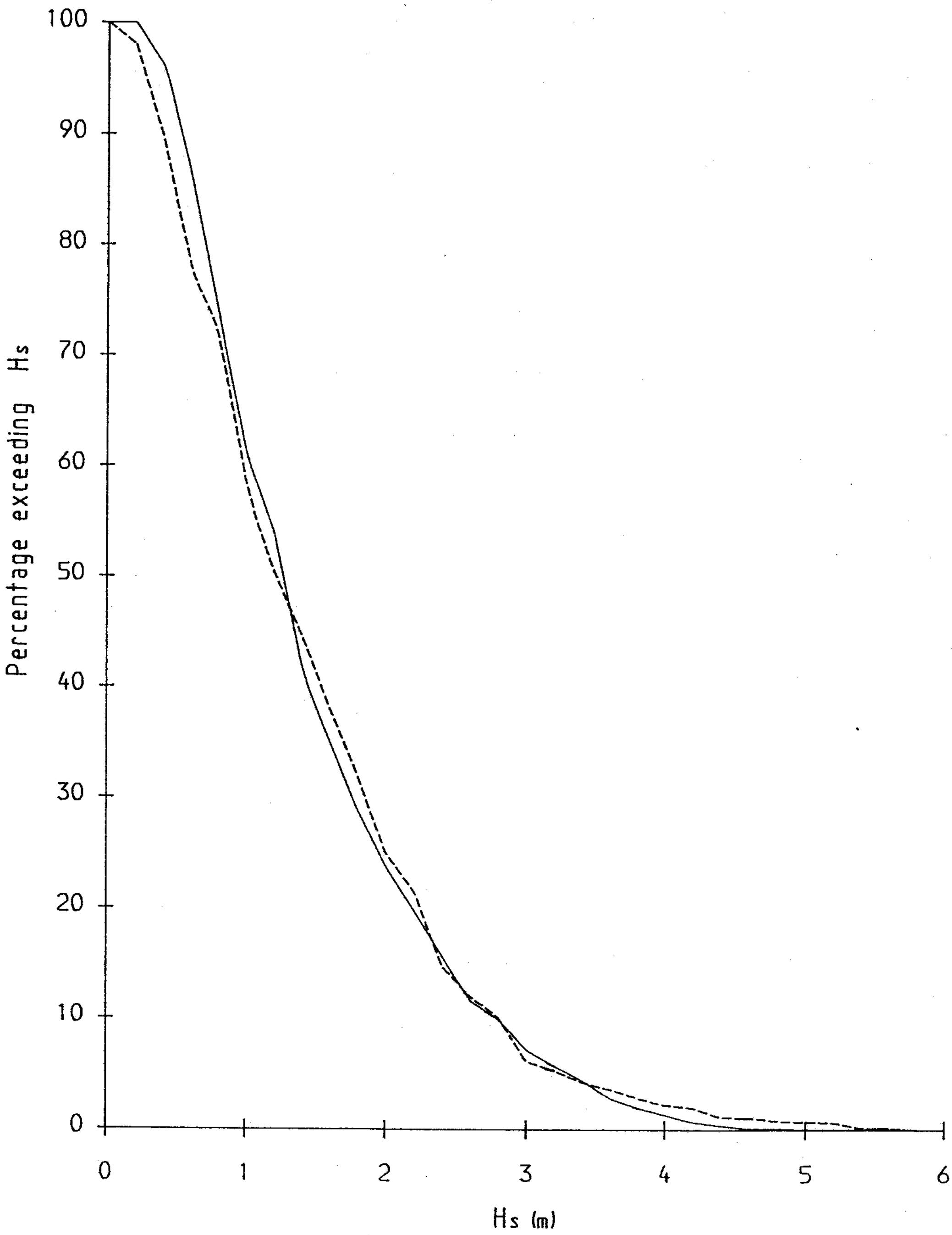

Fig 8 Wave height exceedence curve for Cromer

Shallow water HINDWAVE ------ : measured ———

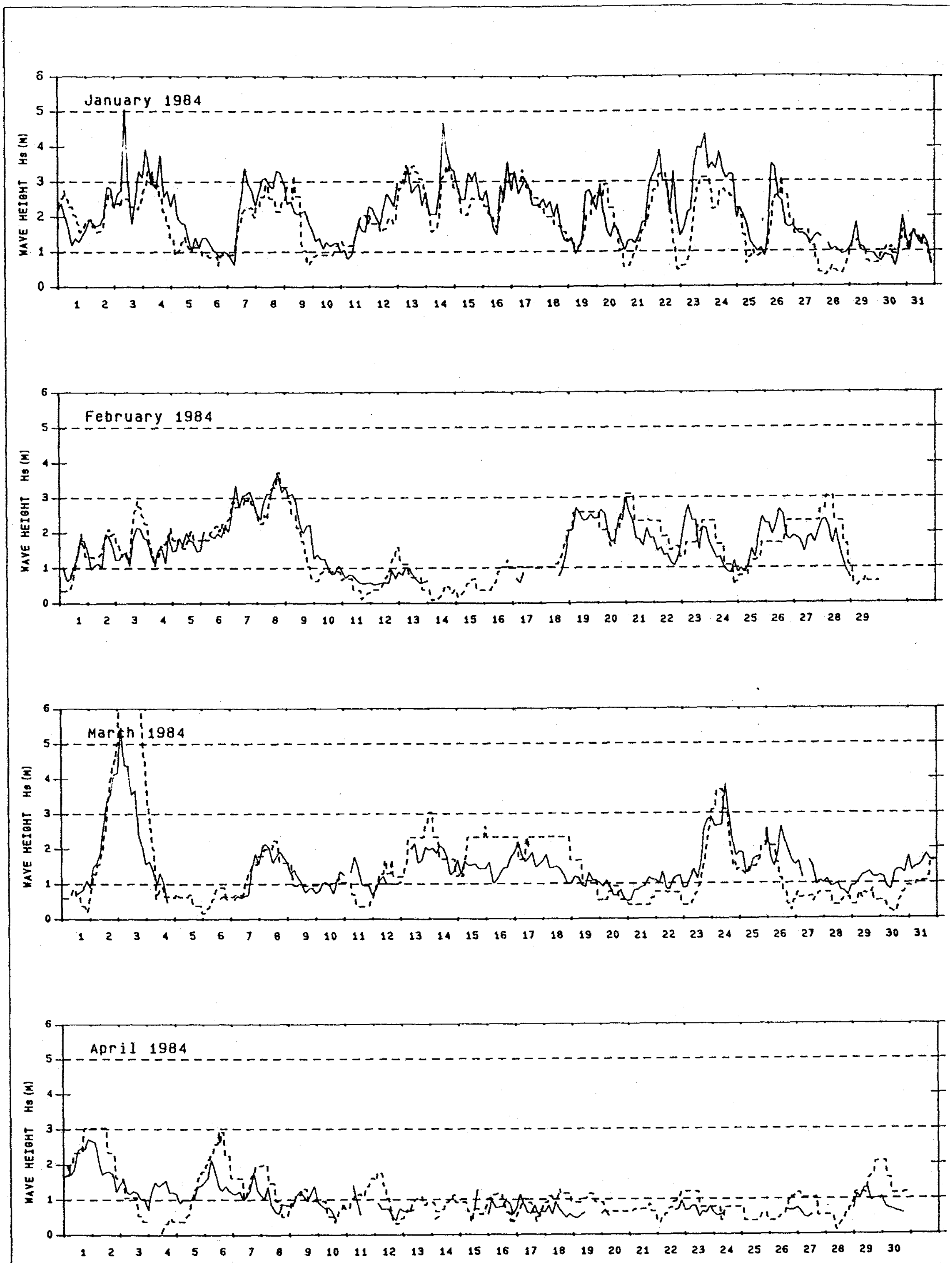

