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WIND SPEEDS AND WAVE HEIGHTS ESTIMATED BY THE VOLUNTARY OBSERVING FLEET COMPARED WITH INSTRUMENTAL MEASUREMENTS AT FIXED POSITIONS

Anne E Graham

SUMMARY

The work described was done as part of a joint Meteorological Office/ National Maritime Institute project. The National Maritime Institute were producing a model to synthesize wave climate by combining visual estimates of winds and waves with wind speed/wave height relationships derived from measured data.

The Meteorological Offices' commitment was; i) to provide wind speed and wave height data, and, ii) to establish that visual wind speeds and wave heights can be used with a degree of confidence.

The two following papers describe the work done for part (ii) above. The first describes the comparison between measured and estimated wind speeds and concludes that visual estimates can be used with confidence where no reliable measured wind data are available. The second describes the comparison of estimated wave heights with instrumental measurements. For this the conclusion was that visually estimated wave heights are less reliable than visual winds, though they are still useful.

PART I

Winds estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions.

WINDS ESTIMATED BY THE VOLUNTARY OBSERVING FLEET COMPARED WITH INSTRUMENTAL MEASUREMENTS AT FIXED POSITIONS.

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1. Introduction

Observations of wind conditions over the ocean and seas come from two main sources, fixed position observing stations and merchant shipping.

Observers located at fixed position observing stations, for example, Ocean Weather Stations (OWS) and light-vessels (LV), make wind measurements using anemometers, whilst the deck officers of merchant ships, which form the Voluntary Observing Fleet (VOF), estimate the windspeed from the sea state at regular intervals during a voyage. Consequently, the fixed stations produce a set of regular observations for each position whereas the merchant ships provide a set of observations which are randomly distributed, along trade routes, in space and time.

Since there are few fixed measuring stations, and these are widely distributed, any analyses of winds over the oceans must depend largely upon observations from the VOF.

Measured observations have usually been considered more accurate than the visual estimates, and results derived from regular data at a fixed location, rather better than those from estimates. Several studies have been made which attempt to relate these two types of observation and determine the relative accuracy of the VOF data, for examples see Quayle (1980) or Kaufeld (1981).

The purpose of this study was to look more closely at several different types of measured observation and at the VOF data in surrounding areas to establish, in general terms, the confidence which can be placed in the VOF data when no suitable measured data are available.

For the VOF estimates 18 years of data were available for this project, 1961-1978 inclusive. Periods covered by the measured data are shown in Table I. Where possible the same period of VOF data was used, for example, OWS 'I' and 'J' and their corresponding VOF data covered 1962-1975, OWS 'M', 1962-1978 and the LV, 1961-1978. For the other stations where only a short period of measured data was available it was decided to use all of the available VOF estimates since using only those from the corresponding periods reduced the number of estimates considerably. For example, for Brent and DB 1 only one year of measurements was available for direct comparison with VOF estimates.

2. Estimated wind data

Wind speeds are estimated by the deck officers of merchant ships of many nationalities using essentially the same method. The observer estimates wind speed from the state of sea or sometimes, particularly at night, from the way the ship is handling. The Beaufort scale of wind force is used which is related to standard descriptions of state of sea. Each Beaufort force has speed limits, in knots (see Appendix Table 1A) assigned to it according to the scale adopted by the World Meteorological Organization in 1946. The observer then estimates, within those limits, a wind speed to the nearest knot.

Because of the use of these discrete groups the wind speed values recorded tend to cluster around the middle value of each Beaufort force range and, consequently, the data can only really be used in the Beaufort force classes. The scale used by the VOF is now considered incorrect and alternative limits have been devised for each scale number (see Appendix Table 1A). This scale is commonly called the 'scientific' Beaufort scale by certain Branches at the Meteorological Office and should correct the speeds in those classes previously overestimated.

The averaging time or representative time for these observations is not really known but in this study it has been taken as equivalent to an hour owing to the relatively slow response of the sea to changes in wind speed. These estimated winds may be taken as hourly mean values of wind speed which are observed every six hours by the majority of VOF ships.

The data used were derived from ships' logbooks and should be complete. This was necessary because many ships do not transmit radio messages at night and so data from telecommunication sources are usually incomplete.

3. Instrumental data sources

A set of 14 stations was used, comprising four OWS, four LV, three stations manned by ships sponsored by the United Kingdom Offshore Operators Association (UKOOA), one island station, one oil rig and one data buoy. Locations are as shown in Figure 1.

All these stations were equipped with anemometers, but observing practice varied from site to site. The methods used are presented in more detail below and a list of these stations with dates and total number of observations is given in Table I, together with the corresponding dates and number of observations for VOF data.

(a) Measured wind observations from ocean weather ships

Ocean Weather ships carry at least one anemometer in a well exposed position. British weather ships carry two anemometers on a yard-arm one on each side of the mast, at a height of 20 m above sea level with dials on the bridge registering instantaneous wind speeds.

The observer is instructed to take an average, by eye, of the dial readings over a period of 10-15 seconds at the time of observation. However, the precise method of making the observations is not clear. The Marine observer's handbook, which refers to British weather ships makes the statement that "even here estimates are made regularly of wind force and direction from the appearance of the sea as a check on the instruments". Informal discussion with the weather ship observers suggests that the visual element may make a large contribution to the observation in some cases. Consequently, how many of the observations are averages over 10-15 seconds and how many are instrument assisted estimates with longer effective averaging time is unknown.

There are also uncertainties regarding the siting of the anemometers on ships of different nationalities and in the non-linear response of anemometers in wind speeds of less than 10 knots; in practice, Meteorological Office anemometers require a gust of approximately 2-4 knots to overcome instrument inertia before they begin to register wind speeds. The wind speeds are not corrected for the ship's pitch and roll, and it is not known whether or not the ship was steaming when the observation was made: this can make a considerable difference to the pitch and roll of the ship, which in turn affects the wind speed recorded by the anemometer because the ship's motion is amplified by the height of the instrument above sea level.

