WAVES AND WINDS IN THE NORTH-WEST APPROACHES TO THE UNITED KINGDOM

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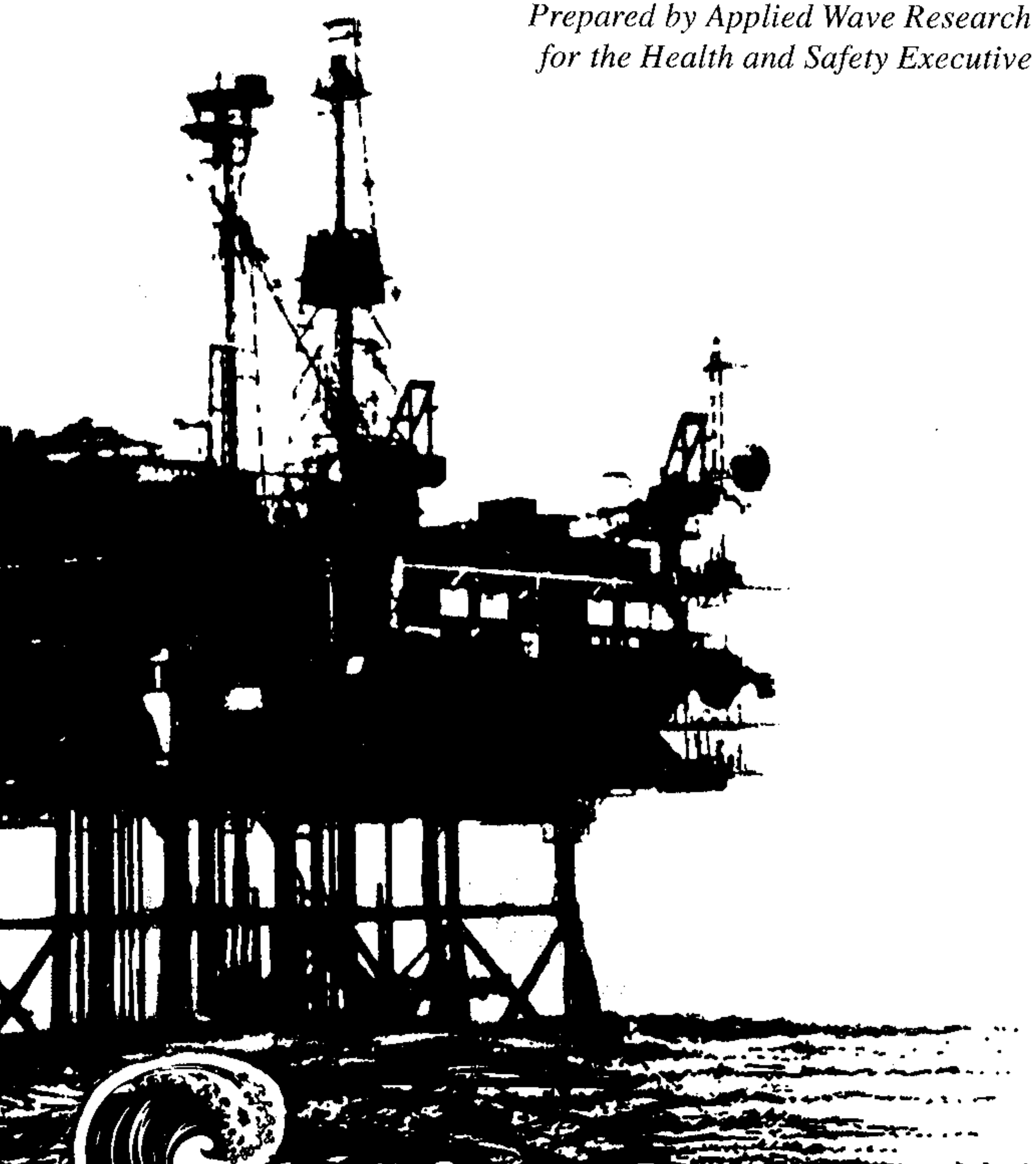

Offshore Technology Report

Health and Safety Executive

WAVES AND WINDS IN THE NORTH-WEST APPROACHES TO THE UNITED KINGDOM

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SUMMARY

This report reviews the 'indicative values' of the 50-year design wave heights and wind speeds contained in the Fourth Edition of the Guidance Notes (Reference 1) and its Supporting Document (Reference 2) in the north-west approaches to the United Kingdom.

WAVE HEIGHTS

Indicative values of design wave heights in the north-west approaches have been derived from three sources:

- Wave height data from the 25 year period of the NESS hindcast study have been extrapolated to return values of 50 years. The estimates of *Hs*(50) are found to be about 0.5m lower than values given in the Fourth Edition of the Guidance Notes (1990) in the north-west approaches.

- A re-analysis of measured data at DB2(NW) and DB3 confirmed previous return values obtained by UKOOA. These values are also lower than estimates given in the Guidance Notes.

- An analysis of satellite *Hs* data measured by Topex/Poseidon over the short period 1992-1994 give much higher values of *Hs*(50) reflecting the severe weather of the last few years.

WIND SPEEDS

Design wind speeds in the north-west approaches were derived from two main sources:

- An analysis of NESS wind speed data using both whole population and POT techniques gave values of *U*(50) substantially below those given in the Guidance Notes.

- An analysis of Topex/Poseidon satellite and DB2(NW) and DB3 wind speed measurements using a number of techniques, including a consideration of growth factors, give results which are close to the values derived from the NESS data and so are much lower than the Guidance Notes values.

It was felt that there were grounds for reviewing the wind speed calibration of Topex/Poseidon σ_0 for high wind speeds.

WAVE SPECTRA

A discussion of the spectral wave climate of the north-west approaches is given in Appendix 3.

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1. INTRODUCTION

Since 1990, when the Guidance Notes were issued, additional wave and wind data for the north-west approaches have become available. These data include measurements made at the UKOOA data buoys DB2 and DB3, wave height and wind speed measurements from satellites and model results from the NESS hindcast project.

The aim of this study is to bring together existing data and results and to derive additional information from new analyses so that an informed judgement can be made on the most appropriate return period values of wave height and wind speed in the north-west approaches.

The report is organised as follows. Section 2 considers the methods used in the Guidance Notes for the estimation of return period wave heights in the north-west approaches. Section 3 reviews return period wave heights at DB2 and DB3 reported by UKOOA and also re-analysed in this study. Section 4 gives new results for wave heights and wind speeds from an analysis of Topex/Poseidon satellite data over six 2-degree by 2-degree areas in the north-west approaches. In Section 5, design wave heights are obtained at selected NESS grid points using, principally, a 'peaks over threshold' analysis technique over 25 winter periods from 1964 to 1989. Section 6 gives a review of the work on NESS wind data carried out by BMT Offshore Ltd for the HSE together with additional, independent, estimates of return period values of wind speed. The conclusions of this study, with recommendations for preferred values of design wave heights and wind speeds, are given in Section 7.

A discussion of the wave spectral climate of the north-west approaches is contained in Appendix 3.

2. GUIDANCE NOTES ESTIMATES OF *HS*(50)

The method used in the Guidance Notes to estimate the 50-year return value of *Hs*, *Hs*(50), is described in Section 6 of Reference 2. Indicative values of *Hs*(50) were determined primarily from wave measurements at 40 sites around the UK with interpolation between these sites being based on 50-year return values of hourly-mean wind speed, *U*(50), derived by the UK Meteorological Office using the method described in Section 1 of Reference 3.

2.1 DESCRIPTION OF THE GUIDANCE NOTES METHOD

The calculations use the distribution of *Hs* determined from the measurements. The method used is that of fitting a Fisher-Tippett Type 1 distribution, given by

$$P(H<h) = \exp[-\exp-(h-\alpha)/\beta],$$

to the three-hourly estimates of *Hs* using data collected for at least one year. The 50-year return value is then estimated from

$$Hs(50) = \alpha' + q\beta'$$

where $q = -\ln\{-\ln[1-1/(2922\times50)]\} = 11.89$

and α' and β' are the estimates of α and β obtained by the method of moments based on the distribution of *Hs*, usually in 0.5m bins. (The formulas for the first two moments of the distribution are given in Appendix 1 of the present report). 2922 is the number of three-hour periods in an average year of 365.25 days.

2.1.1 Interpolation between sites

In Reference 2, an empirical relationship (Equation 47) between *Hs*(50) and *U*(50) and the water depth is developed which is used in the Guidance Notes to interpolate between sites with measured wave data. In the North Sea, water depth can sometimes be used as a crude measure of fetch limitations (i.e. the degree of sheltering from the winds).

In the north-west approaches only two measurement stations (at Fitzroy and South Uist) were available for the Guidance Notes. The contours of 50-year wind speed were then used to give an indication of the orientation of the contours of *Hs*(50) in this region.

A map showing the indicative values of *Hs*(50) taken from Figure 3 of the Guidance Notes is shown in Figure 2.1.

2.2 CONFIDENCE INTERVALS

Section 6.5 of the Guidance Notes discusses the confidence limits to be associated with the estimates of *Hs*(50). Measured wave data at Fitzroy and South Uist were collected over periods of 2 and 7 years respectively. Table 18 from the Guidance Notes, reproduced here as Table 2.1, shows that the 95% confidence limits for *Hs*(50) at these stations are therefore ±14% and ±8% respectively.

Table 2.1: Approximate confidence limits on *Hs*(50)

No of years	95% confidence limits
1	±20%
2	±14%
3	±12%
5	±9%
10	±6%
15	±5%

3. RETURN PERIOD WAVE HEIGHTS AT DB2 AND DB3

Environmental data have been collected by the UK Offshore Operators Association Ltd (UKOOA) in the north-west approaches at DB2 (September 1986 to December 1988) and DB3 (July 1984 to December 1988). The data have been analysed by Marex Technology Ltd and the results given in confidential reports (References 4 and 5).

The principal results are given in Tables 9.6.2 of both References 4 and 5. As part of this study, the return period wave heights have been computed by the method used in the Guidance Notes (see Section 1, above) using the data from the distribution of *Hs* at DB2 and DB3 given in References 4 and 5. For DB2, the data were for the whole-year period from January 1987 to December 1988. For DB3, the data used were for the whole-year period from January 1985 to December 1988. Figures 3.1 and 3.2 show the FT-1 fits to the measured data at DB2 and DB3.

Table 3.1 compares the estimates of return period values from the UKOOA confidential reports with estimates obtained in this study. In the work of MAREX (References 4 and 5), a three-parameter Weibull distribution and a FT-1 distribution were fitted to the measured data. There is excellent agreement between the estimates made by MAREX and those obtained in this study for a FT-1 distribution. [Return period values at DB2 and DB3 are not included in Reference 2]. The fit of the Weibull distribution to these data gives design estimates about 2m lower than those for the FT-1 distribution.

3.1 RETURN PERIOD WAVE HEIGHTS AT FITZROY AND SOUTH UIST

Data for two additional stations, Fitzroy and South Uist, were included by MAREX in Reference 4. Return value wave heights for Fitzroy estimated by MAREX using the FT-1 distribution are 1.6m higher than those given in Reference 2 for the same distribution (see Table 3.1). The results given (in Table 9.6.2 of Reference 4) by MAREX for South Uist are for a Waverider station in a water depth of 42m for which the corresponding return value in Reference 2 is 14.8m. These values are not appropriate to the north-west approaches. The outer Waverider station in 96m has a return value from Reference 2 of 17.2m (see Table 3.1) which is more representative of deep water conditions in this region.

Table 3.1: Comparison of results for *Hs*(50) (m) at stations in the north-west approaches

Station	MAREX		Reference 2	This study
	(Weibull)	(FT-1)	(FT-1)	(FT-1)
DB2(NW)	13.4	15.1	-	15.1
DB3	13.6	15.6	-	15.5
Fitzroy	15.9	17.9	16.3	-
South Uist (42m)	12.6	13.7	14.8	-
South Uist (96m)	-	-	17.2	-

4. ANALYSIS OF TOPEX/POSEIDON SATELLITE MEASUREMENTS

Topex/Poseidon is a joint French (CNES[1]) and American (NASA[2]) satellite system designed to study global ocean dynamics. To achieve this the satellites each carry a dual-frequency radar altimeter which operates simultaneously at 13.6 GHz (Ku-band) and 5.3 GHz (C-band). The measurements made at the two frequencies are used to obtain the height of the satellite above the ocean surface with very high precision. It is also possible to obtain the wave height and the wind speed from the altimeter and the methods used to achieve this will be outlined in Sections 4.1 and 4.2.

The system consists of two satellites called Topex and Poseidon which are in exact repeat orbits with a repeat or cycle time of ten days. Each cycle consists of 127 orbits or 254 passes, ie each orbit is divided into two halves - a descending pass travelling North to South and an ascending pass travelling South to North. The two satellites carry rather similar instrumentation but it has been found that almost all of the reliable wave measurements have been obtained from Topex. Only one satellite is in use at any one time.

The data are processed by AVISO Altimetry, Toulouse and distributed to users on CD-ROMs. Each CD-ROM contains data from two cycles (ie 20 days) in two directories. The data for each pass are contained in a separate file which consists of 'Geophysical Data Records' (GDR's) written in VAX binary.

It was decided to follow Carter (Reference 7) and analyse the satellite data by considering the average over two degree latitude by two degree longitude (2°×2°) areas. Six such areas (some of them overlapping) were chosen to provide coverage of the north-west approaches and are shown in Figure 4.1, together with the satellite passes, each one-second value being marked with a cross.

As the satellite passes over the ocean, altimeter measurements are made ten times per second. These are subjected to onboard quality control and averaged to provide one second values. The speed of the satellite over the earth's surface (5.4 km/s) is so high that the observations of wave height or wind speed made at points along a particular pass within a particular 2°×2° area (referred to hereafter as a 'transect') are effectively simultaneous, and so all these may be combined to provide one sample measurement. This average value is regarded as representative of the whole 2°×2° area at that time. Section 4.1.1 contains a discussion of the relationship between transect averages and measurements at a single position.

4.1 TOPEX/POSEIDON *HS* MEASUREMENTS AND THEIR TREATMENT

The measurement of *Hs* using a satellite-borne radar altimeter is described in Reference 7. Below are listed the essential features of this process:

(i) The sea-state is indicated by the degree of lengthening or 'smearing' of the leading edge of the reflected altimeter pulse.

(ii) On the assumption of quasi-Gaussian sea surface statistics a theory can be constructed which relates *Hs* to the degree of leading-edge smearing.

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[1]Centre National d'Etudes Spatiale

[2]National Aeronautics and Space Administration

(iii) Although this theory is free of empirical constants it has been found that altimeter measurements of *Hs* deviate systematically from collocated and contemporaneous buoy measurements, Carter et al (Reference 8), Cotton and Carter (Reference 9). This is thought to be due to the waveform fitting methods used in the onboard analysis. Cotton and Carter proposed that a linear correction function should be applied to the Topex/Poseidon data as follows

$$Hs = 1.09Hs' - 0.187$$

where *Hs*' is the value in the Topex/Poseidon GDR's and *Hs* is the corrected value.

(iv) Errors (repeatability) in the one-second values are likely to be of order 2%.

One-second values of *Hs* derived from the 10 Hz measurements made at both C-band and Ku-band are included in the GDR's together with their respective RMS about the one-second values and the number of values included in the means. However, the C-band measurements from Poseidon are spurious and default values only are included. Carter and Cotton take the median value of the Ku-band (only) *Hs* measurements as representative of each 2°×2° area. This approach is followed in the present work (called '*Hs*-CC') but in addition the weighted mean of the Ku-band and the C-band data (called '*Hs*-AWR') is calculated, the weights being inversely proportional to the RMS about the respective mean.

Individual one-second values are rejected if:

(i) the GDR quality flags indicate a problem,

(ii) the combined RMS of *Hs*-AWR is greater than 15%, or

(iii) the number of primary values in the one-second mean is less than eight (the full complement is ten).

The GDR values were corrected using Carter and Cotton's results. Since their data set extended to only 10m, much smaller than some of the *Hs* values seen in the present study, the application of this correction implies the assumption that their results are applicable throughout the wave height range.

Whenever Poseidon is switched on or if *Hs*-AWR is rejected by condition 2 (above) the median of the Ku-band data (ie *Hs*-CC) is used. Figure 4.2 shows a comparison between *Hs*-AWR and *Hs*-CC. As can be seen they are essentially the same, but as *Hs*-AWR includes almost twice as many data as *Hs*-CC it has been used in the subsequent analysis.

4.1.1 Relationship between buoy and satellite measurements

Both the surface wave field and the wind field are random processes and it is normally assumed that they are ergodic. That is, under statistically stationary conditions temporal averages and spatial averages are equivalent. A rough estimate of the spatial average which is equivalent to the 2000 second DB2/3 buoy wave record can be made as follows. Assume the modal period of the spectrum is 12 seconds, then the group velocity is 9.4 m/s. In 2000 seconds the wave energy would travel about 19km. Thus a 19km spatial average is roughly equivalent to a 2000 second time average. Note that the individual one-second satellite values are spatial averages over about 6km.

The transect values are averages over 100-150km which is much longer than 19km. If the wave field were indeed stationary over this length scale, the averages would still be equivalent to the buoy averages but with smaller random errors. [In this case the transect average corresponds to a wave record of about three hours duration.] If the wave conditions were not stationary, the transect average would be a smoothed represention of the data leading to a smaller variance overall and a smaller value of β in the FT-1 analysis.

The calibrations reported in References 8 amd 9 compare time-interpolated buoy measurements with one-second satellite values which fall within a radius of 0.25°. These are closely similar measures.

4.1.2 Statistical analysis of Topex/Poseidon *Hs* data

Two years' data, from October 1992 to September 1994 were used in the analysis. The numbers of transects available varied from area to area and are shown in Table 4.1.

Table 4.1: Numbers of Topex/Poseidon transects by area

Area	Number of Transects
1	361
2	429
3	369
4	284
5	428
6	285

There was some variability in the numbers of transects from month to month, but this was judged insufficient to warrant weighting the data.

It will be seen that the frequency of observation varies from about one every 1½ days to one every 2½ days on average. It was found that there were insufficient data for a peaks over threshold analysis such as that described for the NESS data. Instead and initially the data were treated very much as in Reference 7. That is to say a FT-1 distribution was fitted to the cumulative data by the method of moments and the 50-year *Hs* estimated on the basis of a three-hour time step. Values of *Hs*(50) for the six areas together with the associated FT-1 parameters are shown in Table 4.2; plots of the distributions for FT-1 and three-parameter Weibull for Area 2 are shown in Figures 4.3 and 4.4. Figure 4.5 shows Cycle 12, Pass 18 which contained the highest values of *Hs* measured during the two years under consideration. It will be seen that the one-second values of *Hs* (footprint of order 6km long) were as high as 18.4m in area 4. The gaps represent values which failed the quality control checks. Note the sheltering effect of the Orkney Islands.