Fig 9a Comparison of HINDWAVE with wave heights at Dowsing Light Vessel

model - - - - - : measured ———

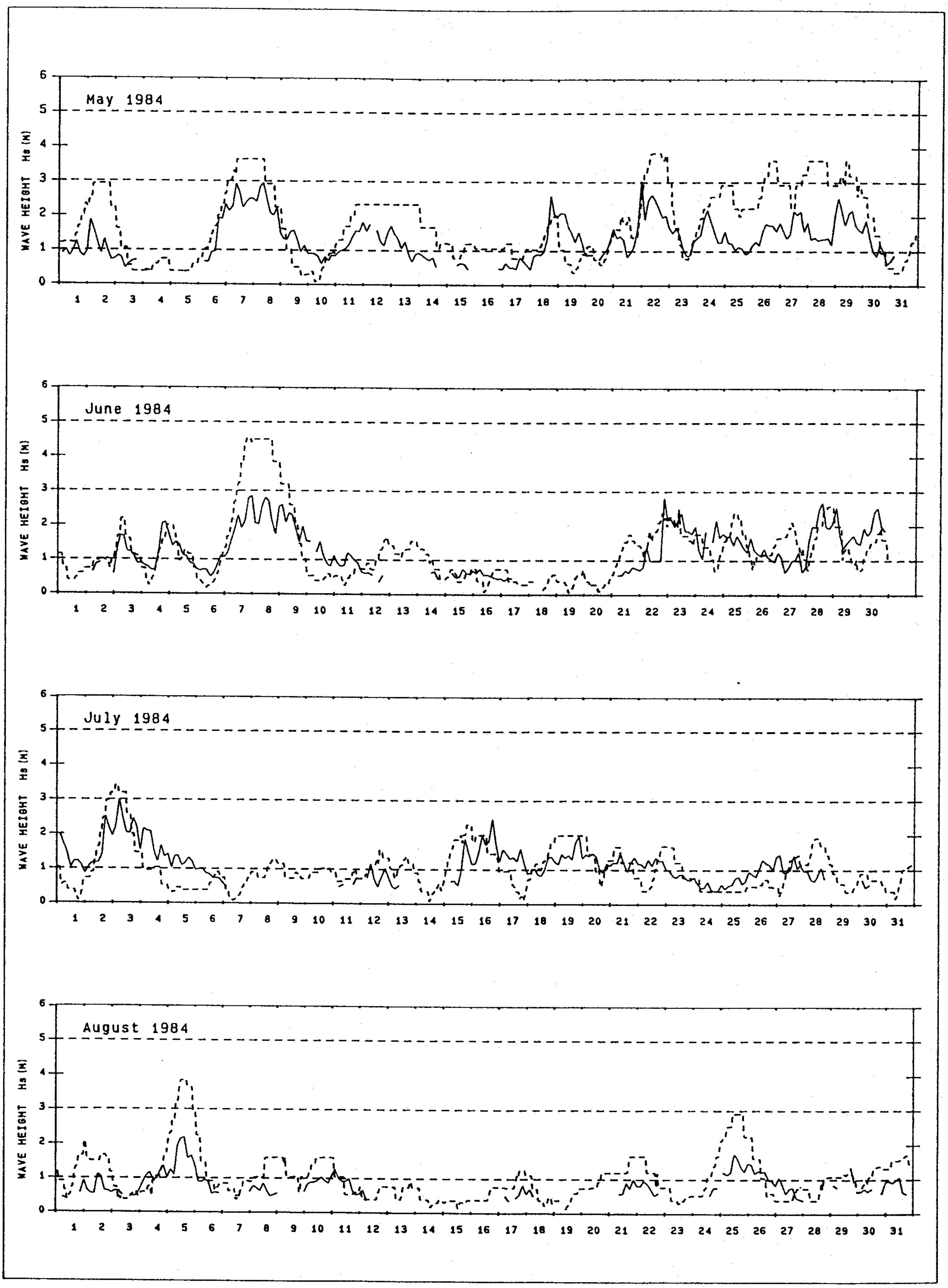

Fig 9b Comparison of HINDWAVE with wave heights at Dowsing Light Vessel