(b) Measured wind speeds from light vessels

Observers on LV are not professional meteorologists but are instructed on how to use hand-held anemometers to make the observation from a well-exposed part of the ship, and to take an average reading, by eye, of the wind speed over a 1-minute period.

It is difficult to achieve reasonable accuracy with a hand-held anemometer and the actual exposure of the anemometer is unknown, as is the actual length of time over which the wind speed is averaged. It is likely that the observer would find some difficulty in making an accurate estimate of the 1-minute mean wind speed and, therefore, the data from the LV are more representative of a shorter averaging time.

(c) Measured wind speeds from UKOOA sponsored ships

The data for the three UKOOA stations were taken from the meteorological logbooks. For Stevenson there is also a data set of quality controlled hourly mean wind speeds.

The data from the meteorological logbooks consists of measured values, but the source of measurement and averaging time is uncertain. It is likely that most of the data are from readings of anemometer dials, as on the OWS, but since chart recorders were available some readings may have been taken from these.

Unfortunately, the data sets cover short periods, about three years each, and have many gaps when no observations were made.

(d) Other stations

South Uist

The data for this position were taken from Benbecula, a land station equipped with an anemograph to record wind speeds. The data were provided by a manual analysis of the average wind speed over a 10-minute observing period in each hour. These data were included because wave data from a buoy moored off South Uist were to be used in the National Maritime Institute's wave climate synthesis project.

DB 1

DB 1 is a data buoy recording meteorological and wave data automatically. It has two anemometers, one mounted at 8.7 m above sea level and the other at 6 m above sea level. These provide instrumentally calculated 10-minute mean wind speeds every hour. This location should provide better 10-minute mean wind speeds than any other site because there is no doubt about averaging time or exposure. Unfortunately, the record is so short that it is of little use in estimation of extreme conditions over long return periods.

Brent B (Oil rig owned by Shell)

The anemometer on this rig is mounted on top of the drilling derrick at a height of 108 m above sea level in the best position available. The observations were made every three hours, readings being taken from a digital display and entered in the meteorological logbook from which the data set used here was compiled. These winds, therefore, must be considered 'spot winds' or 3-second gusts.

4. Reliability of measured data for climatological purposes

Reliability of data is a difficult quality to quantify because the properties that define it vary with the purpose for which the data are required. For example, data sources which are considered useful for synoptic purposes may not be acceptable for climatological investigations.

It is particularly important in climatology to be aware of the limitations of the data. Thus, it is necessary to be aware not only of the accuracy of each individual measurement, but also of the long term consistency of the method of measurement so that there are no discontinuities in the data which could affect any result derived from them. Such discontinuities can be due to changes in instrument type and method of observation, or changes in coding practice.

The prime requirement for climatological data is that it should cover as long a period as possible; three years of data is not really long enough for a data set to be considered representative of climatological conditions, but, often, the quality of the data themselves can be taken into account to increase confidence in the climatological reliability of the data set. This was the case with the data set of quality-controlled hourly mean wind speeds from the Stevenson site. The hourly means were derived from continuous recordings of wind speed from digital or analogue recorders and were fairly complete, 80% of the possible total number of observations being present. This compares favourably with an average of 75% for the OWS 'I' and 'J', although these data sets cover a period of 17 years.

The LV data sets cover a period of 18 years but, as mentioned above, the climatological reliability of each individual measurement is in question. The LV provide very useful observations on the synoptic scale since they can be considered in the light of the current situation. However, the accumulation of the doubtful measurements produces data sets of questionable climatological reliability.

It is unfortunate that there are only 18 months of data available from DB 1. In time these data should prove to be useful for climatological purposes, although the record will still be short. The method of measurement is known exactly and the only variable is the calibration of the instrument which can be checked and the data adjusted accordingly.

5. Analysis of data

The descriptions of observing methods and other factors given above indicate quite clearly the difficulties involved in comparing measured and estimated values of wind speed. It has to be assumed that deck officers on ships of the VOF estimate winds in a similar fashion and this is supported by the similarity in the distributions produced for each site (Fig 2). However, the measured distributions are all very different in shape. This is not only because of the different geographical locations but also the differences in anemometer height, the method of determining wind speed and the different averaging times used. Ideally, corrections would be applied to produce a consistent set of data, but this is not practicable owing to the uncertainty surrounding the observing practice.

Because of these inconsistencies it was not possible to make any direct comparisons between all the wind speed distributions. It was necessary to decide which of the measured distributions should be considered reliable and to compare these with the corresponding estimated distributions. The data were required to cover a long period with few gaps, and with a known method of observation which was thought to be used consistently to make corrections possible.

Within these contraints the OWS were considered "reliable" although with some reservations concerning the short period for OWS 'L'. The hourly data set from the Stevenson station was also considered "reliable" since the data had been studied and quality controlled.

(a) Simultaneous data and calibration of estimates

For each site the instrumental wind speeds were compared with VOF estimated wind speeds made at the same time. These estimates were taken from the 2° x 2° 'square' area around the instrumental source. Comparisons were not made when the wind directions differed by more than 45° unless one of the winds was a calm.

Unfortunately, this process reduced the number of observations from the data sets and only four stations were considered to have enough data for comparison purposes.

For initial comparison the measured wind speeds were grouped according to the scientific Beaufort scale and the means and standard deviations of those estimated winds corresponding to the measured groups were calculated. The results are shown in Fig 3 for OWS 'I' and 'J' and LV Seven Stones and Varne. The mid-point of each Beaufort force class for the measured data is plotted against the mean of the estimates with one standard deviation of the estimated wind speeds shown.