It will be seen that the resulting values of *Hs*(50) are much higher than those derived from the NESS data (Section 5). The values of the FT-1 parameters, especially β, are greater than the corresponding NESS parameters indicating that the two years 1992-94 were more severe than the average of the NESS data but there may also be an effect due to the differing methodologies used in the respective analyses.

The first point to consider concerns the choice of a three-hour time step to calculate the return period probabilities. This requires that values of *Hs* at three-hour intervals be independent, whereas such work as has been done suggests that the decorrelation time of *Hs* is greater than six hours. The extrapolation of such a short and undersampled data set to low exceedance probabilities may be seen as problematical and so, in addition, the growth factor method has been used with growth factors estimated from the NESS data. The results of these alternative calculations are also included in Table 4.2. The average value of all five estimates for each area (Table 4.2) was used to define a representative 50-year return wave height as given in Table 7.2 and shown in Figure 5.7.

4.2 TOPEX/POSEIDON WIND SPEED MEASUREMENTS

An indication of ocean surface wind speed may be obtained from the strength of the altimeter return. The parameter measured is σ_0, the backscatter cross section, which gives the back-scattered power relative to the incident power. It is a pure number and is usually expressed in dB. Near normal incidence σ_0 is proportional to the appropriate Fresnel reflection coefficient and inversely proportional to the mean-square slope (of the waves whose wavelengths are of the order of a few centimetres). The few studies which have been done suggest that the latter is linearly related to wind speed, or possibly logarithmically related. These ideas lead to an exponential relation between σ_0 (expressed in dB) and wind speed, or even a double exponential relationship. However because of the difficulties and uncertainties of the theory it has in effect been abandoned in favour of purely empirical relationships.

4.2.1 Empirical relationships between σ_0 and wind speed

Two widely used empirical algorithms are those due to Chelton and Wentz (Reference 10) and Witter and Chelton (Reference 11). Both of these were given in tabular form, and have to be fitted by an empirical curve; polynomial and piece-wise linear fits have been used.

The wind speed values contained in the AVISO GDR's have been obtained using the Chelton and Wentz algorithm. However it was decided to use the Witter and Chelton algorithm via a polynomial fit provided by Carter (Reference 12). Before applying this model to the GDR Ku band σ_0 values they were corrected using the results of Callahan et al (Reference 13) including the offset of -0.7dB in the Topex σ_0. The overall effect of adopting this procedure rather than using the AVISO values was that the wind speeds were reduced by about 0.4m/s on average.

It should be noted that none of the calibration data sets extends beyond 21 m/s, and moreover the few data points above 15 m/s are not well fitted by presently available algorithms. These give a closely linear relationship in this region in contrast to theoretical indications.

The one second values of Ku band σ_0 were subjected to similar quality control checks as the *Hs* data and the median of the transect values was taken as representative.

4.2.2 Statistical analysis of Topex/Poseidon wind speeds

Two years' data (October 1992 to September 1994) were used in the analysis, and the number of transects for the six areas were the same as for *Hs* and are shown in Table 4.1.

The wind speed data were analysed by fitting the sample cumulative data to a three-parameter Weibull distribution by the method of moments and extrapolating to the once in 50 year level (using a one-hour time step), and also by a consideration of growth factors (see Section 5.2 for a discussion of growth factors). Table 4.3 shows the results of analyses using both extrapolation and the growth factor approach. In the latter case results using both the Guidance Notes growth factors and those estimated from the NESS data are given. Results for DB2(NW) and DB3 are also included in Table 4.3.

It was decided to take the average of the three estimates of *U*(50) shown in Table 4.3 as representative of each area. These values are shown in Figure 6.5 and Table 7.2. The value for Fitzroy was taken from Section 8.6.2 of Reference 4.

A plot of the fit of the three-parameter Weibull distribution for the data for Area 2 is shown in Figure 4.6.

Table 4.2: Topex/Poseidon, estimates of *Hs*(50) (m)

Area	3 hours			6 hours	
	FT-1	Weibull	NESS *GF*	FT-1	NESS *GF*
1	20.1	16.6	19.7	19.1	18.4
2	21.4	19.6	21.0	20.3	19.6
3	22.7	22.5	22.2	21.5	20.6
4	25.3	25.4	24.8	24.0	23.1
5	24.8	25.3	24.3	23.5	22.6
6	24.3	21.1	23.7	23.0	22.2

Table 4.3: Topex/Poseidon, estimates of *U*(50) (m/s)

Area	*U*(50) (extrap)	*U*(50) Met O *GF*	*U*(50) NESS *GF*
1	30.5	35.9	32.7
2	30.7	36.1	32.9
3	31.4	36.9	33.6
4	32.3	37.9	34.5
5	32.0	37.7	34.3
6	32.4	38.2	34.8
DB2	28.9	34.0	31.0
DB3	29.0	33.8	30.9

5. DESIGN WAVE HEIGHTS AT NESS GRID POINTS

The North European Storm Study (NESS) was formed to produce a high quality hindcast data base of winds, waves, storm surges and depth-integrated currents. The project was funded by eleven participants including oil companies and government departments. A description of the project has recently been given by Peters et al (Reference 14).

The archived data base of winds and waves includes 25 winter periods (October to March) from 1964 to 1989. Data from ten selected grid points on the fine-mesh (30km) grid in the north-west approaches were obtained from the Marine Advisory Service of the UK Meteorological Office in the form of a magnetic tape cartridge which was then transferred to the Applied Wave Research computer.

5.1 SELECTION OF NESS GRID POINTS

The ten grid points shown in Figure 5.1 and given in Table 5.1 were chosen as being representative of the north-west approaches area west of the Shetlands.

Table 5.1: Definition of NESS grid points used in this study

Ref No	Grid Point Col	Grid Point Row	Latitude Deg N	Longitude Deg W	Water Depth (m)
ness01	20	67	60.75	2.88	300
ness02	19	68	60.66	3.65	550
ness03	18	69	60.57	4.42	600
ness04	19	69	60.43	3.94	550
ness05	20	69	60.28	3.47	155
ness06	19	70	60.19	4.23	250
ness07	18	71	60.09	4.98	550
ness08	15	73	60.01	6.96	600
ness09	12	75	59.90	8.92	600
ness10	15	81	58.06	8.90	163

The NESS points 01, 04, 07, 08, 09 and 10 are representative of the six larger areas over which the satellite data have been averaged. The four NESS points 02, 03, 05 and 06 give information on a smaller spatial scale near the centre of the area of interest.

5.2 PEAKS OVER THRESHOLD ANALYSIS

A 'peaks-over-threshold' (POT) analysis was used over the 25 winter periods. A peak was defined as the highest wave height which occurred after the upward crossing of a given threshold and before the next downward crossing of this threshold. Three extreme value distributions were fitted to the POT values:

(i) Fisher-Tippett Type 1 (FT-1).

(ii) Three-parameter Weibull.

(iii) Exponential.

The method of moments was used to determine the parameters of the extreme value distributions. This is a straightforward procedure except in the case of the three-parameter Weibull distribution where the method reported in Reference 15 page 127 et seq was used.

The probability value, P, appropriate to a return period of T years, is given by $P = 1 - 1/(\lambda T)$ where λ is the mean number of storms per year exceeding the given threshold. [The length of the NESS database is 25 years, therefore

$$\lambda = \text{(Number of exceedances/25) storms per year}].$$

Appendix 1 gives the definitions of the extreme value distributions and their moments.

5.2.1 Choice of threshold

Preliminary calculations were made on the influence of threshold value on 50-year design wave heights. NESS grid point 01 was chosen and solutions obtained for four different thresholds. The results, given in Table 5.2, show that the 50-year return value slowly increases with threshold for the FT-1 distribution. The range of values is well within the 95% confidence intervals expected for a 25-year data base (±4%). It was therefore decided to choose a threshold of 10m as this gave about 40-90 storm exceedances over the 25-year period. Table 5.3 shows that the method of using annual maxima also gives values close to that for a 10m threshold.

Table 5.2: Effect of threshold on *Hs*(50) at NESS01 (FT-1 distribution)

Threshold (m)	Number of exceedances	*Hs*(50) (m)
8	161	14.7
9	75	14.8
10	40	15.0
11	16	15.0

5.2.2 Results of the analysis

A POT analysis was carried out for the ten selected grid points using a threshold of 10m. Wave heights for a 50-year return period were determined for the three distributions listed in Section 5.3 using the method of moments. In addition, the annual maxima were used together with a FT-1 distribution to derive another estimate of *Hs*(50). The full set of results is shown in Table 5.3.

Table 5.3: POT estimates of *Hs*(50) at NESS grid points (threshold = 10m)

Ref No	No of exceed	*Hs*(50) (m) by mom FT-1	Weib	Exp	Ann
ness01	40	14.9	15.1	15.5	15.0
ness02	36	15.6	15.5	16.1	15.6
ness03	51	15.9	16.0	16.6	16.1
ness04	49	15.8	15.9	16.4	15.9
ness05	39	14.3	14.3	14.7	14.3
ness06	61	15.4	15.6	16.1	15.6
ness07	55	16.4	16.6	17.2	16.7
ness08	74	17.0	17.1	17.9	17.4
ness09	90	17.1	16.6	18.0	17.2
ness10	83	16.1	16.1	16.8	16.3

A plot of the FT-1 distribution for NESS grid point 04 is shown in Figure 5.2. Plots of the remaining fits - three-parameter Weibull and exponential distributions - are given in Figures 5.3 and 5.4 respectively.

A sufficiently accurate estimate of the confidence intervals to be associated with these results can be derived from an extension of Table 2.1 to 25 years. In this case, 95% confidence limits are estimated as ±4% or about ±0.6m for *Hs*(50).

Growth factors *Hs*(50):*Hs*(2) were calculated for each grid point for the 10m threshold FT-1 results and were found to have a mean of 1.29 with standard deviation 0.02.

Table A2.1 contains detailed information on the parameters of the three distributions estimated using data from the ten NESS grid points.

Table 5.3 shows that 50-year values obtained using the FT-1 distribution and the 3-parameter Weibull are in close agreement. (Return period values derived using the exponential distribution are about 0.6m to 1.4m greater than the results from the FT-1 and Weibull distributions). The estimates of *Hs*(50) from annual maxima are also close to the results for the FT-1 distribution.

5.3 ANALYSIS OF THE WHOLE POPULATION

An analysis of the whole population of 25 winter (October to March) periods using a FT-1 distribution fitted by the method of moments was undertaken. The results (which are shown in Table 5.4) are rather higher than the POT values.

A plot of the FT-1 distributions for NESS grid point 04 is shown in Figure 5.5. A plot of the fit to the same grid point with a three-parameter Weibull distribution is shown in Figure 5.6.

Growth factors *Hs*(50):*Hs*(2) were calculated and found to vary remarkably little from one grid point to the next, with mean 1.31 and standard deviation 0.01 (very close to the POT values).

Table 5.4: Whole population estimates of *Hs*(50) at NESS grid points

Grid point	FT-1 *Hs*(50) (m)	Weibull *Hs*(50) (m)
ness01	16.0	14.5
ness02	15.7	15.1
ness03	16.5	15.7
ness04	16.0	15.0
ness05	15.7	14.4
ness06	17.0	14.8
ness07	16.4	15.8
ness08	17.5	16.8
ness09	18.6	17.5
ness10	18.3	16.4

5.4 DISCUSSION OF NESS RESULTS

In order to provide a single value of *Hs*(50) for comparison with the indicative value in the Guidance Notes, it was decided to take the average of the four estimates from the POT analysis in Table 5.3 and the two whole population estimates in Table 5.4. This was justified on the basis of the good fits to the POT data and the small spread of the estimates of *Hs*(50) from the different distributions. Estimates of return values from the whole population were included as they represented a viable alternative technique.

5.5 COMPARISON OF RESULTS WITH DB2, DB3 AND THE GUIDANCE NOTES

The broad geographical variation of *Hs*(50) (as determined in Section 5.4 above) for the NESS grid points is shown in Figure 5.7. More detailed information is given in Figure 5.8. The values are also given in Table 7.1. Values for DB2 and DB3 derived in Section 2 and shown in Table 2.1 are also included in the Figure. The 15m, 16m and 18m contour lines for 50-year values of wave height were taken from the Guidance Notes and are also shown in Figures 5.7 and 5.8.

The value of *Hs*(50) for DB3 at 15.5m is about 0.5m lower than the nearby 16m contour from the Guidance Notes. The three NESS values near DB3 are, on average, slightly lower than the value at DB3.

The value of *Hs*(50) for DB2 at 15.1m is about 2m lower than the contoured values from the Guidance Notes. NESS grid points 08, 09 and 10 also are about 0.5 to 1m lower than nearby contour lines.

6. ANALYSIS OF NESS WIND SPEED DATA

6.1 REVIEW OF THE BMT ANALYSIS

BMT Offshore Ltd were commissioned by the HSE to analyse wind speed data from the NESS project in order to produce a contour map of 50-year return period values of hourly-mean wind speed for comparison with a similar contour map given in the Guidance Notes. This chapter discusses the results and conclusions of this work which is reported in full in Reference 16.

6.1.1 Method of analysis

BMT Ltd carried out a preliminary study to compare results of the NESS data on a 'fine-grid' of size 30km with those based on using alternate points, that is, on a 60km grid. This study was necessary as it was anticipated that the handling of 25 years of wind data on the 'fine-grid' would impose data analysis problems. This preliminary study showed that relatively little effect was found for the contour maps of maximum wind speed. It was therefore concluded that a grid spacing of 60km was adequate to define the NESS wind data. It was also decided to base the analysis on time histories interpolated at one-hourly intervals instead of using the three-hourly values available from NESS. [The interpolation procedures used were shown to be valid by checking against measured wind data at the West Sole platform in the southern North Sea].

6.1.2 Methods for estimation of return values

BMT Ltd carried out a sensitivity study to find out the effects of varying the analysis procedure and parameters on the 50-year return values. It was concluded that differences between estimates obtained by using several different methods were small compared with uncertainties in the data. The method chosen by BMT for the estimation of return values (see Appendix V of Reference 16) is based on the modified Jensen and Franck technique using a FT-1 fit to the maximum wind speed squared within each independent storm. [A number of thresholds were selected and the results were shown to be insensitive to the threshold level]. Confidence intervals associated with this estimation procedure were small at about 0.2 m/s.

6.1.3 Principal conclusions and recommendations

BMT Ltd produced a contour map of 50-year return period values of hourly-mean wind speed which is shown here in Figure 6.1. Comparisons with the corresponding diagram in the Guidance Notes (reproduced here as Figure 6.2) showed that the estimates derived from NESS were several metres per second less than those given in the Guidance Notes. It was concluded that the results given by the analysis of the NESS data were more reliable than the Guidance Notes since the latter were derived from several different sources. It was also concluded that the source of differences between the NESS wind analysis and the Guidance Notes must lie within the data rather than in the method of analysis.

BMT Ltd recommended that two further studies should be made:

(i) The possibility of validating the NESS contour map against recent instrumental data should be investigated further.

(ii) The possible effects of severe storms experienced during the period 1989 to 1992, since the end of the NESS project, should be considered.

6.2 FURTHER ANALYSES OF THE NESS WIND SPEED DATA

A number of analyses of the NESS wind speed data were carried out as part of the present study in order to provide independent estimates of $U(50)$ to compare with the BMT values and as an adjunct to the analysis of the Topex/Poseidon wind speed data. Analyses were undertaken on two classes of population defined as follows:

(i) All the data from the 25 winter (October to March) periods.

(ii) Peaks over a number of thresholds.

In addition to extrapolation to low exceedance probabilities some consideration was given to growth factors, which was the approach used by the Meteorological Office to obtain the Guidance Notes values. A growth factor is defined as the ratio of the value of a random variable (eg wind speed or *Hs*) at a longer return period to its value at a shorter return period. For example,

$$GF = \frac{U(50)}{U(2)}$$

signifies the growth of the 50-year wind speed with respect to the two-year wind speed. Jenkinson (Reference 17) found that for the time series of wind measurements available from a number of coastal anemometer sites (some in excess of 50 years) the growth factors were fairly consistent from one site to another. This allowed a two step approach to estimating the 50-year wind speed for a site with a short series of measurements. First the value of wind speed at a short return period was estimated, essentially by interpolation of the sample distribution or at any rate by only a modest extrapolation, and then this value was multiplied by the appropriate growth factor.

6.2.1 Analyses of the whole population

A three-parameter Weibull distribution was fitted to the cumulative data by the method of moments and the value of *U*(50) estimated by extrapolation assuming a one-hour time step. The use of one hour (which has become conventional) rather than three hours (which is the interval between successive NESS wind fields) resulted in values of *U*(50) which are higher by between 1½ and 2m/s, and assumes that the decorrelation time of wind speed is less than one hour. *U*(2) was also estimated for use in the growth factor analysis. The growth factor from 2 years to 50 years was found to vary remarkably little from grid point to grid point and had a mean of 1.146 with standard deviation 0.003. Note that the growth factor calculated from the formula below Table 11.2 in the Guidance Notes is 1.31.

A plot of the cumulative data for NESS grid point 04 with a three-parameter Weibull distribution fitted is shown in Figure 6.3. The main results of the analysis are included in Table 6.2.

6.2.2 Analysis by POT methods

A three-parameter Weibull distribution was fitted by the method of moments to peaks over thresholds of 15m/s, 20m/s and 25m/s. It was found that *U*(50) was a slowly decreasing function of threshold, but that the number of peaks fell very abruptly between 20m/s and 25m/s (see Table 6.1). It was decided to adopt a threshold of 20m/s for the bulk of the calculations.

Table 6.1: Effect of threshold on *U*(50) at NESS01

Threshold (m/s)	Number of exceedances	*U*(50) (m/s)
15	363	34.7
20	326	33.8
25	45	32.7

U(2) and U(50) were estimated using a probability of non-exceedance given by

$$P = 1 - 1/(\lambda T)$$

where λ is the average number of peaks per year and T is the number of years (either 2 or 50 in this case). The 2-year to 50-year growth factor was found to be 1.25 with standard deviation 0.01. This is 9% higher than the whole population *GF* so the mean (1.20) was taken for use in the analysis of Topex/Poseidon winds. A summary of results is included in Table 6.2. Figure 6.4 shows the peaks over threshold analysis for NESS grid point 04 with a three-parameter Weibull distribution fitted.