model ----- : measured ———

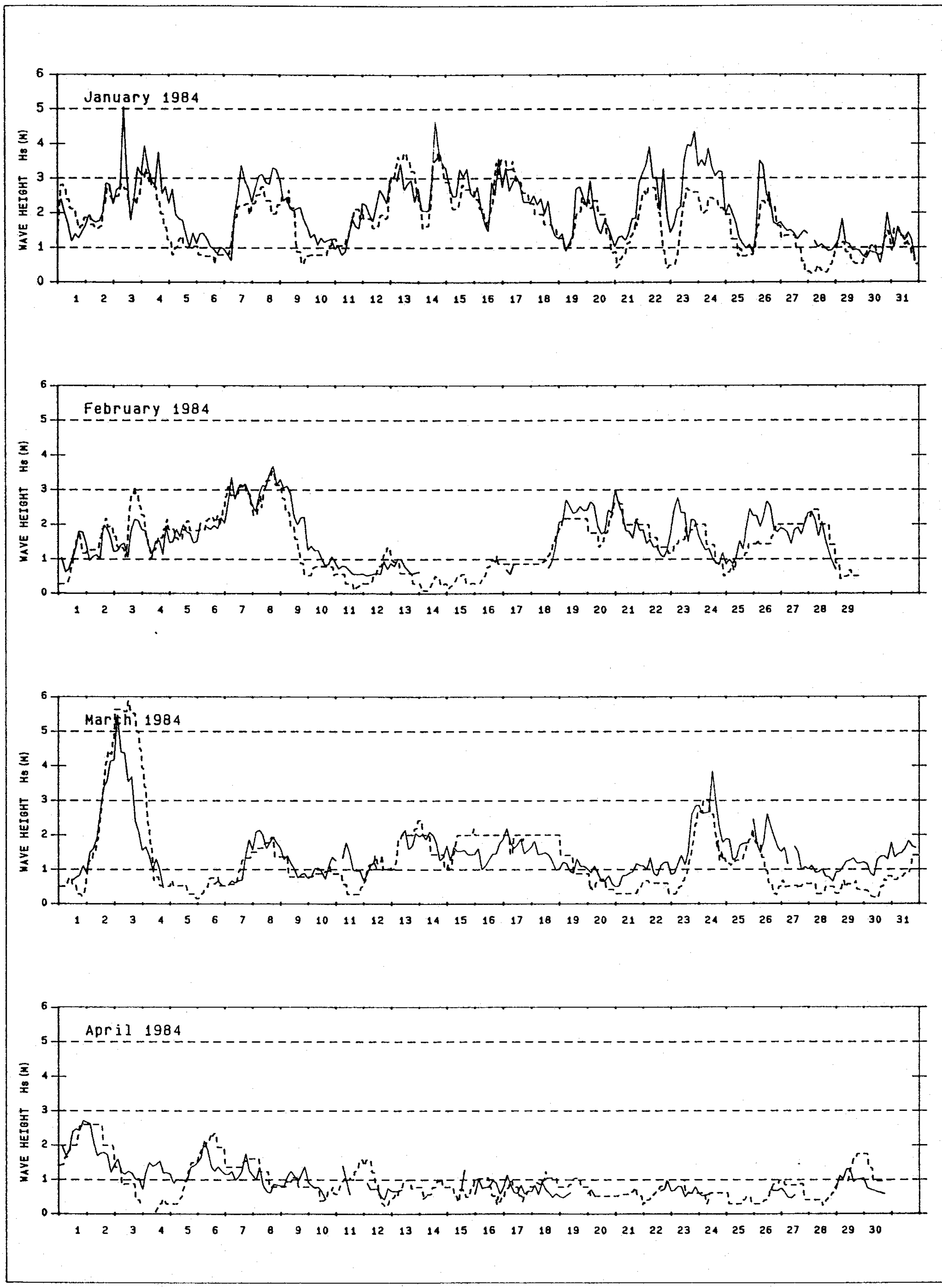

Fig 10a Comparison of shallow water version of HINDWAVE with wave heights at Dowsing Light Vessel
model ------ : measured ———