The data fit a straight line fairly well but there is a large scatter in estimated data. The visual observations appear to be underestimated but this effect could well be due to the different averaging times used for each type of instrumental observation.The use of very short averaging times,as on the OWS

(10-15 seconds), is likely to cause the observer to bias the estimation of the average wind speed towards the higher speeds registered by gusts. In such small samples of data produced here by the selection of simultaneous data this bias is likely to dominate the results. Over a long period of time and with a large number of observations, the mean wind speed should be independent of the averaging time (except where this is very short) although the scatter about the mean will be greater for the short averaging times.

The calibration of the estimated wind speeds from the comparison described above simply produces a single correction for each Beaufort force. The scientific Beaufort scale was developed to produce such a correction and although some doubt has been expressed about its accuracy it is still generally held to be good (Kaufeld, 1981).

An alternative method could be to correct each estimated speed individually. This would produce calibrated wind speeds equivalent to those of a different averaging time and the calibration would vary according to the type of instrumental data used. Such an attempt at calibration was made for OWS 'I' and 'J' from measured wind speeds and the corresponding estimates.

For each value of wind speed V(V=1,2,3.....knots) a calibrated speed was derived by taking the mean of all measured winds corresponding to estimates of V. The resulting wind speed distributions were rather distorted. It is likely that this was due to the method of estimation of wind speeds in Beaufort forces; this produces clusters of wind speed estimates around a mid-point value for each force.

In all the following analyses the complete data sets were used, not simultaneous data. This was because the process of producing data sets of simultaneous data takes only a sample of the original data. The VOF data is already only a small sample of the possible population of observations in the area and this sample should be compared with the best estimate of the whole population that is available.

The measured distributions are the best estimates available for the whole population even when the data set covers only a relatively short period. For those sites where the measured data cover approximately the same period as the estimated data sets, and the data is considered climatologically reliable, the comparisons should produce reliable results. It must be remembered, however, that the measured distributions are still only samples of the whole population and, though they are much better estimates of the whole population than are the VOF samples, they are still subject to possible sampling errors.

(b) The effect of normalisation of the VOF data

There is a high density of observations during the summer of each year, possibly because there are more ships at sea during the summer than the winter. Consequently, there may be biassing of the VOF data towards the less severe summer conditions.

An attempt was made to reduce any such bias by defining a mean monthly observation count. The effect of setting such a count was that each observation for a month with M observations (where $M > 30$) was reduced by a factor of 30/M. Months with $M < 30$ were not adjusted, all observations being used without the scaling.

This normalization, or weighting, of the data should reduce the effect of the larger number of observations available in the summer months without altering the distribution of wind speeds observed during those months.

Although this weighting action did produce some differences in the distributions it was very slight in all cases and could not be said to be significant.

(c) Extreme-value analysis

The estimation of extreme values is important for design and planning purposes. It is, therefore, of interest, to compare the extremes derived from both the measured and estimated wind speeds.

Extreme values are estimated by fitting a distribution of the available data and extrapolating the tail of the distribution to the value having a cumulative probability of exceedance corresponding to the return period required. This gives the value expected to be exceeded, on average, once in N years where N is the return period.

There are many distributions that can be used to estimate extreme values. Several require the identification of annual maxima. This means that a long period (several years) of regularly observed data is necessary. Since the VOF data are randomly distributed in space and time such methods cannot be used because the maxima cannot be identified. The method used here to predict extremes from both measured and estimated data is to fit a 3-parameter Weibull distribution to the data.

The form of the distribution function (Weibull 1951) is

$$1 - P(V) = exp\left\{-\left(\frac{V - V_0}{B}\right)^A\right\}$$

where 1 – P(V) is the probability of exceedance and A, B and Vo are the three parameters to be determined. This expression can be rearranged to give a straight line of the form

$$\ln\left[-\ln\left\{1 - P(V)\right\}\right] = A \ln(V - V_0) - A \ln B .$$

The data were fitted by computer program to this straight line by finding the best correlation between $\ln[-\ln\{1 - P(V)\}]$ and $\ln(V - V_0)$ for various values of Vo. The other two parameters A and B, were given by the line of best fit with the optimum value of Vo. The once in N-year value was then estimated by assuming that the number of observations which could be expected in N years was n. The corresponding probability of exceedance was 1/n and could be used in the expression

$$V_N = \exp\left(\frac{\ln\{-\ln(1/n)\} + A\ln B}{A}\right) + V_0$$

where V_N is the once in N-year extreme.

Because of the varous averaging times (see Table II) it was necessary to convert the extreme values deduced for each station to extreme values appropriate to averaging times of one hour. This conversion, necessary for comparison purposes, was effected by means of figures derived by the Meteorological Office and given in Table III. Similar figures can be found in the Department of Energy Offshore Installation Guidance Notes (1977).

6. Results

The results of the extreme-value analysis are shown in Table IV for the 50-year return period. Both normalized and unnormalized VOF data were used. The normalized distributions tended to produce higher extremes, but for five stations there was no difference. Of the other ten stations, seven were increased by 1 kn, two by 2 kn and one, Varne, decreased by 2 kn because of normalization and an abnormal frequency distribution; the only wind of Beaufort force 11 occurred in a month of more than 30 observations so that its contribution to the normalized distribution was insignificant in the extreme-value analysis.

The large difference between extremes derived from the instrumental data from Brent B and the corresponding VOF data may be due to the height of the anemometer on the rig (108m) and, also, to variations in observing practice. The extreme has been corrected to an equivalent hourly mean wind speed at 10m but the original data were uncorrected.

The very high extreme wind of the Stevenson 10-minute may be due to sampling errors. There were only 23% of the possible total number of observations in the data set and three values above 60 kn contributed a comparatively large percentage to the distribution.