6.2.3 Discussion

It will be seen that the whole population results are comparable with but somewhat lower than the POT results, while the use of the growth factor from the Guidance Notes gives substantially higher values which are broadly consistent with Figure 1 of the Guidance Notes. Thus it appears that the very high Guidance Notes values can be attributed to the use of an inappropriate growth factor. This conclusion is at variance with BMT's findings, Section 6.1.3 above.

It was decided to take the average value of the POT and whole population estimates of U(50) as a representative single value; these are given in Table 7.1.

Table 6.2: Analysis of NESS wind speed data (m/s) (Three-parameter Weibull distribution)

Grid Ref	Whole population			POT	
	U(2) Extrapolation	U(50) Extrapolation	U(50) Met O+	U(2) Extrapolation	U(50) Extrapolation
ness01	29.3	33.5	38.4	27.5	33.8
ness02	29.4	33.6	38.5	27.8	34.7
ness03	29.4	33.7	38.5	28.0	35.1
ness04	29.6	33.9	38.8	28.0	34.9
ness05	29.7	34.1	38.9	27.9	34.3
ness06	29.7	34.1	38.9	28.1	34.8
ness07	30.0	34.4	39.3	28.4	35.3
ness08	30.6	35.1	40.1	29.0	36.7
ness09	31.2	35.7	40.9	29.4	36.4
ness10	30.2	34.8	39.6	28.3	35.9

+ Using a *GF* (50:2) of 1.31

NESS values of U(50) for the area as a whole are shown in Figure 6.5. More detailed information is given in Figure 6.6.

7. SUMMARY

7.1 DESIGN WAVE HEIGHTS IN THE NORTH-WEST APPROACHES

7.1.1 From NESS hindcast data

Estimates of *Hs*(50) were derived by two different methods for ten NESS grid points in the north-west approaches. In the first method a 'peaks over threshold' (POT) analysis technique was used while a 'whole population' analysis was used in the second method. In the POT analysis, consistent values of return period wave heights were obtained by fitting FT-1, three-parameter Weibull and exponential distributions to the data, as well as the method of annual maxima. For the whole population, the FT-1 and three-parameter Weibull analyses gave higher values than with the POT technique. A single recommended value was obtained from the average of all six estimates and these are shown, in comparison with contours from the Guidance Notes, in Figures 5.7 and 5.8. Table 7.1 lists the average NESS values together with Guidance Notes values linearly interpolated to the NESS positions.

The values of *Hs*(50) from this study were found to be about 0.5m to 1.5m lower than values given in the Fourth Edition of the Guidance Notes (1989) in the north-west approaches. 95% confidence intervals for these return values are estimated to be ±0.6m. *Hs*(50) values from NESS increased to the north and to the west, in accordance with trends given in the Guidance Notes.

7.1.2 DB2(NW) and DB3

A re-analysis of the measured data at these positions confirmed the design wave values given by MAREX Ltd. Table 7.2 compares these values with Guidance Notes values interpolated to the DB2(NW) and DB3 positions and (as far as possible) NESS values appropriate to the DB2(NW) and DB3 positions.

7.1.3 Analysis of Topex/Poseidon satellite data

Analysis of the satellite data gave values of *Hs*(50) about 3m greater than those in the Guidance Notes for six areas in the north-west approaches (and therefore higher than the NESS values). It is believed that these high values are due to the short data base (two years) of wave data presently available and the severity of 1992-1994 compared with the period of earlier measurements and of the NESS data base (1964-1989). The values are given in Table 7.3 and shown in Figure 5.7.

An earlier study by Carter (Reference 7) for the HSE, with GEOSAT data from 1986 to 1989, gave values about 1m lower than the Guidance Notes in the north-west approaches.

Satellite data collected since 1989 and therefore following the NESS project provide important information on the severe conditions which have occurred during the last few years. These data should be included in any future consideration of design wave conditions.

Table 7.1: Design waves and winds - average values at NESS grid points compared with interpolated Guidance values

Grid point	Averaged *Hs*(50) (m)	Guidance *Hs*(50) (m)	Averaged *U*(50) (m/s)	Guidance *U*(50) (m/s)
ness01	15.2	16.4	33.7	40.0
ness02	15.6	16.8	34.1	40.1
ness03	16.1	17.3	34.4	40.1
ness04	15.8	16.7	34.4	40.0
ness05	14.6	16.0	34.2	39.7
ness06	15.8	16.5	34.4	40.0
ness07	16.5	17.0	34.9	40.1
ness08	17.3	18.1	35.9	40.4
ness09	17.5	18.6	36.0	40.6
ness10	16.7	17.5	35.4	40.3

Table 7.2: *Hs*(50) and *U*(50) at DB2 and DB3 - values derived from measurements compared with interpolated Guidance and NESS values

Data Buoy	Waves *Hs*(50) (m)			Winds *U*(50) (m/s)		
	Meas	Guidance	NESS	Meas	Guidance	NESS
DB2	15.1	17.0	NA	31.1*	40.2	NA
DB3	15.5	15.9	14.6+	31.2*	39.6	34.2+

+ Value at ness05 (nearest grid point)

* Average of values in Table 4.3

7.2 DESIGN WIND SPEEDS IN THE NORTH-WEST APPROACHES

7.2.1 From NESS hindcast data

Analyses were undertaken both on the whole population and on peaks over thresholds and the 50-year wind speed was estimated by extrapolation of three-parameter Weibull fits using a one-hour time step. The POT values were comparable with but somewhat higher than the whole population results, and both were much lower (4 to 5 m/s) than the Guidance Notes values. The average of the whole population and the POT results are given in Table 7.1 together with Guidance Notes linearly interpolated to the NESS positions, and are also shown in Figure 6.5 and Figure 6.6.

Design wind speeds for DB2(NW) and DB3 were estimated as the average of the values given in Table 4.3. Table 7.2 compares these values with Guidance Notes values interpolated to the DB2(NW) and DB3 positions and (as far as possible) NESS values appropriate to the DB2(NW) and DB3 positions.

An analysis carried out by BMT Ltd also showed that the estimates derived from the NESS data were several metres per second less than those given by the Guidance Notes. BMT concluded that the source of differences between the NESS wind analysis and the Guidance Notes was due to the data base rather than the method of analysis. However, it is noted that the growth factors for winds recommended in the Guidance Notes are higher than those which were estimated from the NESS data in this study.

7.2.2 From Topex/Poseidon wind speed data

The 50-year return value was estimated by extrapolation of the three-parameter Weibull fit to the whole population cumulative data using a one-hour time step and by the use of growth factors. In the latter case both the growth factor from the Guidance Notes and the growth factor estimated from the NESS data were used. It was found that the results using the Guidance Notes growth factor were largest followed by the results using the NESS growth factor, with the extrapolation results being the smallest (Table 4.3). The average values are shown in Table 7.3 and are plotted in Figure 6.5. This shows that the averaged Topex/Poseidon values of $U(50)$ are close to but somewhat lower than the averaged NESS values. They are both much lower than the Guidance Notes values.

It is surprising that the Topex/Poseidon design winds should be close to the NESS design winds while the Topex/Poseidon waves are substantially greater than the NESS waves. Some concern has been expressed (Section 4.2.1) about the calibration of the wind speed algorithms at high wind speeds, and it may be considered useful to undertake a review of the available calibration data in this regime.

Table 7.3: Topex/Poseidon, average values of 50 year waves and winds

Area	Averaged $Hs(50)$ (m)	Averaged $U(50)$ (m/s)
1	18.8	33.0
2	20.4	33.2
3	21.9	34.0
4	24.5	34.9
5	24.1	34.7
6	22.9	35.1

8. ACKNOWLEDGEMENT

The coastlines shown in Figures 4.1, 4.5, 4.7, 5.1, 5.7, 5.8, 6.5 and 6.6 were abstracted from the GEBCO Digital Atlas, which is published by the Natural Environment Research Council.

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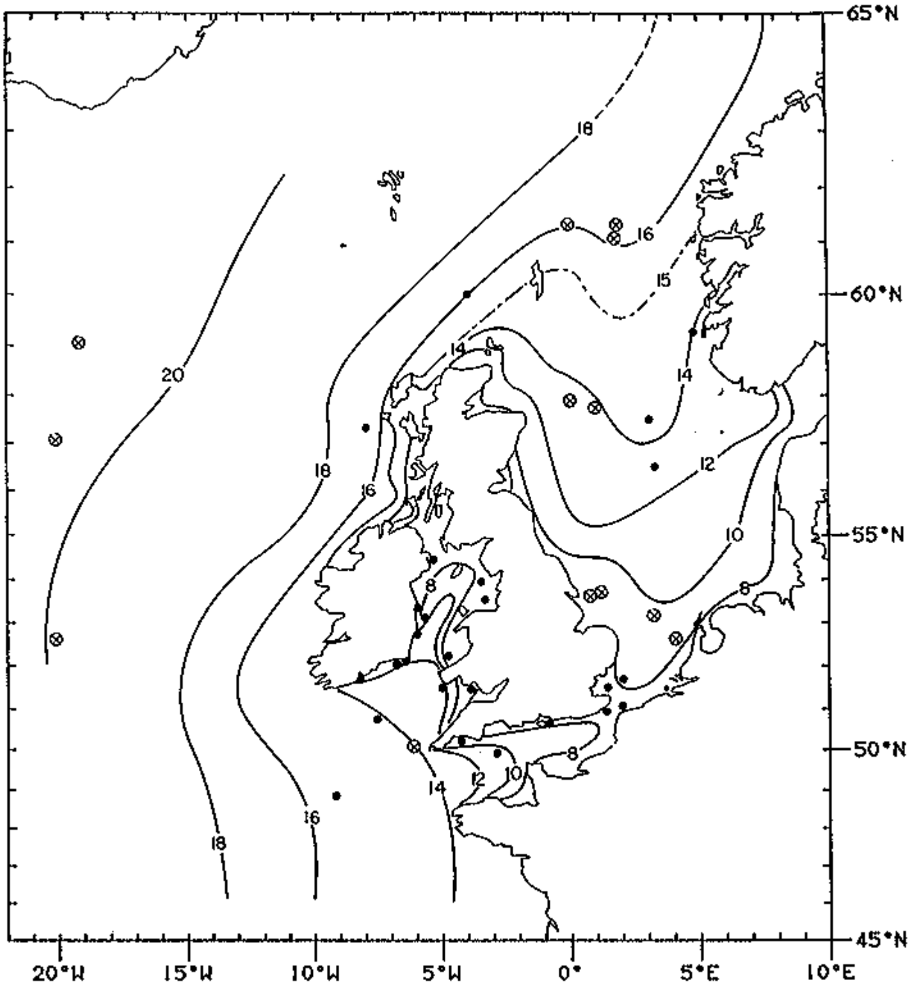
Met O 13 Branch Memo 55, Meteorological Office, Bracknell.

FIGURES

Figure 2.1



Map of indicative values of 50-year return value of significant wave height (m)