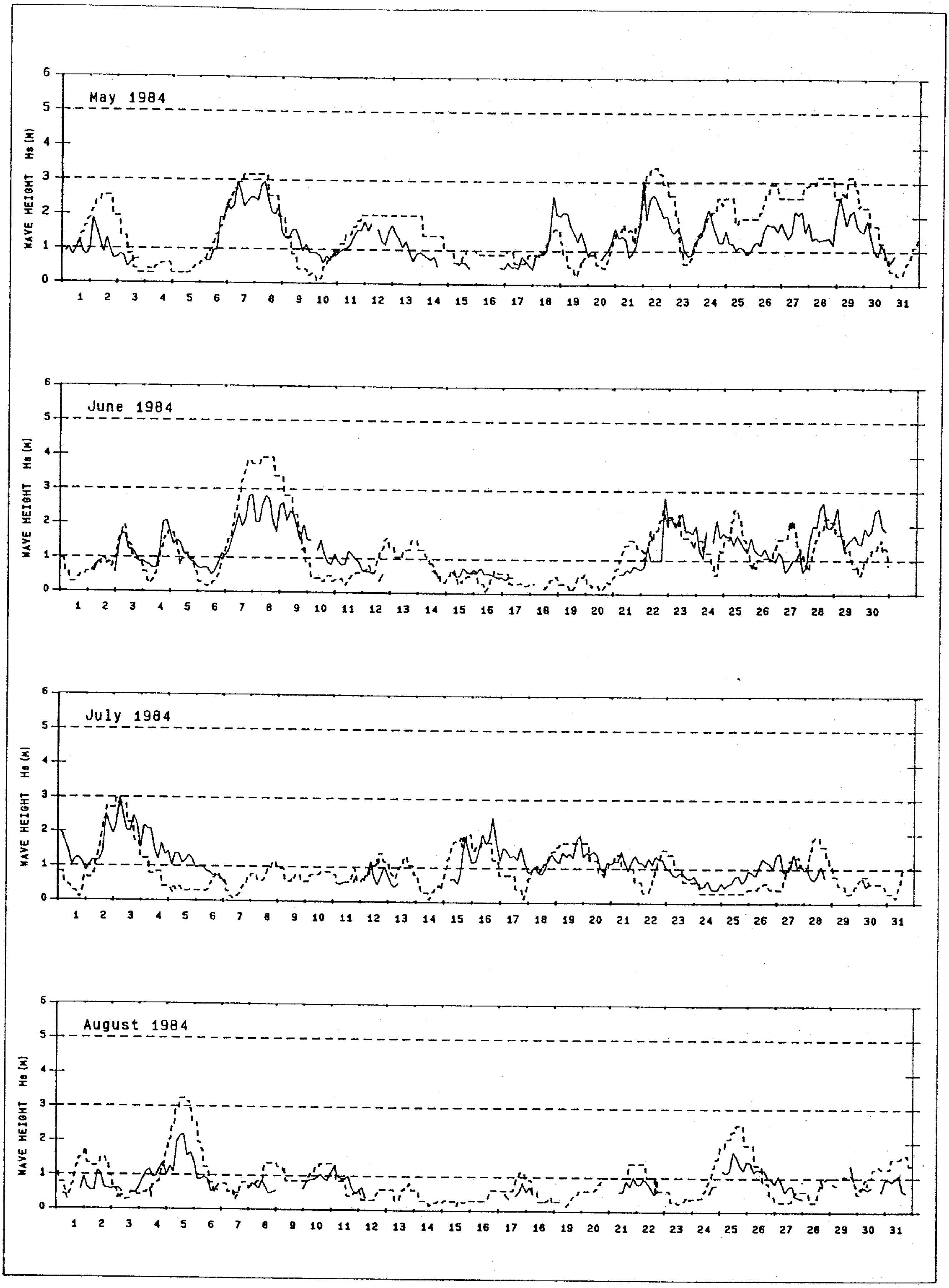

Fig 10b Comparison of shallow water version of HINDWAVE with wave heights at Dowsing Light Vessel
model ------ : measured ———