The differences between the extremes for 50 years from instrumental and estimated data are also shown. In 11 cases out of 15, the differences at the 50-year return period between extremes derived from instrumental data and from the estimated data were either reduced or remained the same when the estimated data were normalized.

Considering climatological reliability, as discussed above, and the number of observations in each sample it can be concluded that reliable data samples exist for OWS 'I', 'J', 'L' and the Stevenson hourly data. OWS 'M' is not included because of the low number of VOF estimates. This conclusion does not mean that the samples of data considered reliable are necessarily true representations of the climate in that area, only that it seems reasonable to assume so. It is quite possible that the data samples from other stations are good representations of the conditions despite reservations about their climatological reliability.

The difference between the 50-year return period extremes derived from the measured data and the normalized distribution of VOF estimates from the area surrounding the 'reliable' stations OWS 'I', 'J', 'L' and Stevenson (hourly) are respectively, -2, +3, +2 and +7 kn (Table 4). If it is borne in mind that the extremes are derived from wind speeds in Beaufort force classes (average range 5 kn) the extremes can only be considered accurate to within ±5 kn at best and, more likely ±7 kn, since the range of the Beauforce force classes increases with increasing wind speed. Consequently, the estimates of the 50-year extremes derived from each source are quite close. In fact only two stations have differences of more than ±7 kn, so, in most cases, the 50-year extremes estimated from the VOF distributions are correct within the range of accuracy of the extremes derived from the measured distribution. Of the remaining five, three are stations with short periods of measured data, FitzRoy, Boyle and DB 1. One, South Uist, has measured observations from a land station (Benbecula) which would be expected to underestimate the wind speeds compared with open sea values. The remaining station is OWS 'I' with an overestimation from the VOF distribution of 2 kn. There is no obvious explanation for this difference though it is most likely due to the sampling in one of the data sets concerned. For the OWS 'I' measured data, annual maximum wind speeds were extracted and fitted to the Gumbel (or Fisher-Tippett Type I) distribution to give estimates of extreme values. Extreme wind speeds were also estimated in this way for OWS 'J'. Since 'I' and 'J' are in similar climatic locations it should be possible to determine whether, or not, the results from OWS 'I' are reasonable by comparing the extremes from each OWS derived using each method of extreme value estimation.

Table V shows some of the resulting extremes from both methods of analysis and Fig 4 shows plots of extreme wind speed against the return period. The estimated extremes from the Gumbel analysis are similar for both OWS 'I' and 'J' as are those estimated using the Weibull distribution. It would seem that the results for OWS 'I' can be considered reasonable and that it is the VOF distribution of estimated wind speeds which is unrepresentative of the climatic conditions in the area. The extreme values for the 50-year return period for OWS 'I' and 'J' wind speeds here are very similar. This is a coincidence and it should not be assumed that similar results are given for the 50-year return period for every location. There is no very obvious anomaly in the VOF distribution, but there is a small percentage of observations of wind speeds greater than 60 kn (0.04%). These observations are not necessarily incorrect but have not been matched by lower observations in the rest of the distribution.

Therefore, the whole distribution becomes unrepresentative due to a quirk of sampling.

The two stations with very large differences between estimated 50-year extremes can be discounted for reasons explained above. Most of the sites have underestimates of the 50-year extreme derived from the VOF distribution compared with the corresponding extremes from the measured distribution. The average value of this underestimation is 5 kn. It does not seem unreasonable to assume that, in most cases, if 5 kn is added to the extremes estimated from the VOF distribution the resulting extreme value will be a better estimate. Obviously this will not always be true and, although sensible assumptions can be made regarding the apparent reliability of the data samples, there is no rule which will say whether or not any sample is a good representation of the conditions in the area over which it is taken.

If one considers the average differences between the extremes derived from the VOF estimates and the measured observations a similar conclusion can be drawn for extremes for the other return periods. That is, the average difference for the stations is about 5 kn, so a 5 kn addition to the VOF estimate in general would improve the estimated extreme. It must be emphasised that this correction is an average result and will not necessarily improve the result in every individual case.

7. Conclusions

The distributions of estimated wind speed observations are different from those derived from wind speeds taken from instrumental sources. These differences are most likely due to the different observing techniques used.

This study suggests that a distribution should not be considered reliable simply because it has been taken from instrumental sources. It may not be any better than a distribution of estimated observations. The quality of measurements must be taken into account and the length of time over which the data set exists is also important.

It seems that where there is no absolutely reliable set of instrumental data the VOF data in that area can be used with confidence and it is likely that if an addition of one Beaufort class is made to the 50-year return period extreme (and similarly to all other return period extremes) the result will be somewhat improved.

6. References

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Station	Measured windspeeds period	Measured windspeeds number	Estimated windspeeds period	Estimated windspeeds number
OWS 'I'	1962–75	113 072	1962–75	2 355
OWS 'J'	1962–75	112 317	1962–75	3 356
OWS 'L'	1975–79	28 957	1962–78	2 975
OWS 'M'	1962–78	126 335	1961–78	666
Seven Stones LV	1961–78	13 100	1961–78	12 410
Shambles LV	1961–76	9 988	1961–78	12 797
Mersey Bar LV	1961–78	8 192	1961–78	1 608
Varne LV	1970–78	46 194	1961–78	9 932
Stevenson (10 minute)	1973–76	2 005	1961–78	5 702
FitzRoy	1973–76	2 379	1961–78	3 088
Boyle	1974–77	3 643	1961–78	6 315
Stevenson (hourly)	1973–76	21 010	1961–78	5 702
DB 1	1978–79	5 888	1961–78	13 338
Brent B	1978–79	4 950	1961–78	9 178
South Uist	1961–78	29 266	1961–78	1 743

Table I Availability of measured wind data and periods for which estimated data were used in the analysis.