Figure 3.1

DB2(NW) – September 1986 to December 1988

Cumulative distribution of Hs

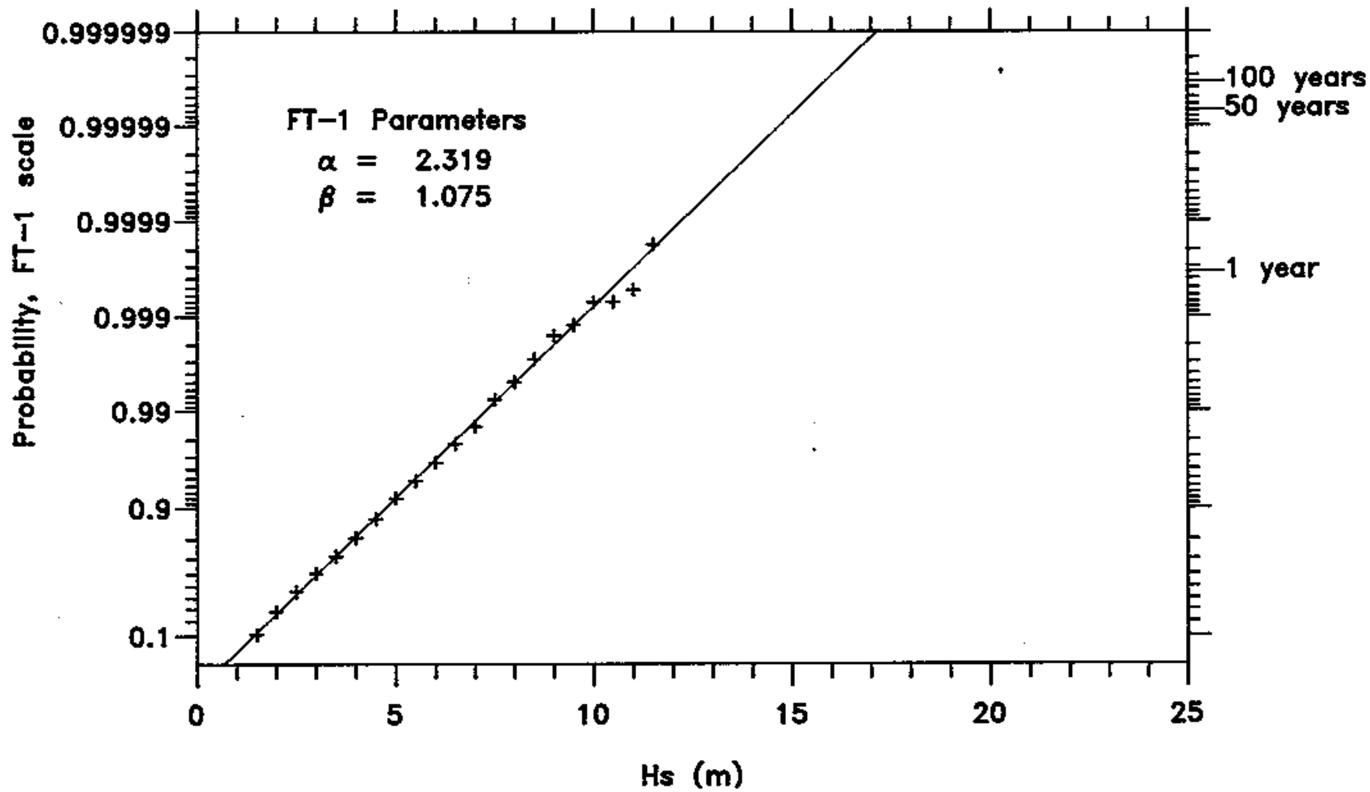


Figure 3.2

DB3 – July 1984 to December 1988

Cumulative distribution of Hs

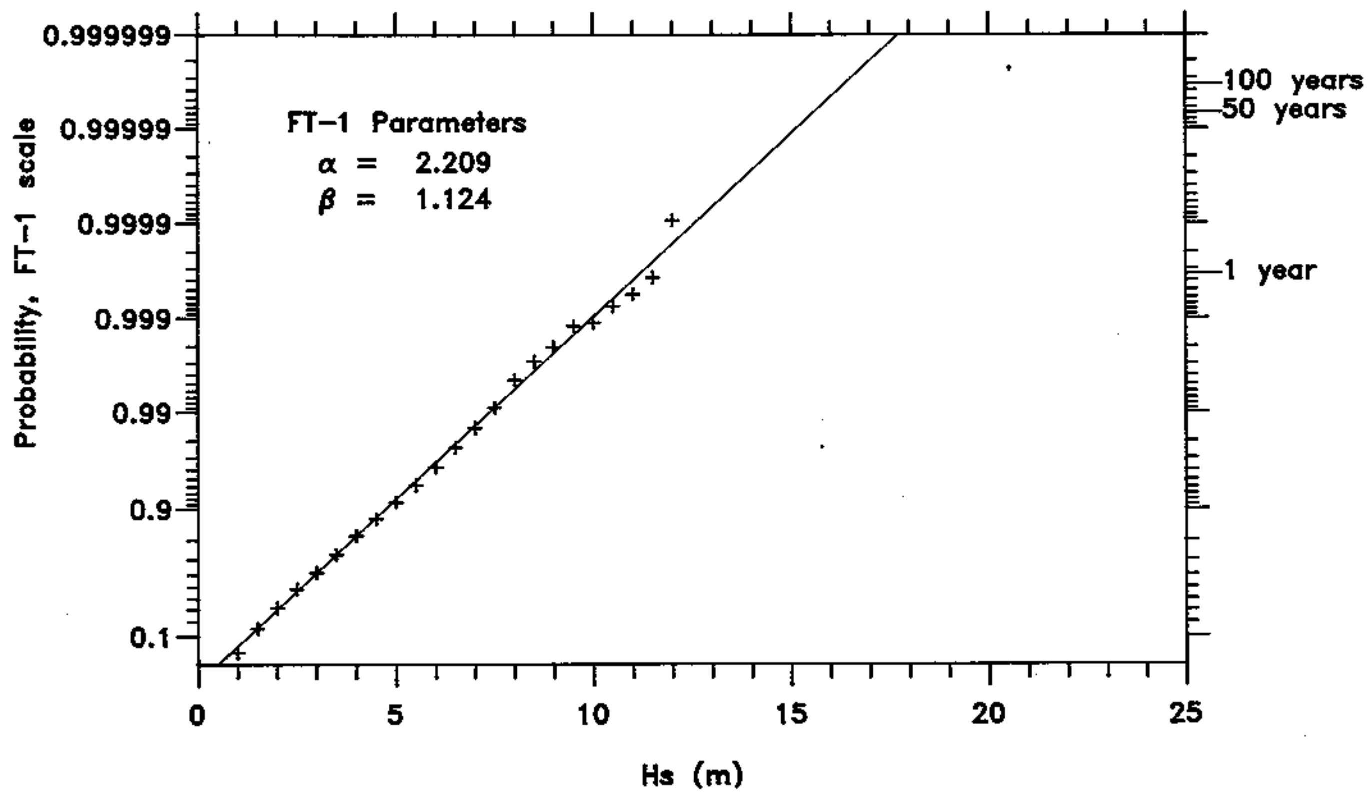


Figure 4.1

Topex/Poseidon passes and six $2^0 x\ 2^0$ areas in the NW approaches to the UK

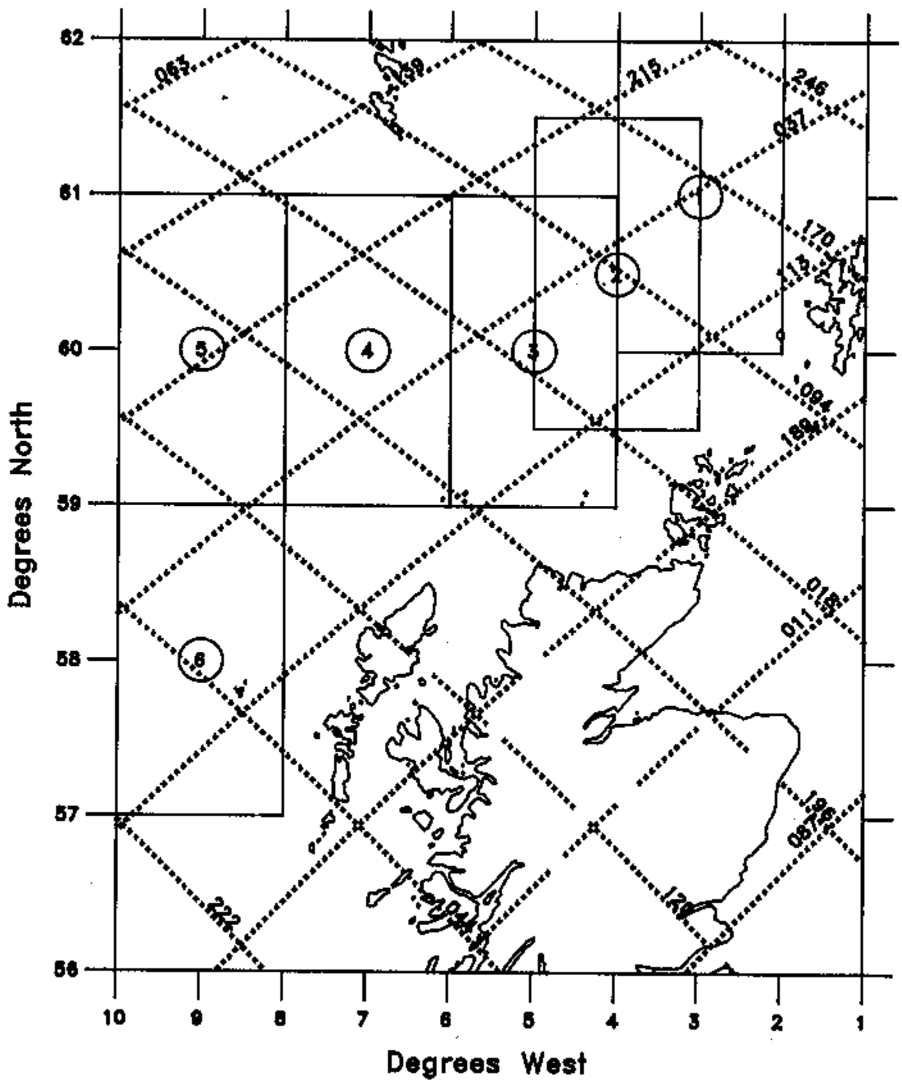
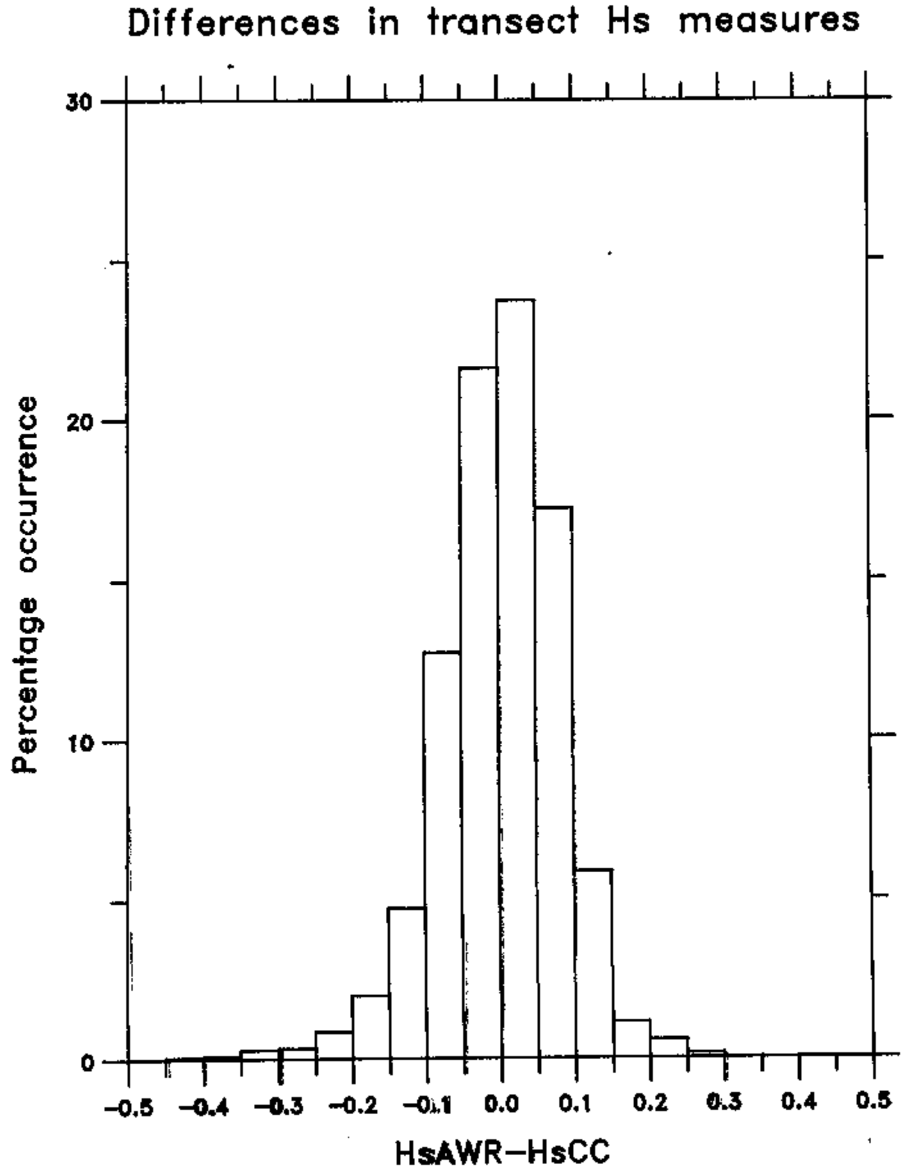


Figure 4.2



Differences in transect Hs measures
30
20
10
0
Percentage occurrence
-0.5
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
HsAWR-HsCC

Figure 4.3

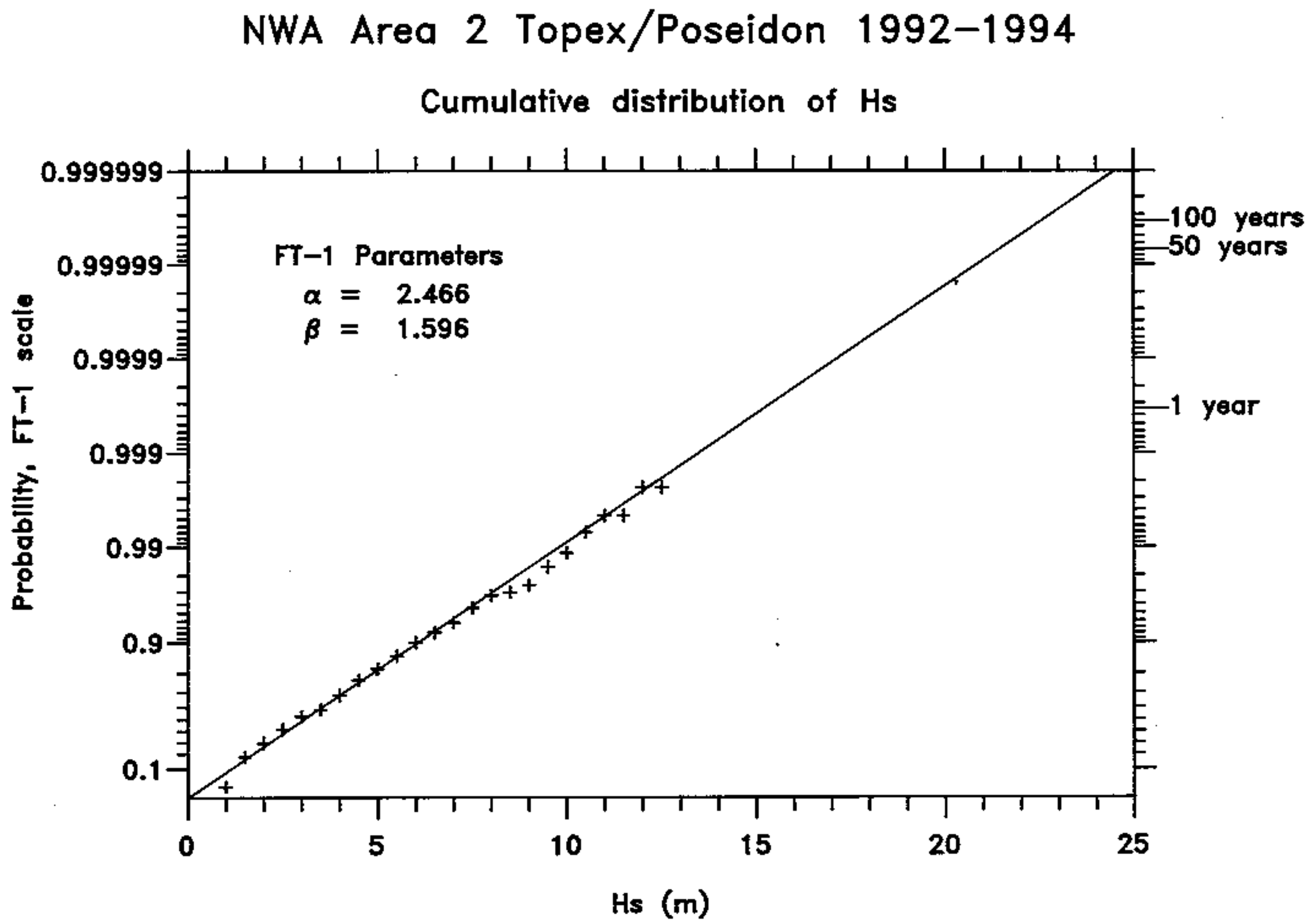

NWA Area 2 Topex/Poseidon 1992–1994
Cumulative distribution of Hs
FT–1 Parameters
α = 2.466
β = 1.596
Probability, FT–1 scale
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
100 years
50 years
1 year
0
5
10
15
20
25
Hs (m)

Figure 4.4

NWA Area 2 Topex/Poseidon 1992–1994

Cumulative distribution of Hs

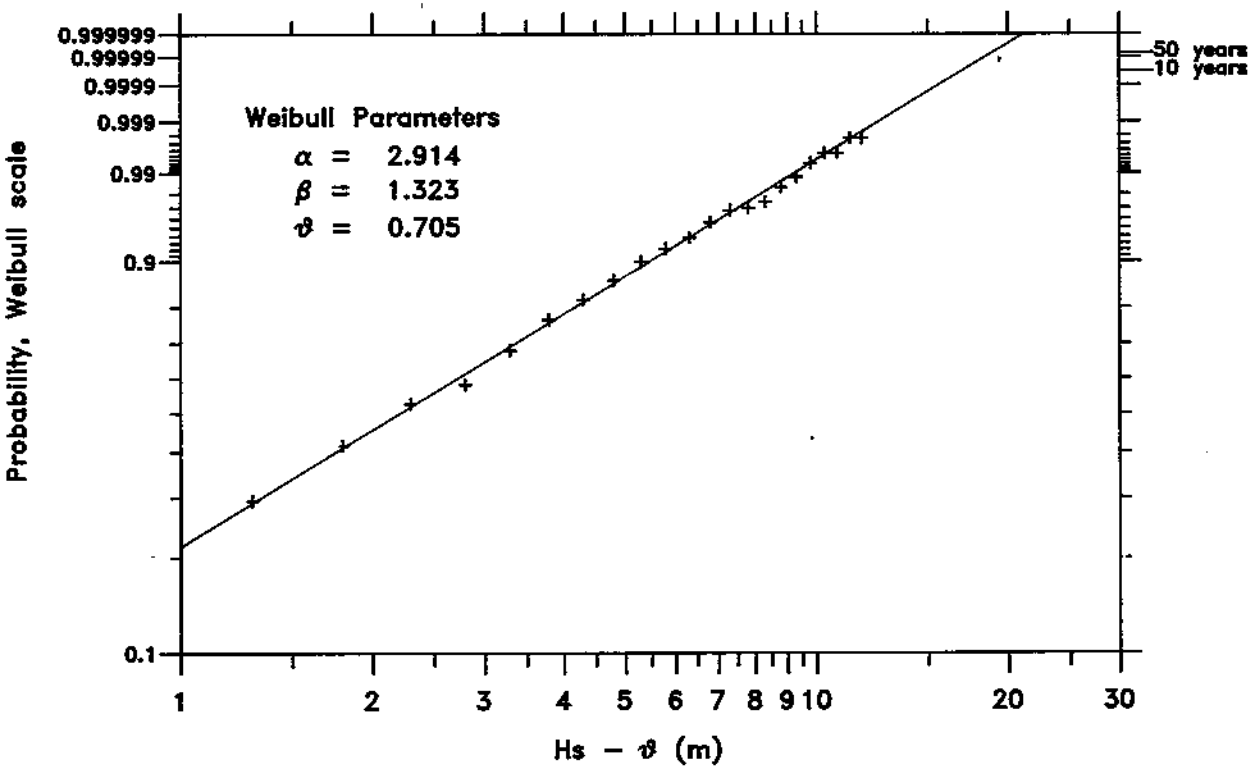


Figure 4.5

North–west approaches to the UK

Topex/Poseidon cycle 012 pass 018 Hs (m)