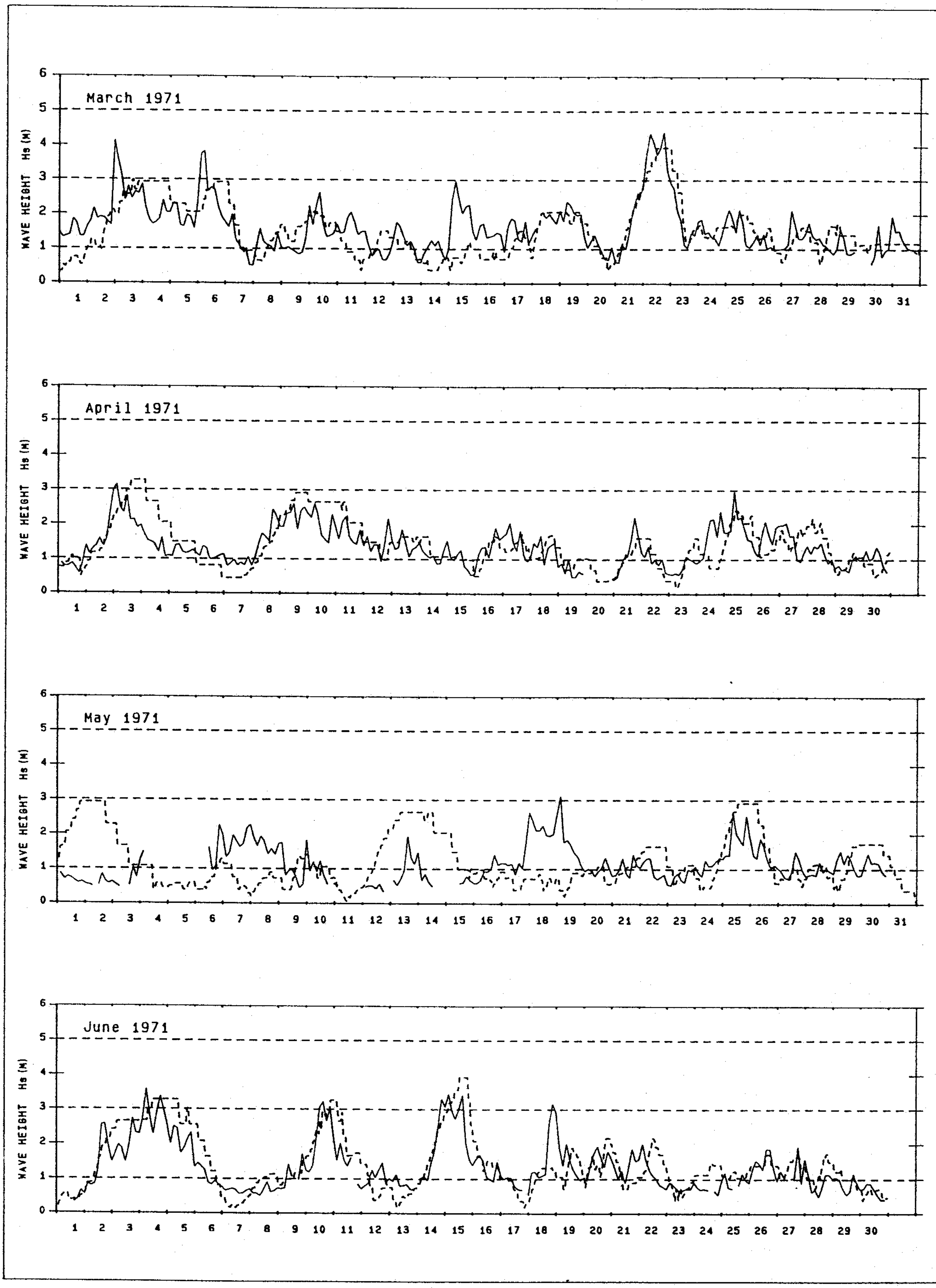

Fig 11 Comparison of HINDWAVE with wave heights at Galloper Light Vessel

model ------- : measured ———

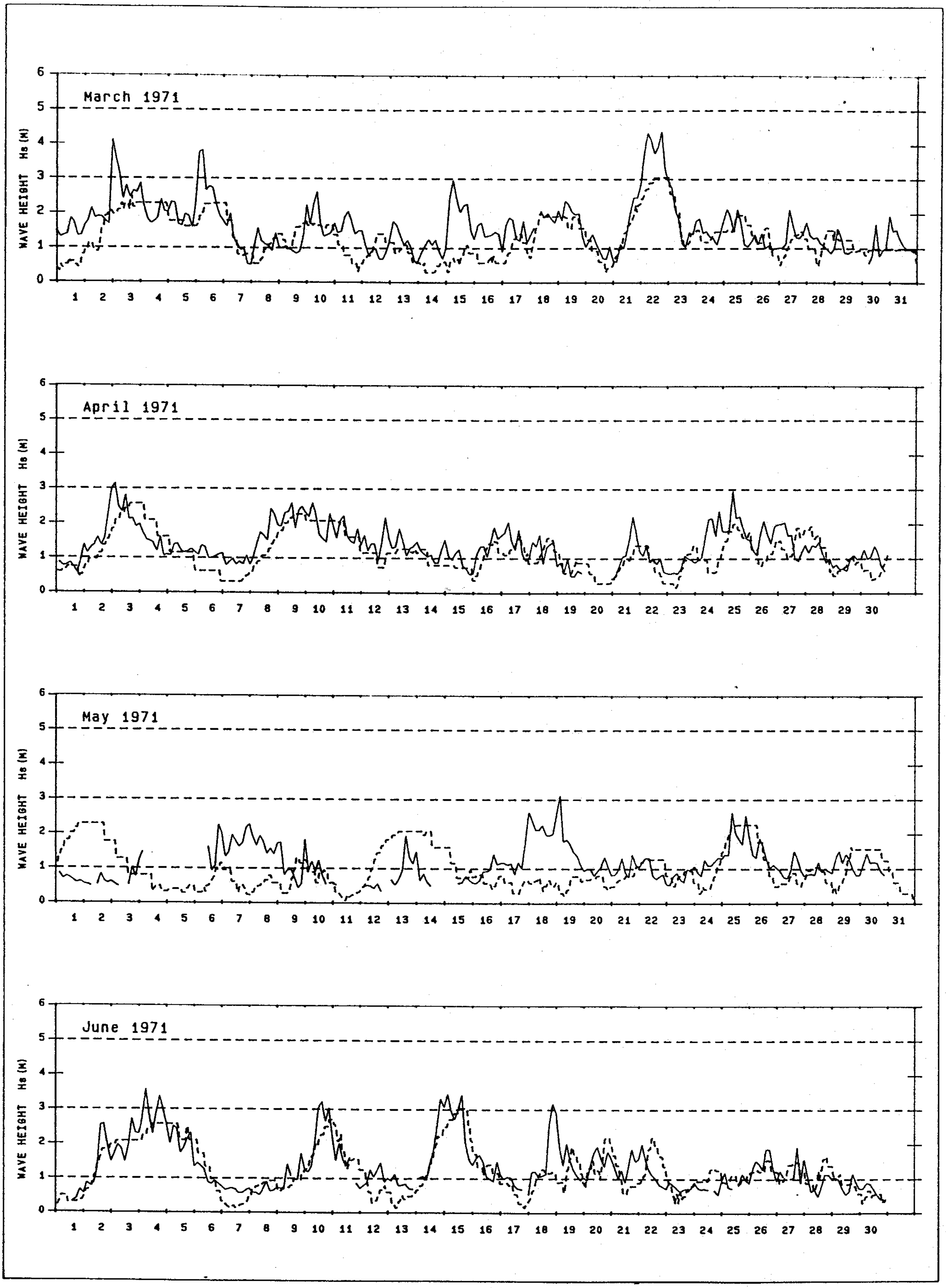

Fig 12 Comparison of shallow water version of HINDWAVE with wave heights at Galloper Light Vessel
model ------ : measured ———