3 seconds	15 seconds	1 minute	10 minutes	1 hour
Brent B	OWS	LV	UKOOA DB 1 Benbecula	VOF Stevenson

Table II Effective averaging times for the various sources of data.

Height	Averaging time				
	10 min	1 min	15 sec	5 sec	3 sec
10m	1.05	1.17	1.27	1.34	1.37
100m	1.39	1.54	1.56	1.61	1.63

Table III 1 in 50-year extreme winds at 10m and 100m above sea level for various averaging times expressed as ratios of the 1 in 50-year hourly 10m wind.

Station	50-year extreme wind speeds (kn) derived from			Differences between extremes derived using measured and estimated data (kn)	
	Measured data	Estimated data			
		not normalized	normalized	not normalized	normalized
OWS 'I'	65	66	67	-1	-2
OWS 'J'	65	61	62	+4	+3
OWS 'L'	67	64	65	+3	+2
OWS 'M'	59	53	54	+6	+5
Seven Stones LV	66	58	59	+8	+7
Shambles LV	66	61	62	+5	+4
Varne LV	64	61	59	+3	+5
Mersey Bar LV	69	66	66	+3	+3
Stevenson (10 minute)	84	62	62	+18	+18
Fitzroy	57	59	60	-2	-3
Boyle	56	59	59	-3	-3
Stevenson (hourly)	69	62	62	+7	+7
DB 1	55	62	62	-7	-7
Brent B	78	62	64	+16	+14
South Uist	58	59	61	-1	-3

Table IV Comparisons of 1 in 50-year extreme winds derived from measured and estimated data.

	OWS 'I'		OWS 'J'	
Return period (years)	Weibull extremes	Gumbel extremes	Weibull extremes	Gumbel extremes
	(Kn)		(Kn)	
10	63	57	62	58
50	65	64	64	65
100	66	66	66	68

Table V Extreme wind speeds for OWS 'I' and 'J' derived using the Weibull and Gumbel (or Fisher-Tippett Type I) distributions.

APPENDIX

Table IA. Comparison between the limits of wind speed for the Beaufort scale numbers with those for the 'scientific' Beaufort scale.

Beaufort Scale Equivalent speed at 10 m above ground. Limit (Knots)	Force	'Scientific' Beaufort scale. Equivalent speed at 20 m above sea surface Limit (knots)
1	0	0-2
1-3	1	3-5
4-6	2	6-8
7-10	3	9-12
11-16	4	13-16
17-21	5	17-21
22-27	6	22-26
28-33	7	27-31
34-40	8	32-37
41-47	9	38-43
48-55	10	44-50
56-63	11	51-57
64	12	58

Figure 1. Positions of fixed stations used in the analysis.