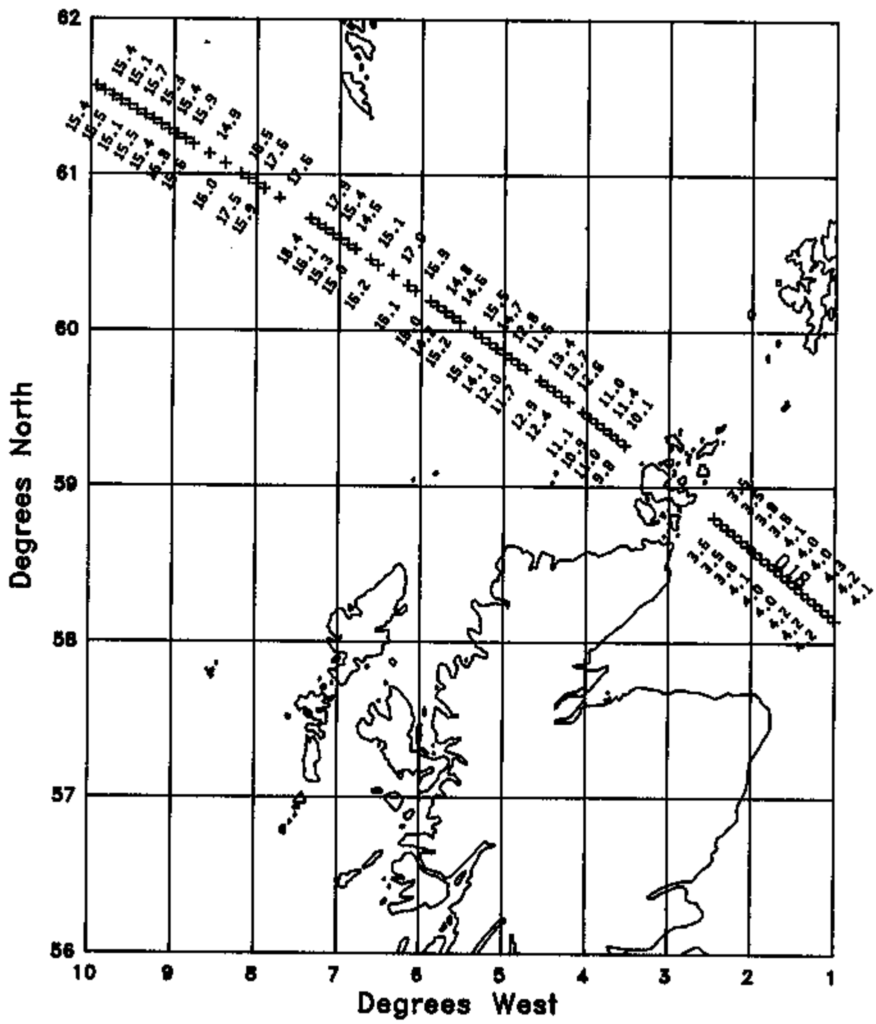


Figure 4.6

NWA Area 2 Topex/Poseidon 1992–1994

Cumulative distribution of wind speed

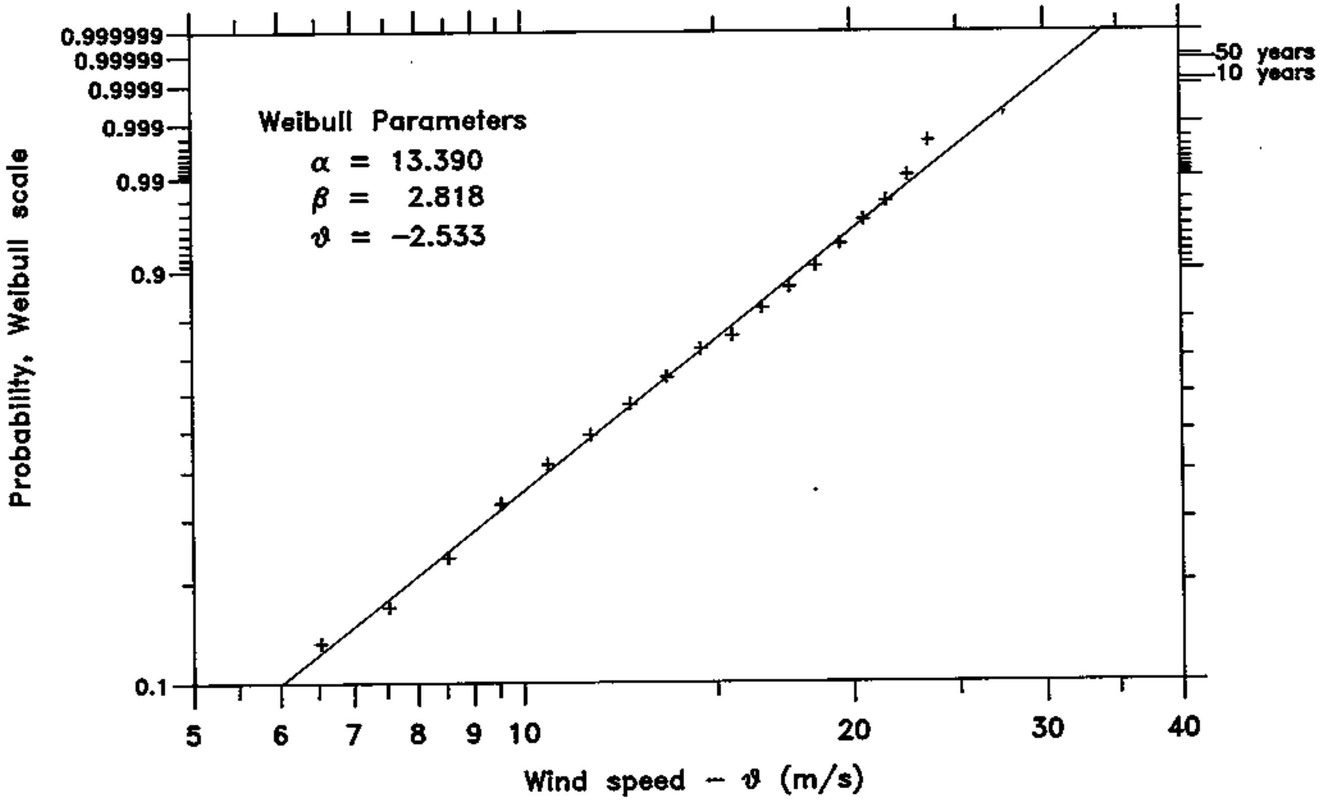


Figure 4.7

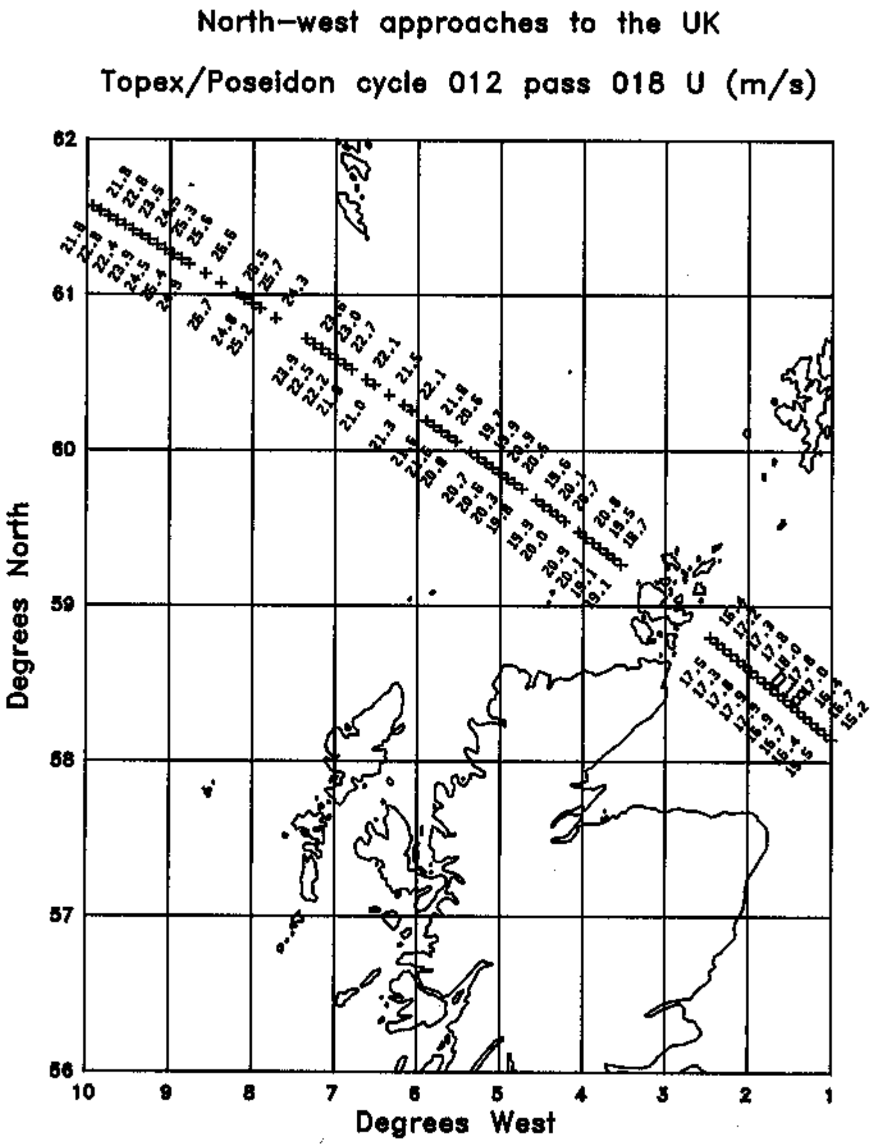

North–west approaches to the UK
Topex/Poseidon cycle 012 pass 018 U (m/s)
Degrees North
62
61
60
59
58
57
56
10
9
8
7
6
5
4
3
2
1
Degrees West

Figure 5.1

Positions of the ten selected NESS grid points in the NW approaches to the UK

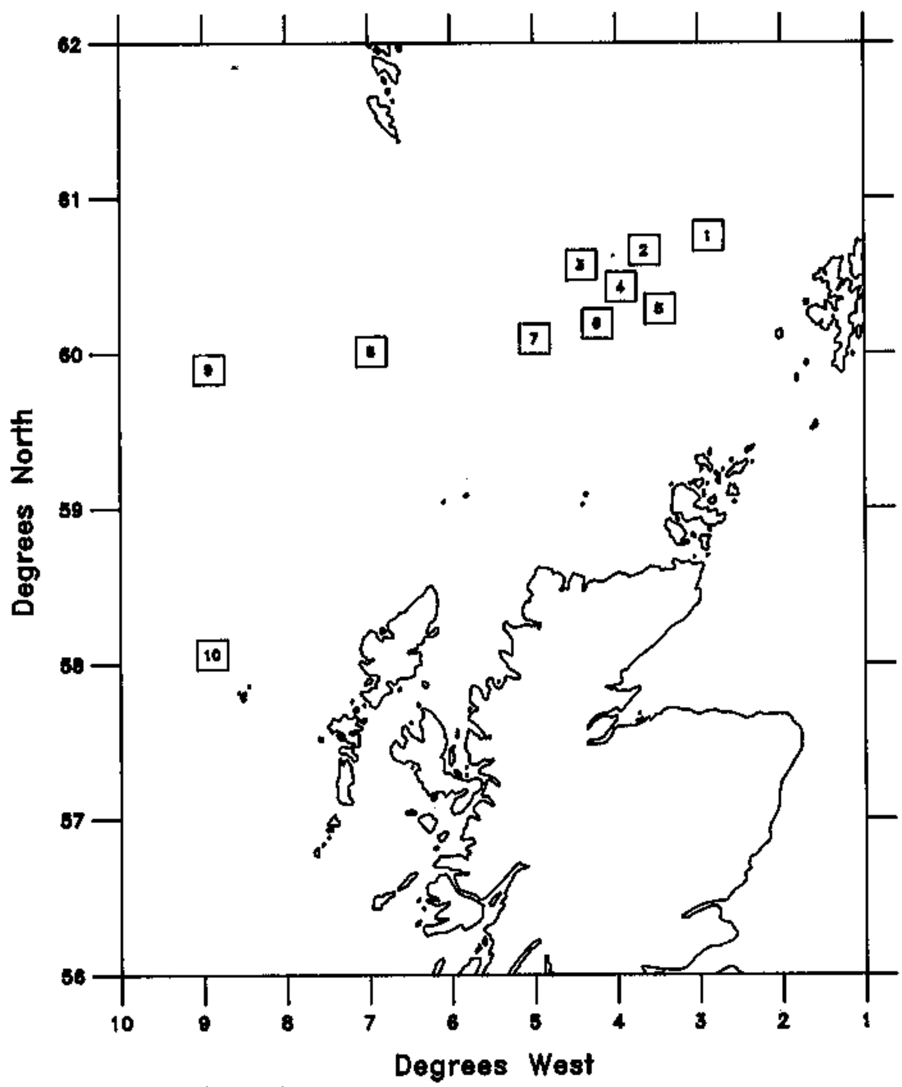


Figure 5.2

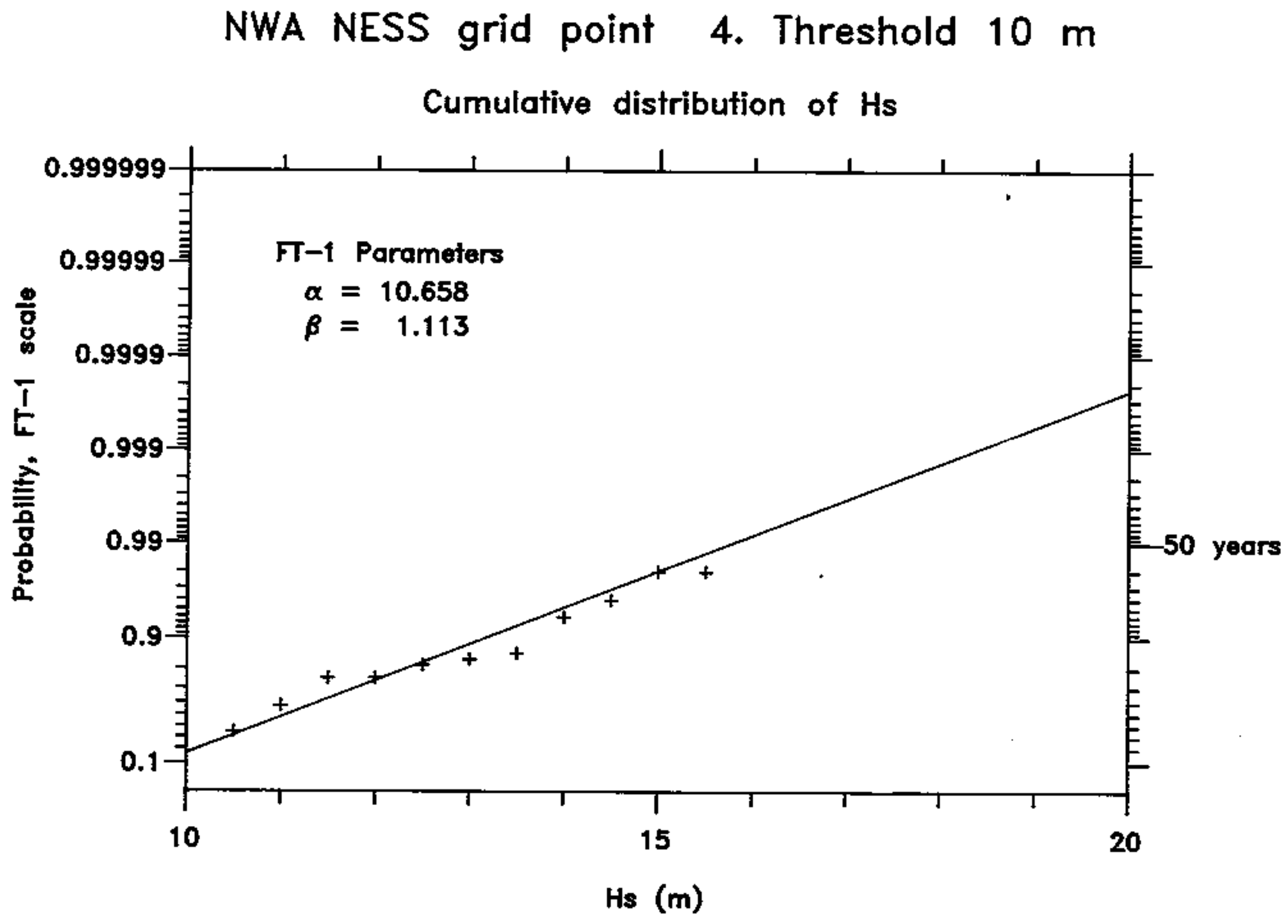
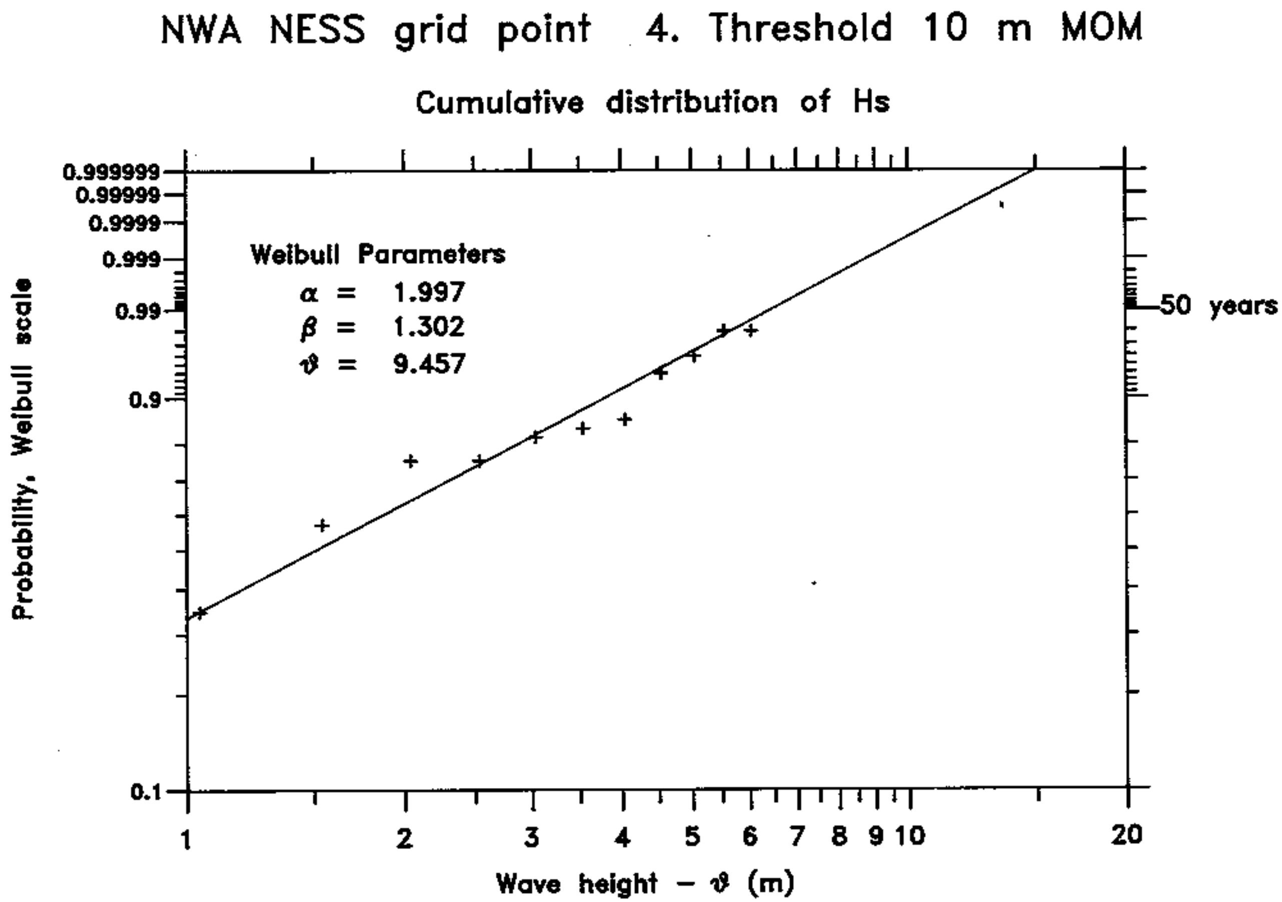

NWA NESS grid point 4. Threshold 10 m
Cumulative distribution of Hs
FT-1 Parameters
α = 10.658
β = 1.113
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
Probability, FT-1 scale
50 years
10
15
20
Hs (m)

Figure 5.3



NWA NESS grid point 4. Threshold 10 m MOM
Cumulative distribution of Hs
Weibull Parameters
α = 1.997
β = 1.302
ϑ = 9.457
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
50 years
Probability, Weibull scale
1
2
3
4
5
6
7
8
9
10
20
Wave height − ϑ (m)