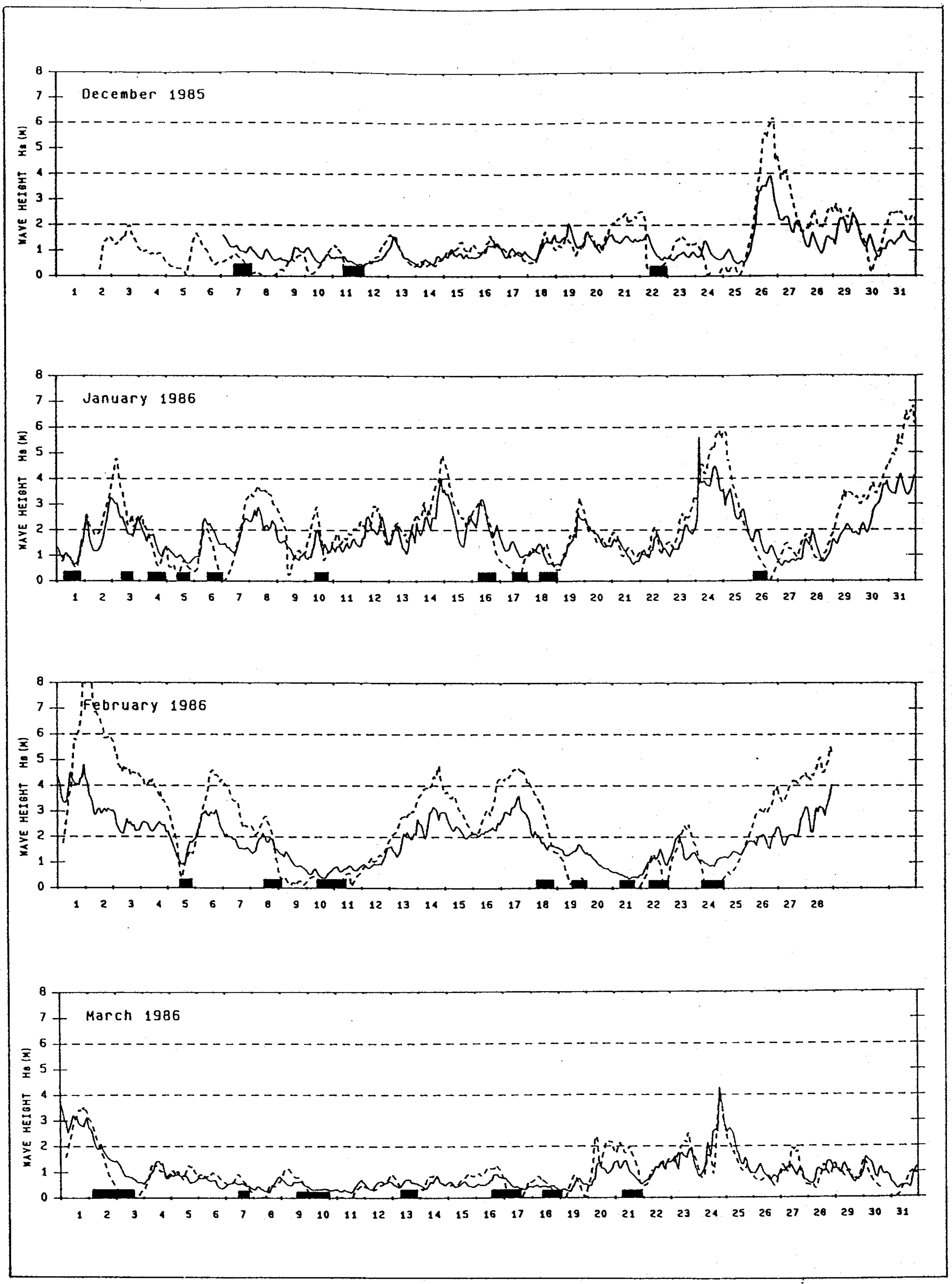

Fig 13 Comparison of BRISTWAVE with wave heights at Cromer

model - - - - - - - : measured ————

Swell wave energy exceeding 60% of the total energy is identified along the time axis