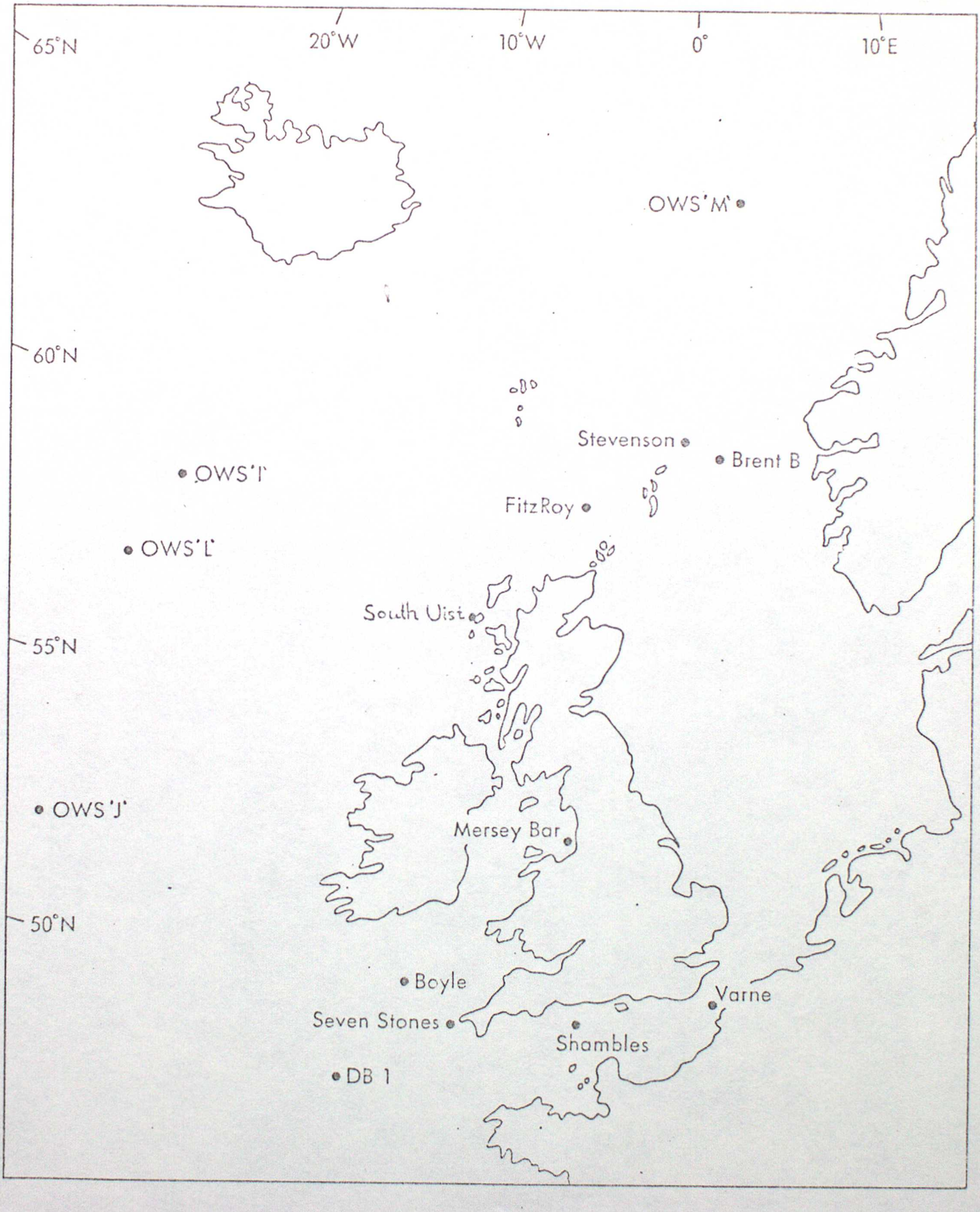


Figure 2(a). Wind-speed frequency distributions for OWS compared with those for co-located VOF ships within $2^{\circ} \times 2^{\circ}$ squares centred on the OWS.

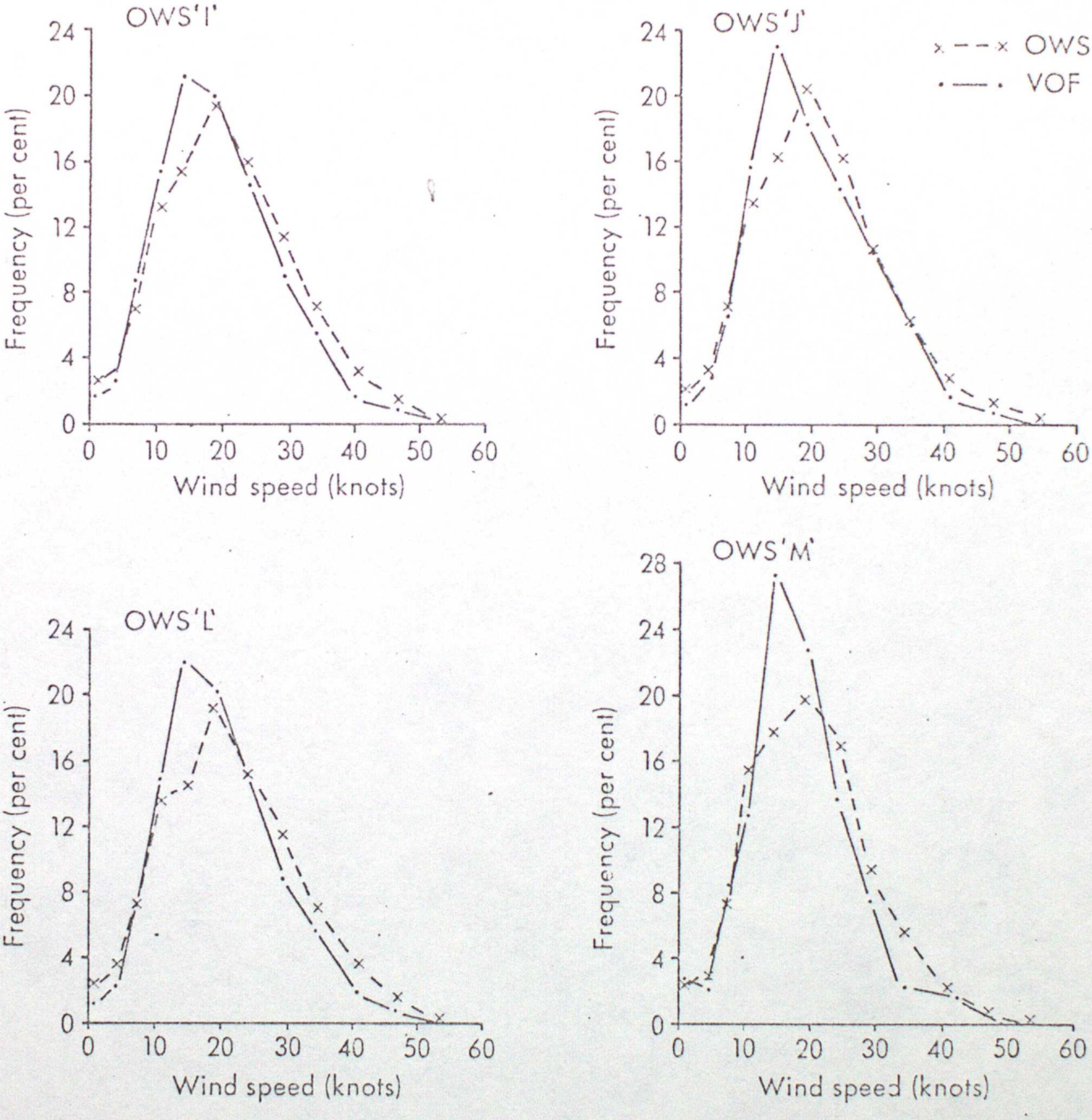


Figure 2(b). Wind-speed frequency distributions for light-vessels compared with those for co-located VOF ships.