Figure 5.4

NWA NESS grid point 4. Threshold 10 m

Cumulative distribution of Hs

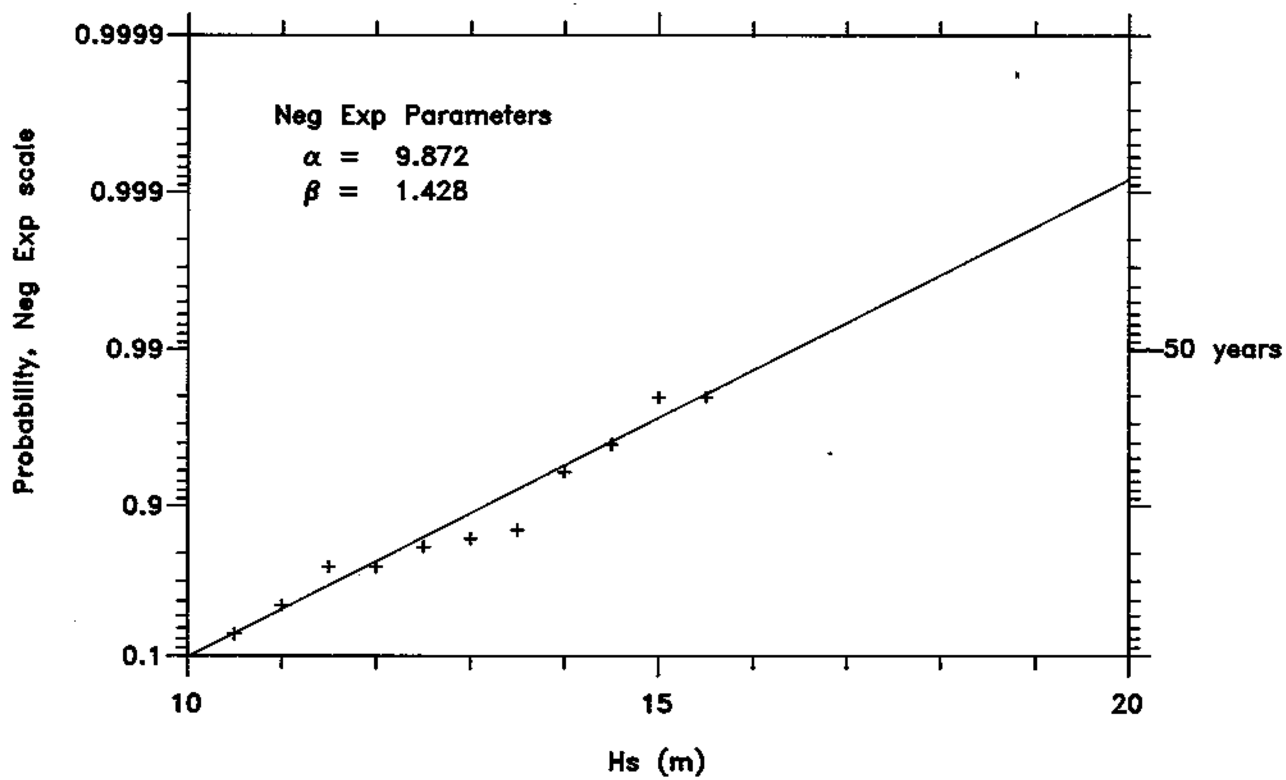


Figure 5.5

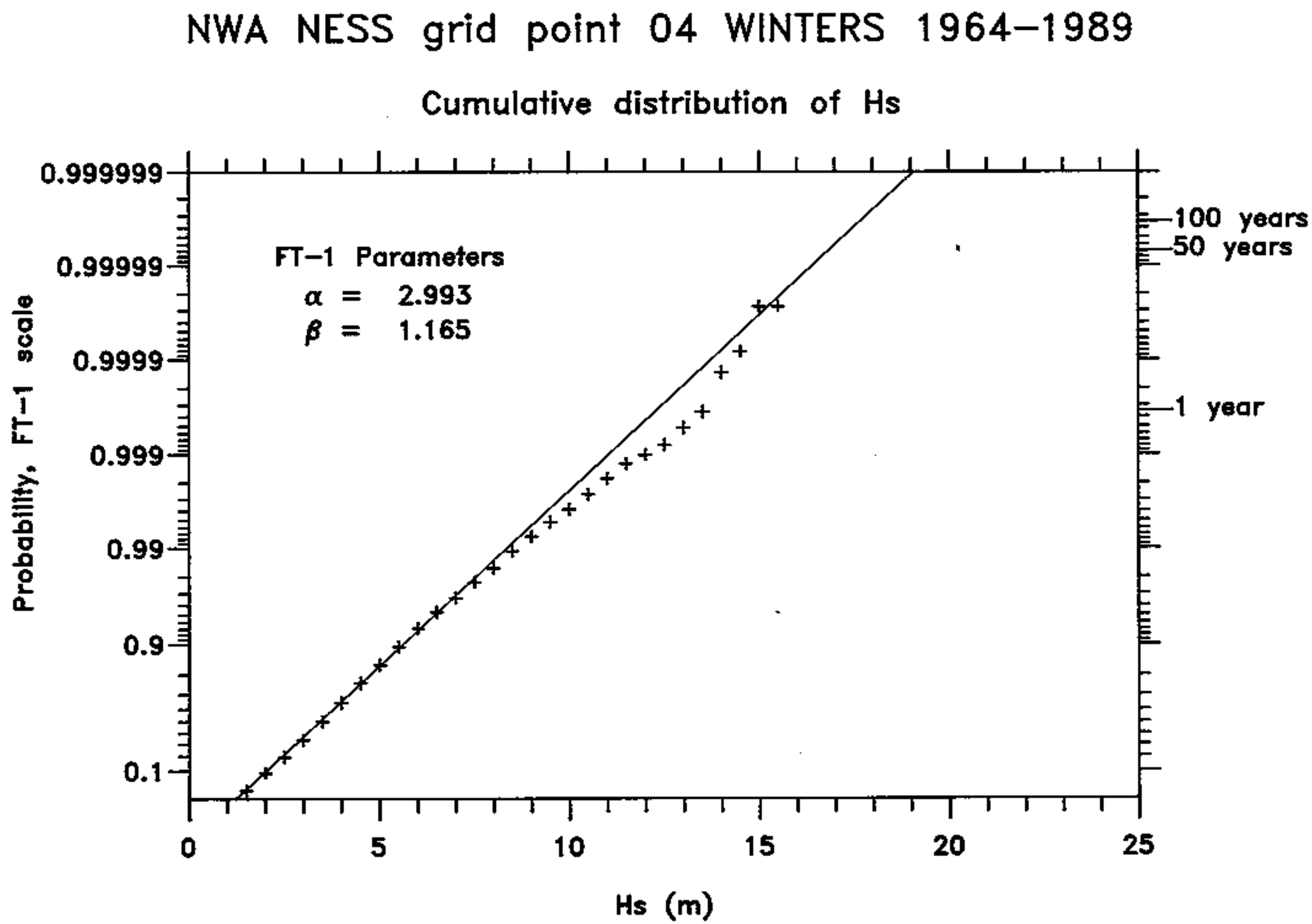

NWA NESS grid point 04 WINTERS 1964–1989
Cumulative distribution of Hs
FT–1 Parameters
α = 2.993
β = 1.165
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
Probability, FT–1 scale
100 years
50 years
1 year
0
5
10
15
20
25
Hs (m)

Figure 5.6

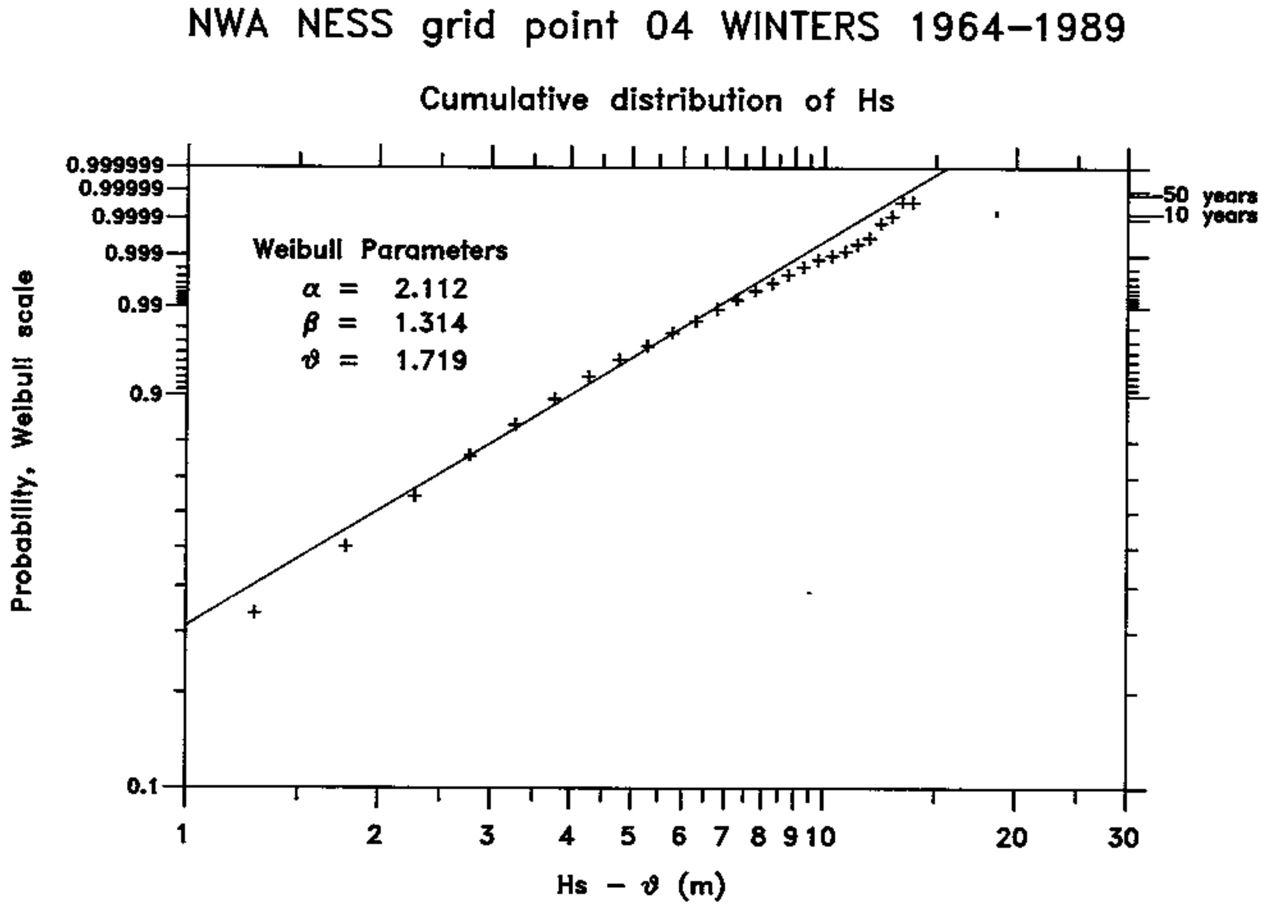

NWA NESS grid point 04 WINTERS 1964–1989
Cumulative distribution of Hs
Weibull Parameters
α = 2.112
β = 1.314
ϑ = 1.719
Probability, Weibull scale
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
50 years
10 years
1
2
3
4
5
6
7
8
9
10
20
30
Hs − ϑ (m)

Figure 5.7

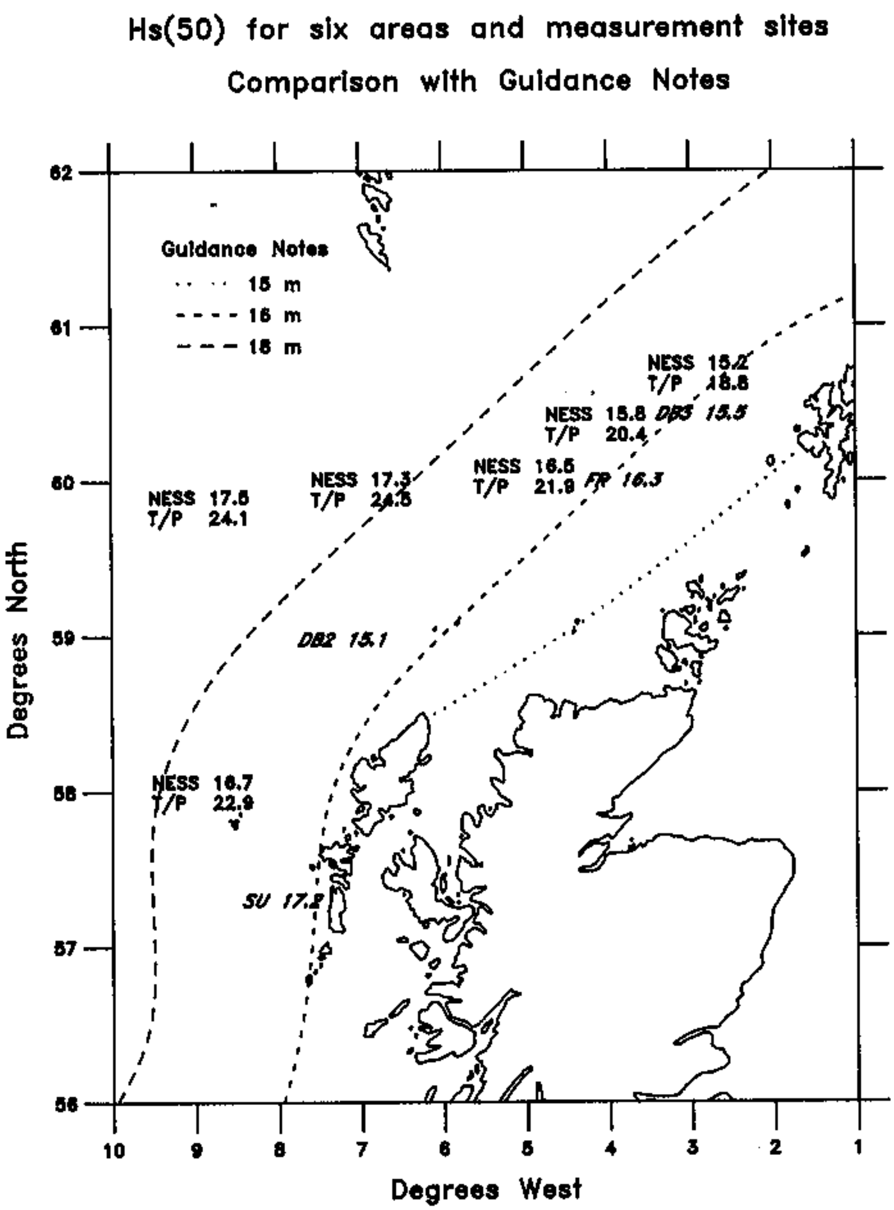

Hs(50) for six areas and measurement sites
Comparison with Guidance Notes
Guidance Notes
15 m
16 m
18 m
NESS 15.2
T/P 18.8
NESS 15.8 DB3 15.5
T/P 20.4
NESS 16.6
T/P 21.9 FP 16.3
NESS 17.3
T/P 24.5
NESS 17.6
T/P 24.1
DB2 15.1
NESS 16.7
T/P 22.9
SU 17.2
Degrees North
62
61
60
59
58
57
56
10
9
8
7
6
5
4
3
2
1
Degrees West

Figure 5.8

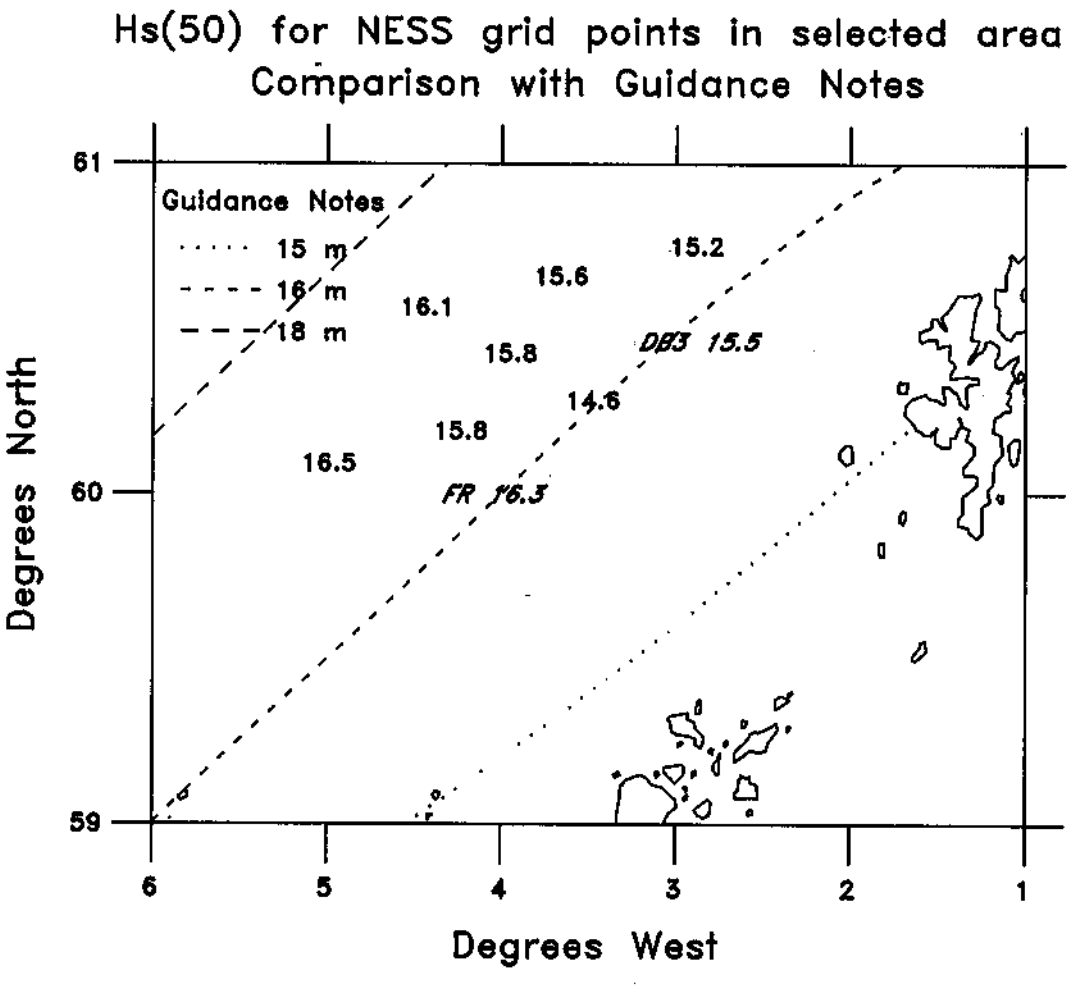
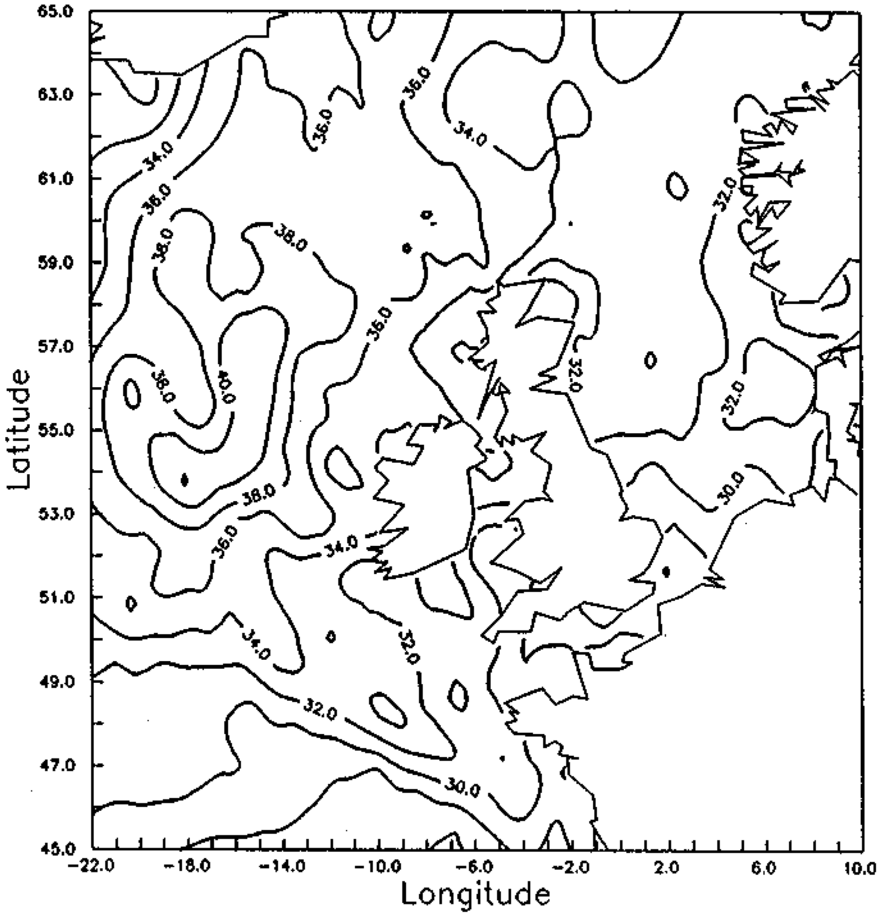
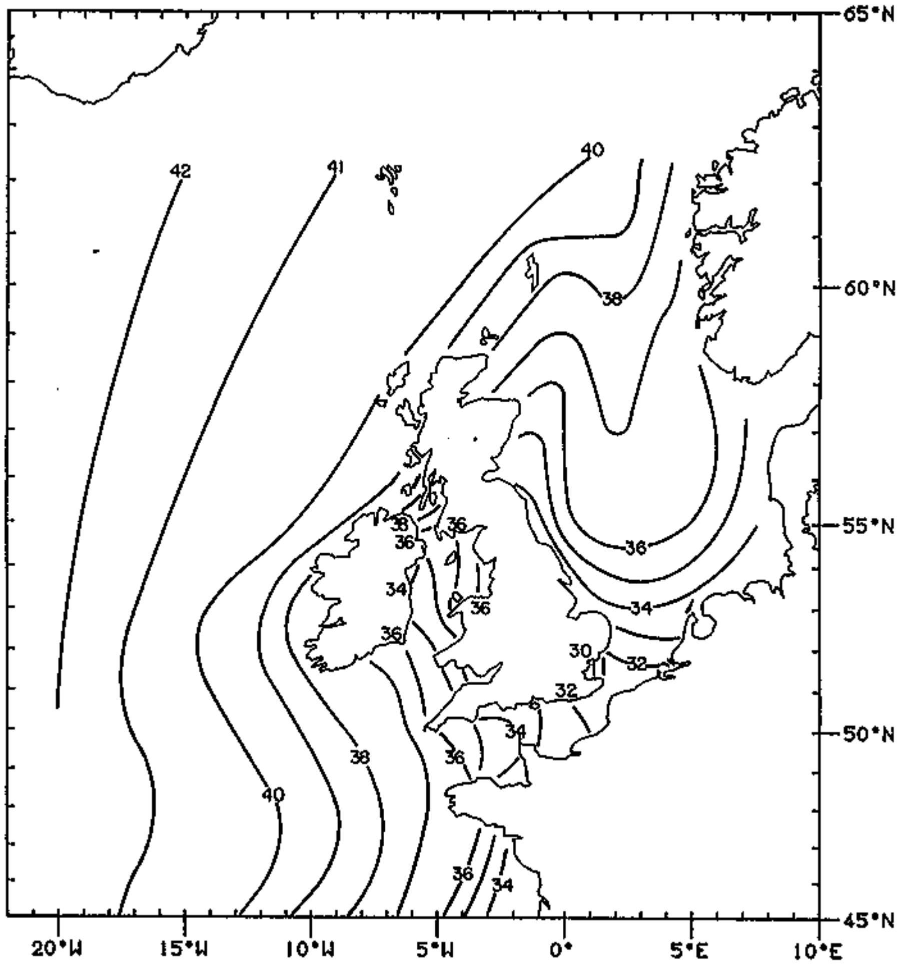