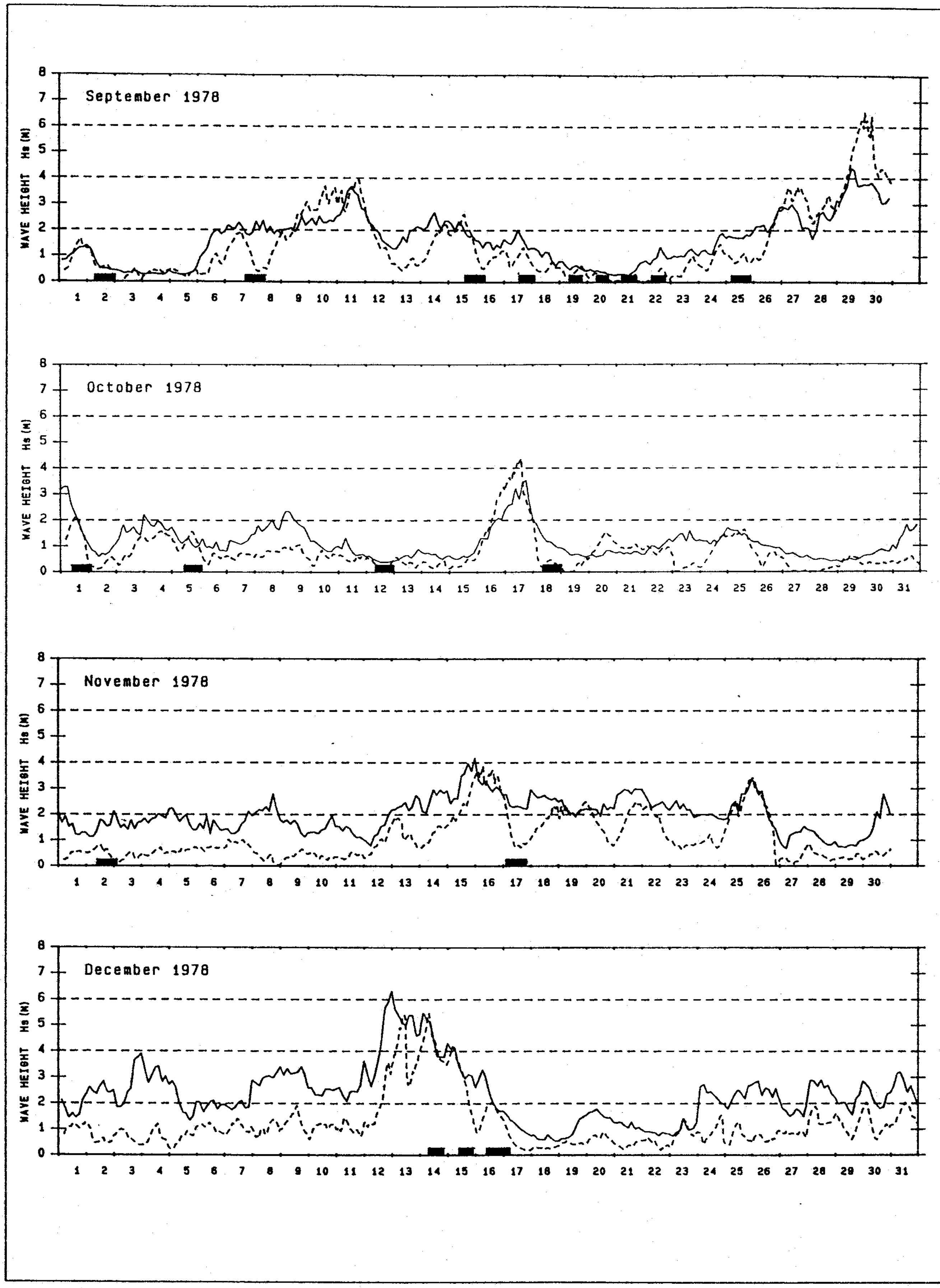

Fig 14 Comparison of BRISTWAVE with wave heights at Perranporth

model - - - - - - - : measured ————

Swell wave energy exceeding 60% of the total energy is identified along the time axis

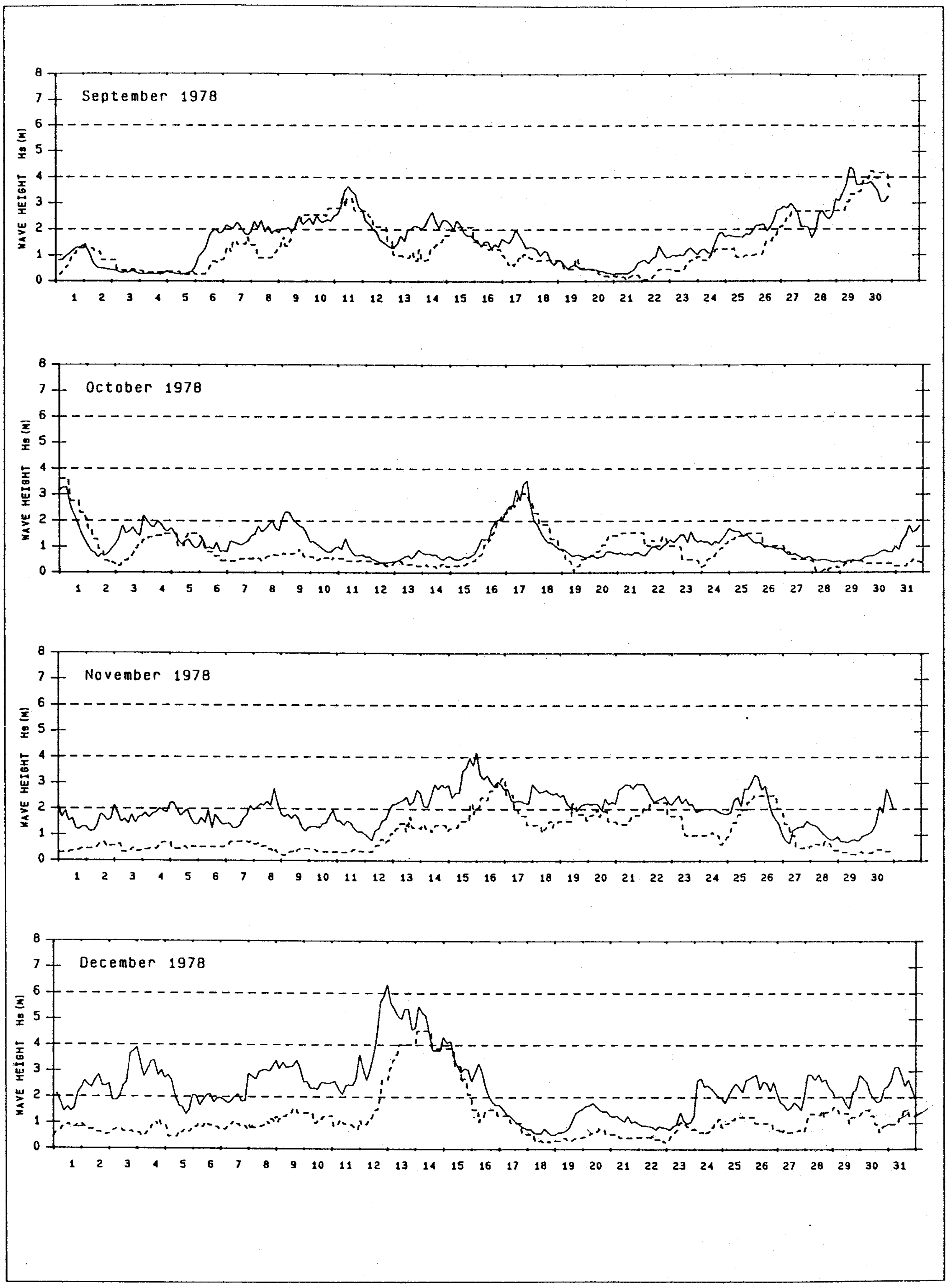

Fig 15 Comparison of HINDWAVE with wave heights at Perranporth

model ------ : measured ———

APPENDICES.