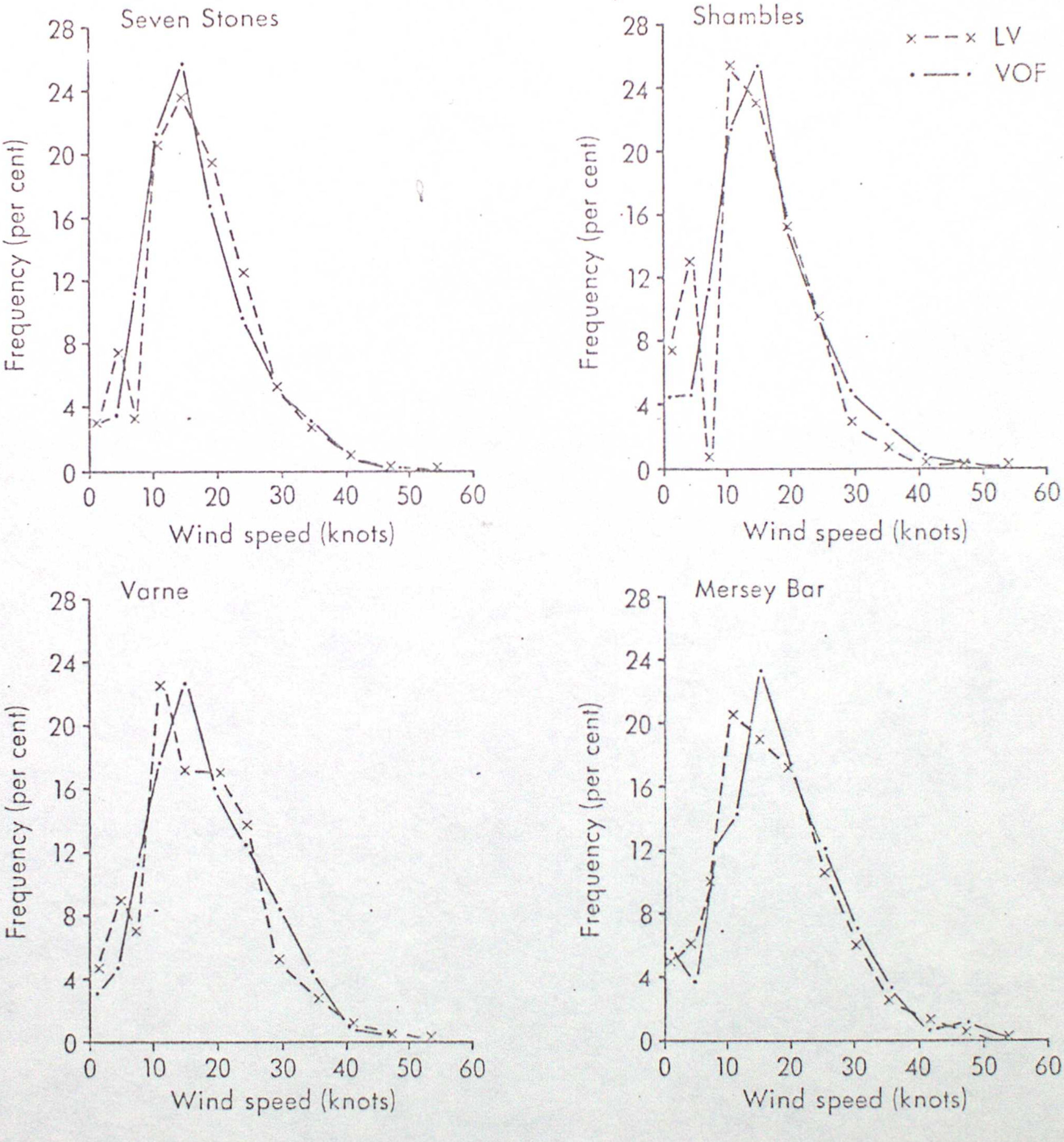


Figure 2(c). Wind-speed frequency distributions for UKOOA ships compared with those for co-located VOF ships.