Hs(50) for NESS grid points in selected area
Comparison with Guidance Notes
Guidance Notes
15 m
16 m
18 m
15.2
15.6
16.1
15.8
DB3 15.5
14.6
15.8
16.5
FR 16.3
61
60
59
Degrees North
6
5
4
3
2
1
Degrees West

Figure 6.1



Contour plot showing 50-year return period values of hourly-mean wind speeds from the NESS data set. (m/s)

Figure 6.2



Maximum hourly-mean wind speed in m/s at 10 m above the sea surface with an average recurrence of fifty years

Figure 6.3

NWA NESS grid point 04 WINTERS 1964–1989

Cumulative distribution of wind speed

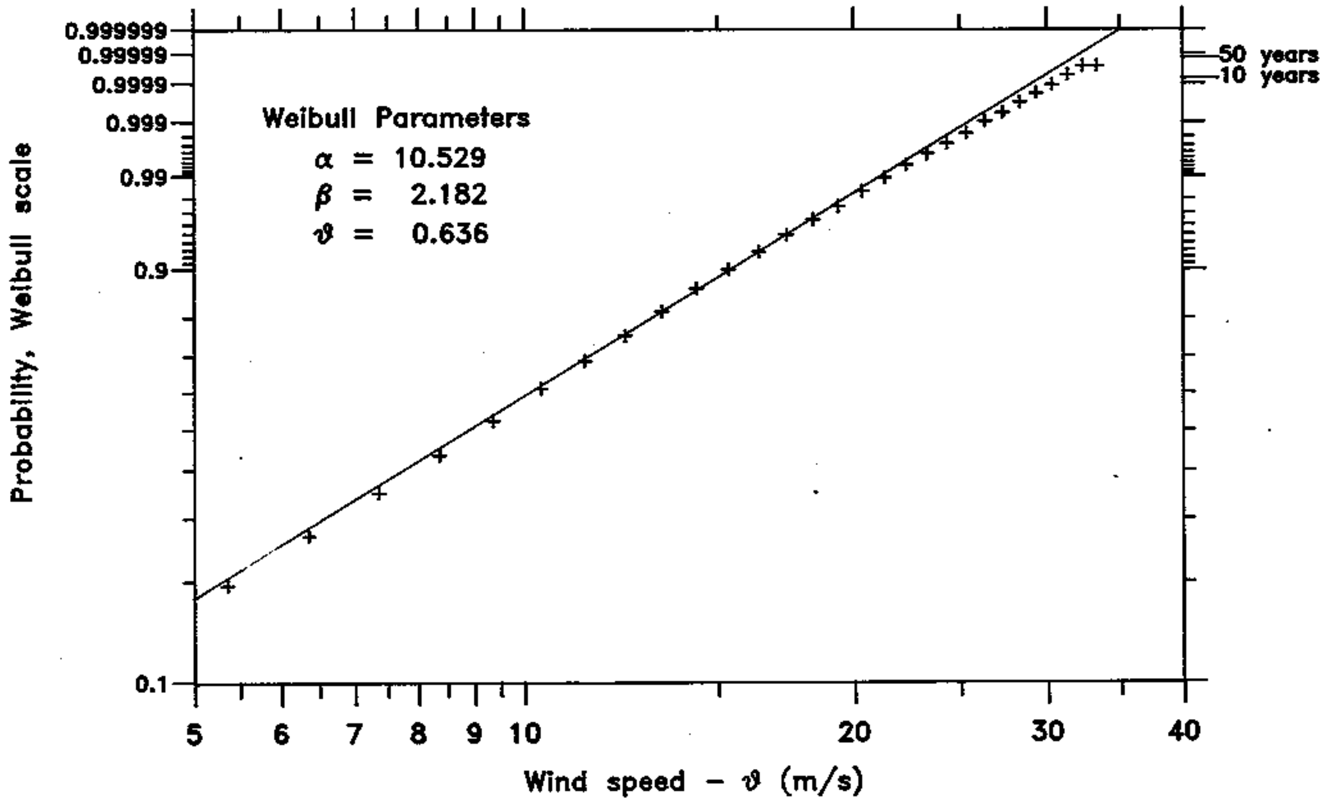
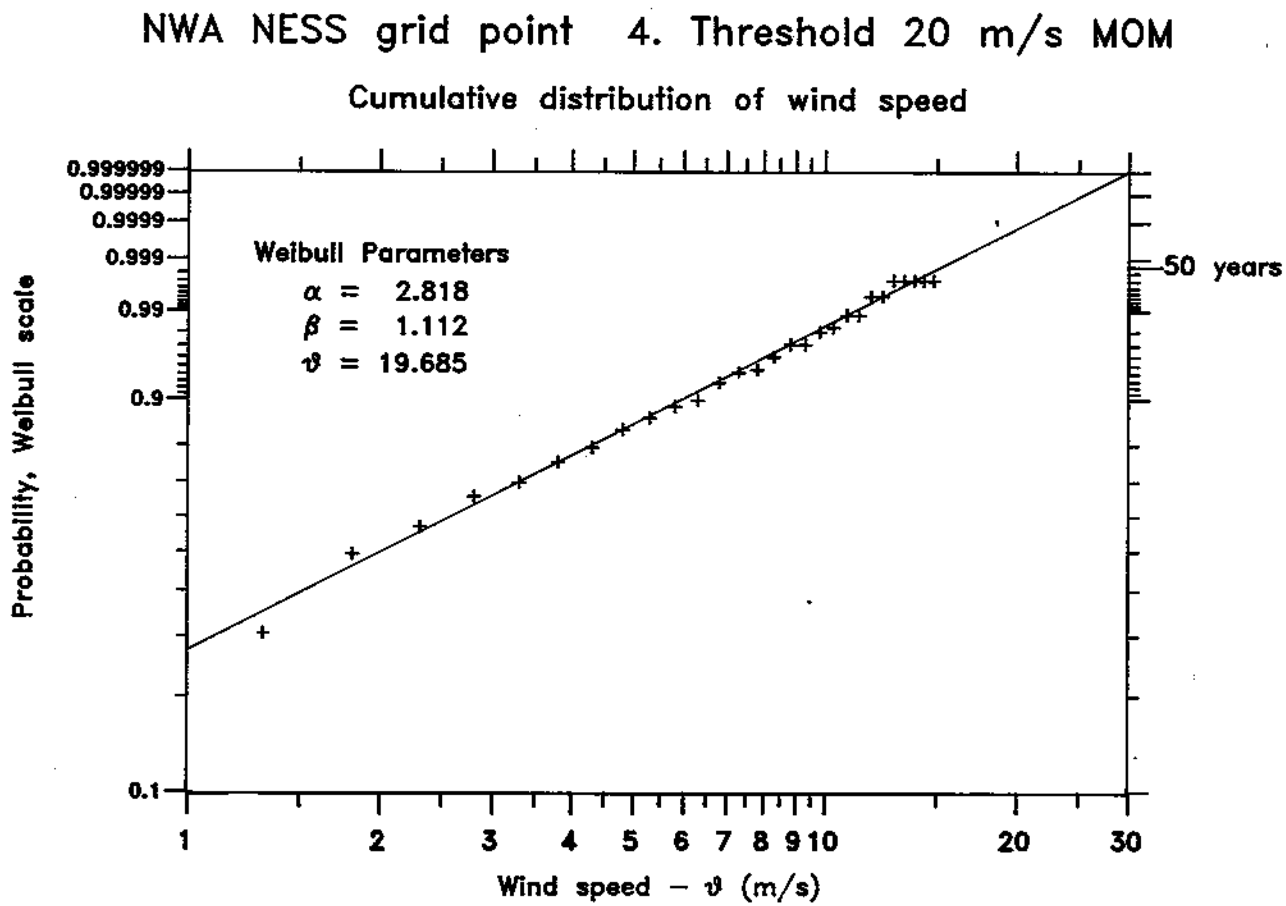


Figure 6.4



NWA NESS grid point 4. Threshold 20 m/s MOM
Cumulative distribution of wind speed
Weibull Parameters
α = 2.818
β = 1.112
ϑ = 19.685
50 years
Probability, Weibull scale
0.999999
0.99999
0.9999
0.999
0.99
0.9
0.1
1
2
3
4
5
6
7
8
9
10
20
30
Wind speed − ϑ (m/s)

Figure 6.5

U(50) for six areas and measurement sites
Comparison with Guidance Notes

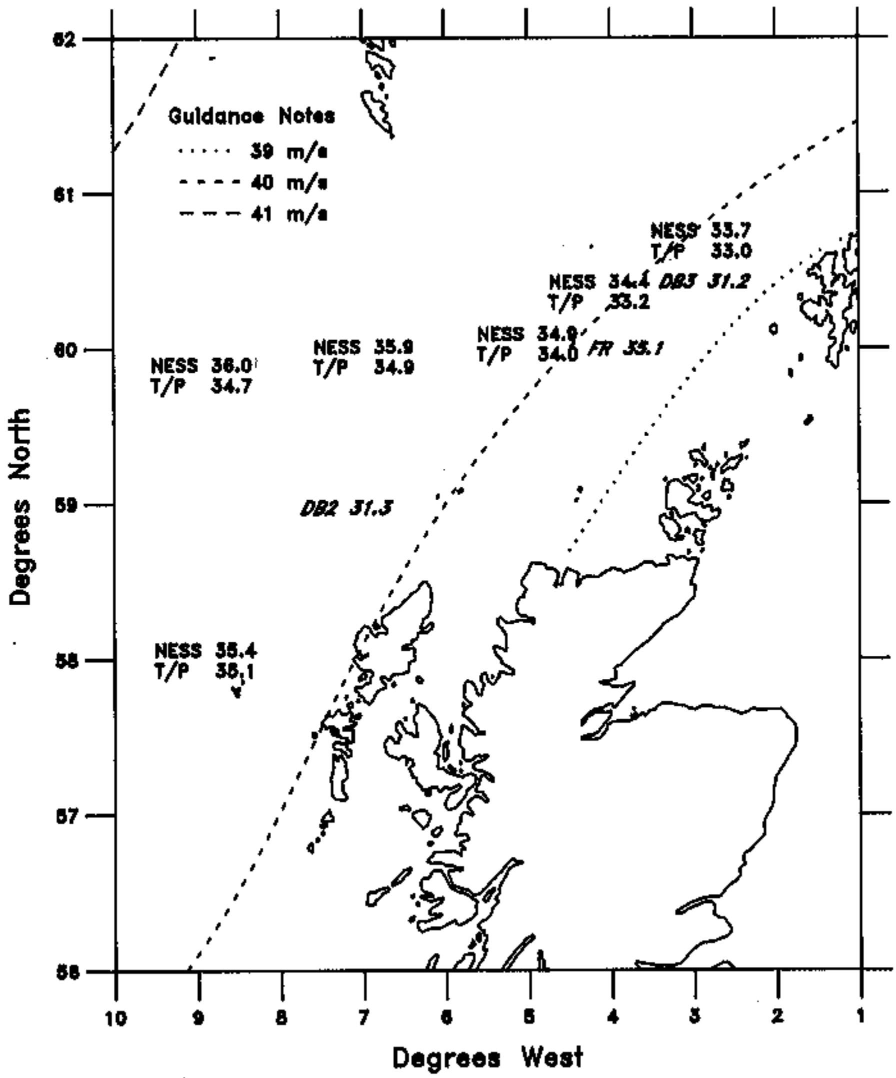
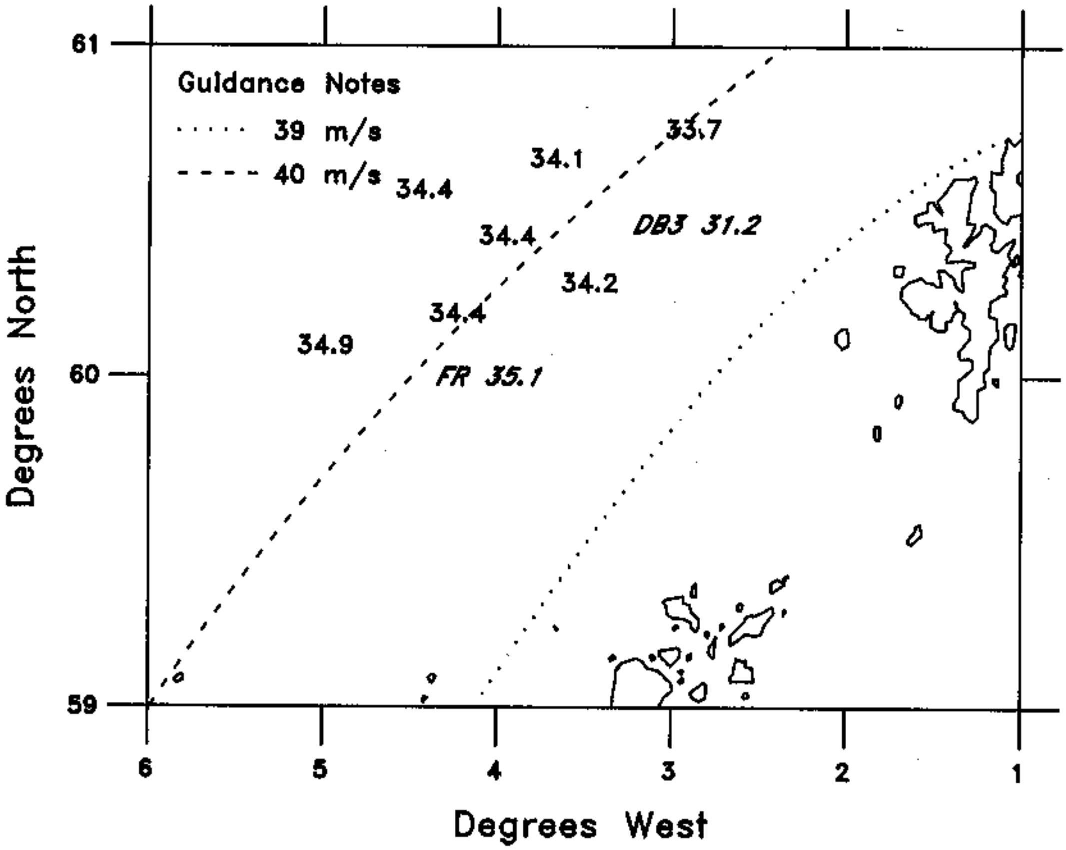


Figure 6.6

U(50) for NESS grid points in selected area
Comparison with Guidance Notes



APPENDIX 1 STATISTICAL FORMULAS FOR EXTREME VALUE DISTRIBUTIONS

1. THE FISHER-TIPPETT TYPE I DISTRIBUTION

The distribution function is given by

$$P(H<h) = \exp\{-\exp[-(h-\alpha)/\beta]\} \qquad \beta>0$$

with mean $= \alpha + \gamma\beta$ where $\gamma = 0.5772...$
and variance $= \beta^2\pi^2/6$.