APPENDIX 1

THE JONSWAP/SEYMOUR WAVE PREDICTION MODEL

THE JONSWAP/SEYMOUR WAVE PREDICTION MODEL

It is observed that wind-generated waves show some directional spreading about their mean direction of propagation. Wind travelling over a water surface transmits energy to the water in directions on either side of its own direction, which may fluctuate during the period of wave generation.

To incorporate this effect in the model, components of the total wave directional spectrum are calculated for various directions either side of the mean, and then a weighted average is taken using a standard spreading function. The significant wave height, period and direction are then calculated at the target point, by numerical integration of the spectrum.

The component directions (i = 1 to n) are spaced at regular intervals ($\Delta\Theta$) in the range ±90° from the mean (Θ_o). For each one (Θ_i), the mean Jonswap equation, representing a growing wind sea, is used to define the spectrum (E_i), given as a function of frequency (f):

$$E_i\ (f) = \alpha g^2\ (2\pi)^{-4}\ f^{-5}\ \exp\ \{-1.25\ (f/f_m)^{-4}\}\ \gamma^{\eta} \qquad (1)$$

where:

$$\alpha = 0.032\ (f_m\ U/g)^{2/3}$$

$$\gamma = 3.3$$

$$\eta = \exp\ \left\{\frac{-\ (f - f_m)^2}{2\ f_m^2\ \sigma^2}\right\}$$

$$\sigma = 0.07 \text{ for } f \le f_m$$
$$\quad 0.09 \text{ for } f \ge f_m$$

f_m = the peak frequency (Hz)
$= 2.84 g^{0.7}\ F^{-0.3}\ U^{-0.4}$

U = the windspeed (ms^{-1})

F = the fetch (m) (fetch-limited conditions)
= $0.008515t^{1.298}g^{0.298}U^{0.702}$ (duration-limited)

g = the acceleration due to gravity (ms^{-2})

t = the duration (s)

The summation of the component spectra is then performed using the Seymour equation (Ref 1), which includes the cosine-squared directional spreading function for a directional wave spectrum ($E(f,\Theta)$). It is applied in the range ±90° from the principle wind direction. If the fetches are measured at say 10° intervals ($\Delta\Theta$), then the effective wave spectrum (E) for a particular direction (Θ_0) is calculated as the weighted average for seventeen component spectra ($E_i(\Theta_i)$, Θ_i = -80°, -70°, ..., 80° for i = 1, 17), as indicated in equation (2).

$$E = (2\Delta\Theta/\pi) \sum_{i=1}^{17} E_i \cos^2(\Theta_i - \Theta_0) \qquad (2)$$

Although it is not part of the original theory, experience at HR indicates that cosine-sixth is sometimes a better spreading function to use. This is particularly true when the wave generation area is unusually narrow or the peak period is unusually long. In order to use this modification, the cosine term in equation (2) is raised to the power six rather than two, and the coefficient $2/\pi$ is increased to $3.2/\pi$. In exceptional circumstances, involving a very short narrow wave generation area, cosine-thirtieth may also be used for the spreading function.

The significant wave height (H_s) is the average height of the largest one third of the waves. The mean zero-upcrossing period (T_z) is the period measure most frequently used in engineering, this being the average time between successive upcrossings of the mean level by the water surface. The mean wave direction (Θ_w) is taken as the average of the spectral components over all frequencies and directions. They are all approximated by numerical integration of equation (2).

$$H_s = 4m_0^{1/2} \tag{3}$$

$$T_z = (m_0/m_2)^{1/2} \tag{4}$$

$$\Theta_w = \Theta_0 + \frac{\int\int E(f,\Theta)(\Theta - \Theta_0)dfd\Theta}{\int\int E(f,\Theta)dfd\Theta} \tag{5}$$

where $m_n = \int E(f)\ f^n df$

In order to use this method, fetch lengths must be known over a range of at least 180° around a point. It is convenient to use discrete frequencies in equations (1) and (2) which should also be specified.

For each application of the method, a duration and a fetch are given, although only one or other of these will produce the limiting condition used in equation (1). A complete directional spectrum is calculated, from which is obtained the one-dimensional spectrum as well as H_s, T_z and Θ_w.

The directional spread of the predicted wave spectrum will generally be frequency dependent. The cosine-squared function is applied to component spectra, which are generated over different fetch lengths, and which will consequently have different total energies and different peak frequencies. This has the following realistic effect upon the calculated directional spread of energy. If the wind direction corresponds to one of the long fetch directions, then the spreading of energy at the peak will be lower than average, whilst more spreading will be observed at the highest frequencies. If the wind is blowing along one of the shorter fetches, then the spread will tend to be more even across different frequencies, and in an extreme case, may produce greater than average spreading at lower frequencies.

References

1. Seymour, R J. "Estimating wave generation on restricted fetches". Proc. ASCE, Vol 103, No WW2, May 1977.