2. THE WEIBULL DISTRIBUTION

The distribution function is given by

$$P(H<h) = 1 - \exp\{-[(h-\theta)/\alpha]^\beta\} \qquad h>0$$

with mean $= \alpha\Gamma(\beta^{-1} + 1) + \theta$,
variance $= \alpha^2\{\Gamma(2\beta^{-1} + 1) - [\Gamma(\beta^{-1} + 1)]^2\}$
and third moment about the mean
$= \alpha^3\{\Gamma(3\beta^{-1} + 1) - 3\Gamma(2\beta^{-1} + 1)\Gamma(\beta^{-1} + 1) + 2[\Gamma(\beta^{-1} + 1)]^3\}$

3. THE EXPONENTIAL DISTRIBUTION

The distribution function is given by

$$P(H<h) = 1 - \exp[-(h-\alpha)/\beta] \qquad \beta>0$$

with mean $= \alpha + \beta$
and variance $= \beta^2$

APPENDIX 2

Table A2.1: Parameters of distributions fitted to NESS *Hs* POT data (threshold = 10m)

Ref no	FT-1				Weibull				Exponential		
	γ	α	β	*Hs*(50)	α	β	θ	*Hs*(50)	α	β	*Hs*(50)
ness01	1.60	10.58	0.99	14.9	1.78	1.29	9.51	15.1	9.87	1.28	15.5
ness02	1.44	10.85	1.11	15.6	2.31	1.50	9.41	15.5	10.07	1.42	16.1
ness03	2.04	10.79	1.11	15.9	2.09	1.36	9.51	16.0	10.00	1.43	16.6
ness04	1.96	10.66	1.11	15.8	2.00	1.30	9.46	15.9	9.87	1.43	16.4
ness05	1.56	10.60	0.84	14.3	1.63	1.39	9.60	14.3	10.00	1.08	14.7
ness06	2.44	10.59	1.01	15.4	1.76	1.28	9.54	15.6	9.88	1.29	16.1
ness07	2.20	10.80	1.20	16.4	2.08	1.27	9.56	16.6	9.95	1.54	17.2
ness08	2.96	10.92	1.22	17.0	2.30	1.36	9.52	17.1	10.06	1.57	17.9
ness09	3.60	11.04	1.16	17.1	2.71	1.66	9.29	16.6	10.22	1.49	18.0
ness10	3.32	10.82	1.03	16.1	1.87	1.32	9.69	16.1	10.09	1.32	16.8

Table A2.2: Topex/Poseidon *Hs* analysis summary (all heights in m)

Area	FT-1 Parameters		*Hs*(2)	*Hs*(50)	*Hs*(50)	*Hs*(2)	*Hs*(50)	*Hs*(50)	α	β	θ	*Hs*(50)
	α	β	(extrap 3 hr)		NESS *GF*	(extrap 6 hr)		NESS *GF*	Weibull			
1	2.410	1.488	15.3	20.1	19.7	14.3	19.1	18.4	3.129	1.507	0.446	16.6
2	2.466	1.596	16.3	21.4	21.0	15.2	20.3	19.6	2.915	1.323	0.705	19.6
3	2.470	1.698	17.2	22.7	22.2	16.0	21.5	20.6	2.784	1.206	0.835	22.5
4	2.711	1.898	19.2	25.3	24.8	17.9	24.0	23.1	3.063	1.191	0.920	25.4
5	2.794	1.849	18.8	24.8	24.3	17.5	23.5	22.6	2.930	1.173	1.088	25.3
6	2.774	1.807	18.4	24.3	23.7	17.2	23.0	22.2	3.537	1.409	0.597	21.1

Table A2.3 Topex/Poseidon wind speed analysis summary (all speeds in m/s)

Area	Weibull Parameters α	β	θ	U(2) (extrapolation)	U(50) (extrapolation)	U(50) Met O *GF*	U(50) NESS *GF*
1	13.614	2.874	−2.758	27.3	30.5	35.9	32.7
2	13.390	2.818	−2.533	27.5	30.7	36.1	32.9
3	13.483	2.786	−2.442	28.1	31.4	36.9	33.6
4	13.498	2.708	−2.474	28.9	32.3	37.9	34.5
5	14.298	2.884	−2.823	28.7	32.0	37.7	34.3
6	14.839	2.915	−3.336	29.1	32.4	38.2	34.8
DB2	11.885	2.719	−1.594	25.9	28.9	34.0	31.0
DB3	11.065	2.563	−1.112	25.8	29.0	33.8	30.9

APPENDIX A3

WAVE SPECTRA IN THE NORTH-WEST APPROACHES

TABLE OF CONTENTS

A3. WAVE SPECTRA IN THE NORTH-WEST APPROACHES

A3.1 AVAILABILITY OF WAVE SPECTRA

There have been a number of measurement programmes in the north-west approaches which have resulted in time series of wave spectra which extend over one or more years:

(i) The South Uist Waverider programmes which were undertaken by the Institute of Oceanographic Sciences (IOS) with Department of Energy funding.

(ii) The Foula databuoy project which was undertaken for the United Kingdom Offshore Operators Association by IOS with Marex Ltd as the main sub-contractor.

(iii) The deployment of DB2 to the north of the Hebrides by EMI Electronics Ltd for UKOOA.

(iv) The deployment of DB3 to the west of Shetland by UKOOA.

Projects (i) and (ii) measured the temporal spectrum only, while the DB2 and DB3 databuoys gave directional information as well. Data from these projects have been archived at the British Oceanographic Data Centre.

A3.2 ANALYSIS AND INTERPRETATION OF THE SPECTRA

A3.2.1 South Uist data

The spectral data from the South Uist 44m deployment have been analysed in detail for use in the evaluation of the wave power resource in that area. While the results are in general not directly applicable in the offshore oil and gas area a number of useful inferences can be drawn. A problem with these data is the limited depth of 44m and the restricted exposure to waves from the east. Spectral data from the 100m deployment have so far not been analysed in detail.

A3.2.2 Foula spectral data

These data have not yet been subjected to detailed analysis.

A3.2.3 DB3 databuoy

The directional spectra from the UKOOA databuoy DB3 have been subjected to an extensive analysis and interpretation effort. This has been carried out in two parts:

(i) A division of every spectrum into wind-sea and swell, followed by the calculation of average parameters for each part of the spectrum. This was the standard analysis procedure adopted by UKOOA and implemented by Marex Ltd in the production of the DB3 report (Reference A1).

(ii) The parameterisation of each spectrum as the sum of one or two JONSWAP spectra. This work was undertaken for BP Ltd by Paras Ltd with AWR as subcontractor. The results are presented in a confidential report (Reference A2).

A3.2.4 DB2 databuoy

The spectral wave data from this source have been analysed as in A3.2.3 (i) above and the results presented in Reference A3.

A3.2.5 North Sea Spectra

Although there have been many wave measurement programmes in the North Sea, as far as is known none of the resulting wave spectra have been subjected to as comprehensive an analysis as that presented in Reference A2. It has not therefore been possible to provide a strict comparison between the wave spectral climate in the north-west approaches and North Sea conditions. Differences between the results presented in Reference A2 and the JONSWAP results are highlighted where appropriate.

A3.3 RELATIVE PROPORTIONS OF WIND SEA AND SWELL

The north-west approaches are exposed to waves generated by wind associated with the mid-latitude depressions as well as swell which has propagated over distances of hundreds or even thousands of kilometres. Both the South Uist and the DB2 and DB3 measurements confirm that a large proportion of the wave energy in the north-west approaches is in the form of swell. The South Uist results are given in terms of energy flux (power) rather than energy (in effect the spectra are weighted inversely as the frequency). It was found that about two thirds of the power was in the form of swell. Examination of the DB3 results shows, for example, that swell constitutes more than half of the measured energy for more than 74% of the time.

A3.4 FORM OF THE SPECTRUM IN THE NORTH-WEST APPROACHES

Because the area is exposed to the whole of the Atlantic Ocean the wave spectra show a remarkable diversity of forms, particularly in low sea states. In general these sea states consist of one or more of the following:

(i) one or more swell systems which have been generated in areas distant from the measurement position;

(ii) 'old wind-sea', a wave system generated comparatively locally but which has recently (within the last six to twelve hours) become uncoupled from the local wind, and

(iii) wind-sea, a wave system under active generation by the local wind.

At higher sea states there is some simplification, but even so about half the measured spectra overall consist of two or occasionally more than two wave systems.

A3.4.1 Processes producing spectra with multiple peaks

There are two main processes involved in the evolution of swell waves and the way they contribute to spectra with multiple peaks. In the first, referred to below as 'process 1', the swell is modified during its propagation across the ocean mainly by dispersion but also by the loss of energy due to internal frictional dissipation which removes energy preferentially from the higher frequencies. When combined with a wind-sea generated locally at comparatively high frequencies the result is a spectrum consisting of two separate peaks: the wind-sea peak and a swell peak at lower frequencies. These spectra can be modelled satisfactorily by the sum of two JONSWAP spectra, one corresponding to the wind-sea and one corresponding to the swell - although because of modifications to the spectrum the swell is not a priori of the JONSWAP form (see Figure 1 for definitions of the JONSWAP and Pierson-Moskowitz spectra).

Examples of such spectra occur frequently at moderate to low sea states, rather less frequently at higher sea states. The directional difference between the two peaks can be very large, values of between 70° and 160° have been observed in sea states with *Hs* from 5 to 8m.

In process 2, swell from a generating area with rather different conditions from the local area (typically, a different wind direction) is eroded by a growing wind-sea which gradually moves to lower frequencies and subsumes the swell energy. The resulting spectrum often appears as a single peak in the frequency domain; it is only by examining the change of mean direction with frequency that it becomes clear that two wave systems are present, their dividing frequency being marked by a more or less abrupt change of mean direction. This type of spectrum is common at moderate to high sea states. In this case the swell peak may not be well-modelled by the JONSWAP spectral form and in fact a Gaussian form sometimes fits rather better. However, if for the sake of uniformity of approach the swell is modelled by a JONSWAP spectrum the implication is that it must have a high value of γ and a low value of α.

A3.4.2 Spectral form in the highest sea states

The highest sea states are generated by winds associated with very large, deep and slow-moving depressions since only these provide the necessary combination of fetch, wind speed and duration. The spectra produced under such conditions are a special case of the process 2 type with the wave direction changing gradually by 30° to 50° over the spectrum. The spectra generally appear unimodal in the frequency domain and are not highly peaked with JONSWAP γ between 1.0 and 1.5. However the JONSWAP spectrum assumes a single mean direction and so in order to reproduce the change of mean direction with frequency requires the use of (at least) two peaks with different mean directions, the lower frequency (swell) peak having a very abrupt high frequency cut-off. If it is required to model such a spectrum the comments of Section A3.4.1 apply.

A3.5 TYPICAL AND EXTREME VALUES OF SPECTRAL PARAMETERS

In the DB2 and DB3 results the values of the spectral parameters are given as spectrum-weighted averages for the swell and wind-sea bands respectively - they thus reflect the values of those parameters in the most energetic part of their respective bands.

A3.5.1 Highest measured sea state

The highest value of *Hs* measured by DB3 was 12.3m which is well below the *Hs*(50) of approximately 19m suggested by the Topex/Poseidon measurements. The modal frequency (fm) of the highest sea state was 0.0578 Hz, corresponding to a modal period of 17.3 seconds; γ was 1.45. Unfortunately, the directions were suspect for this measurement, but following spectra had directional characteristics rather as described in Section A3.4.2 above, the mean direction changing from west-north-west to west-south-west from the lower frequencies to the higher frequencies.

A3.5.2 Longest swell period

The longest swell peak period was 21 seconds, corresponding to a modal frequency of 0.0476 Hz. This occurred in a bimodal sea state with an *Hs* of 5.4m.

A3.5.3 Directional spread

The spread of energy about the mean direction at each frequency is characterised by estimating from the measurements the parameter s in the following model:

$$S(\theta,f) = S(f)/N \cos^{2s}(\theta - \bar{\theta})/2$$

where $\bar{\theta}$ is the mean direction, and

where $$N = \int_{-\pi}^{\pi} \cos^{2s}\theta/2 \, d\theta$$

Note that the higher s the narrower the width of the distribution. Two estimates of s are available called s_1 and s_2 (see Reference A1, page 7) and moreover s_2 is consistently about twice as large as s_1. Tucker (Reference A4) argues that s_2 is likely to be the more accurate, and it was decided to adopt this as the best estimate of s.

Previous studies have shown that s has its maximum value at the peak of the spectrum and decreases at higher and lower frequencies. Inspection of the statistics of s in Reference A1 shows that the overall average s_2 for DB3 (swell) is 11.4, and for wind-waves is 6.1. These lead to exponents in

$$\cos^{2s}(\theta - \bar{\theta})/2$$

of about 23 and 12 respectively.

Long-travelled swell tends to have a very narrow directional distribution because of the collimating effect of distance, and values of s_2 into the 40's occur fairly frequently. The overall maximum for DB3 was 88, corresponding to an angular spread (defined as the RMS half-width) of 13.2°.

Goda (page 31 of Reference A5) proposes values of s at the spectral peak for respectively long-travelled swell, short travelled swell and wind-sea which are broadly consistent with the s_2 values from DB3.

A3.5.4 Spectral width

As well as having narrow directional spreads long-travelled swell tends to be narrow in the frequency domain, ie to have small spectral width. This is because of the erosion of high-frequency energy by the filtering effect of dispersion and also to some extent by frictional dissipation.

In the JONSWAP parameterisation γ gives the maximum spectral value as a multiple of the maximum of a Pierson-Moskowitz spectrum with the same peak frequency, and $fm\sigma_a$ and $fm\sigma_b$ characterise the low-frequency and high-frequency widths of the peak (Figure 1). In the work alluded to in Section A3.2.2 (ii) above only the unimodal spectra were analysed for spectral width - both peaks of bimodal spectra were assigned the mean JONSWAP values of $\sigma_a = 0.07$ and $\sigma_b = 0.09$. For unimodal spectra the values of γ were found to be rather smaller than those found in JONSWAP with a mean of 1.9 against 3.3. The reasons for this are concerned with the greatly differing circumstances of the measurements - JONSWAP was undertaken in fetch-limited conditions - and also the different fitting methods. Individual high values of γ (5 to 10) occur in unimodal sea states at moderate wave heights (5m), but are almost entirely absent from the highest sea states.

Both σ_a and σ_b were smaller overall than the JONSWAP values, σ_b being very much smaller. The ranges of both were very wide.

A3.6 REFERENCES

A1 MAREX TECHNOLOGY LTD (1992) Analysis of meteorological and oceanographic data recorded by DB3 in the north west approaches during the period July 1984-December 1988. Volume 1 - Documentation and statistical presentations.
Confidential Report No.1140, November 1992.

A2 PARAS Ltd (1994) Individual wave statistics and wave spectra ...
Confidential report to BP Exploration. Paras Report No 0016 Vol 1.

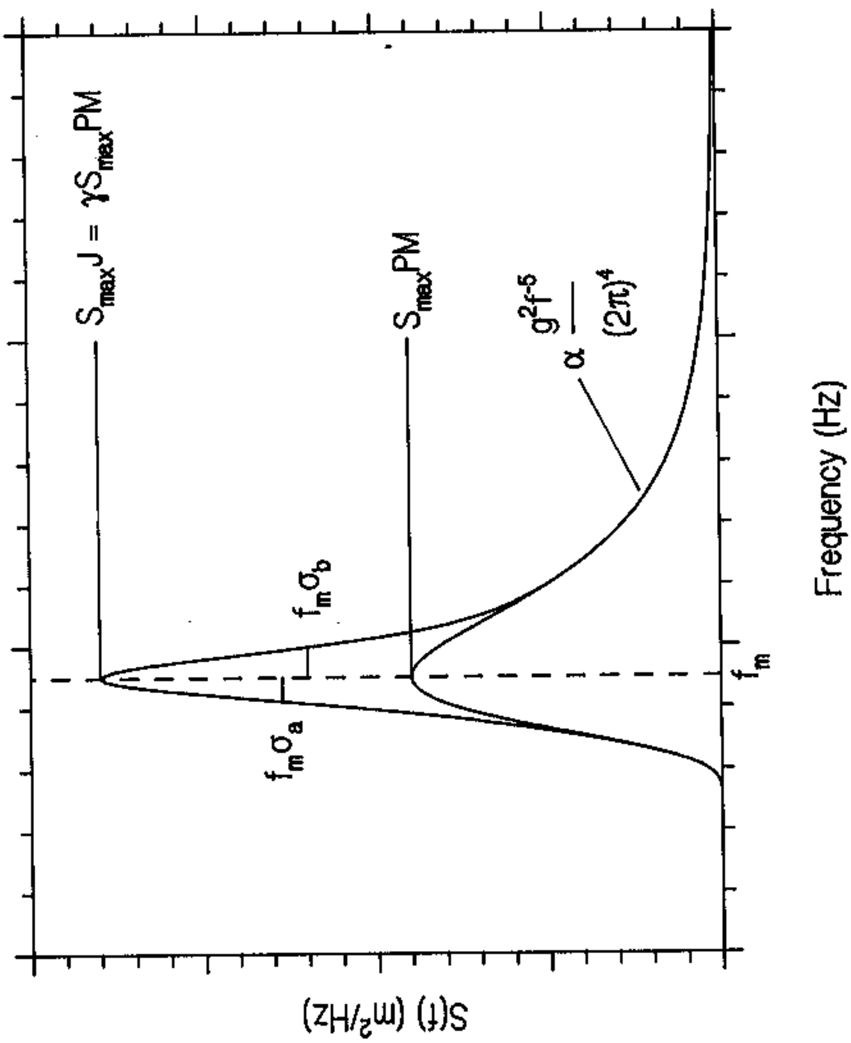
A3 MAREX TECHNOLOGY LTD (1992) Analysis of meteorological and oceanographic data recorded by DB2 in the north west approaches during the period September 1986-December 1988. Volume 1 - Documentation and statistical presentations.
Confidential Report No.1139, December 1992.

A4 TUCKER M J (1989) Interpreting directional data from large pitch-roll-heave buoys. Ocean Engineering, 16(2), 173-192.

A5 GODA Y (1985) Random seas and design of maritime structures. Univ of Tokyo Press.

JONSWAP spectrum

Figure A3.1



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