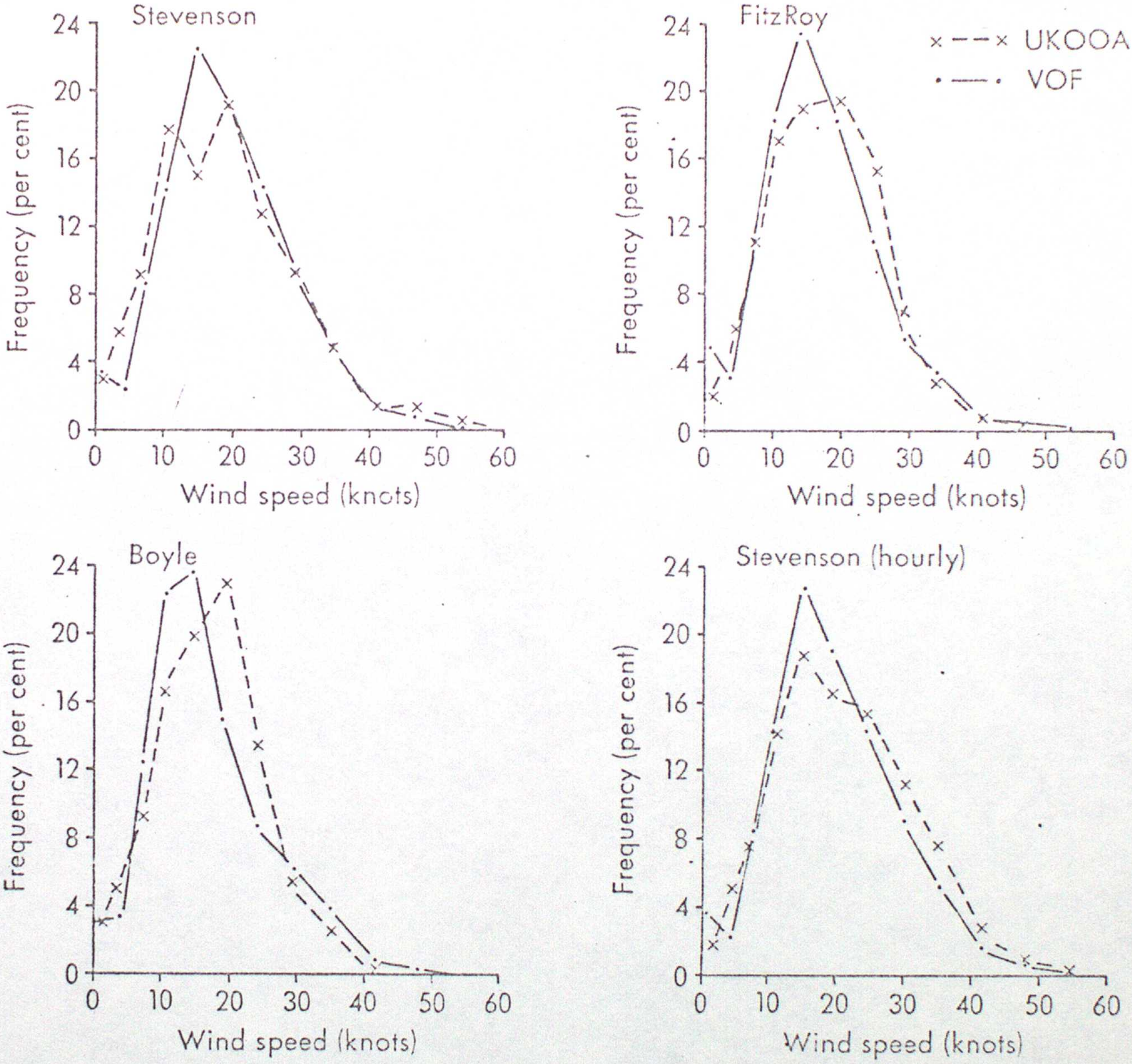


Figure 2(d). Wind-speed frequency distributions for South Uist (Benbecula), Brent and DB 1 compared with those for co-located VOF ships.

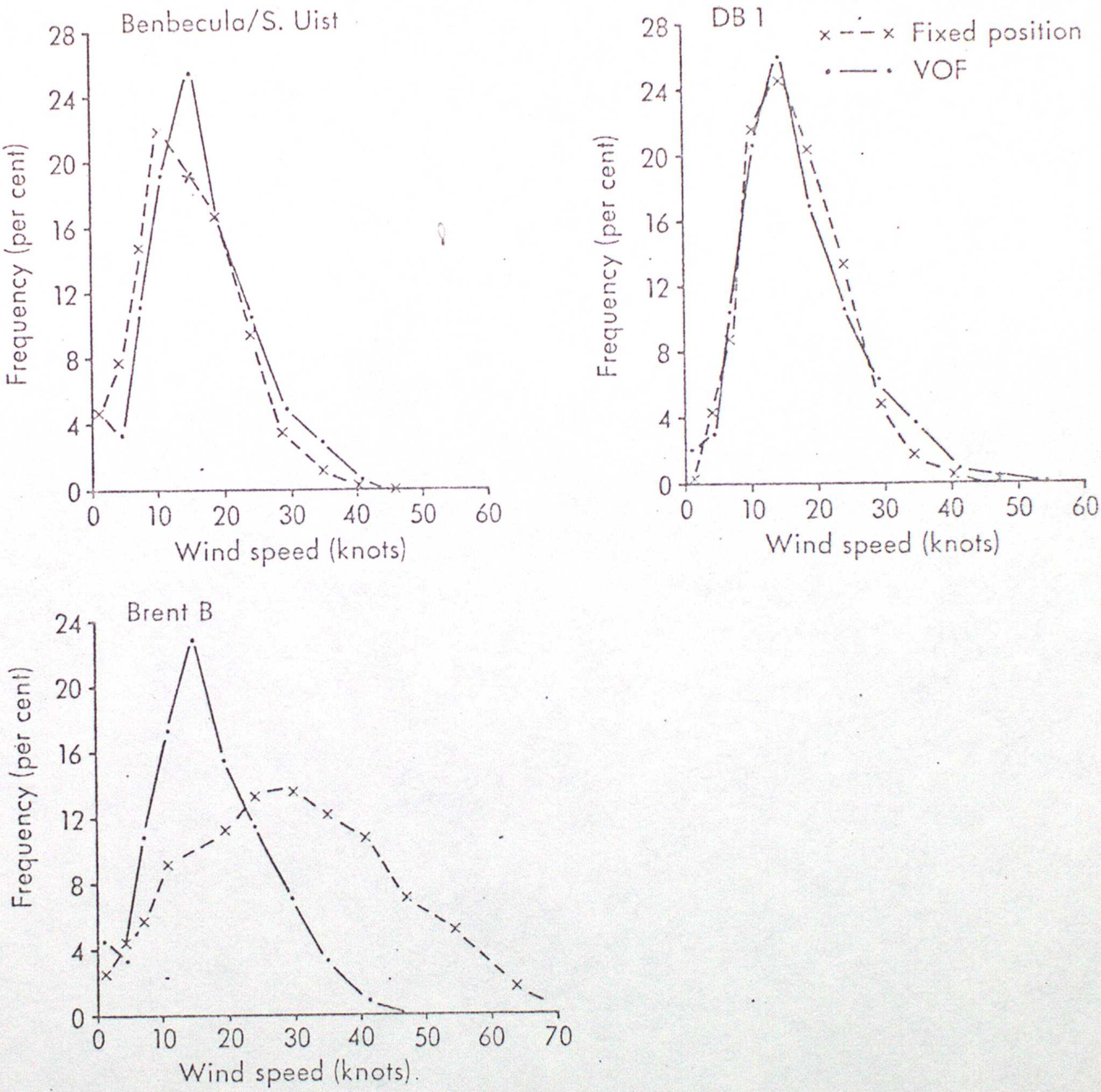


Figure 3. Mean of estimated data and standard deviation plotted against measured data using contemporaneous information. (Numbers of observations used are indicated.)

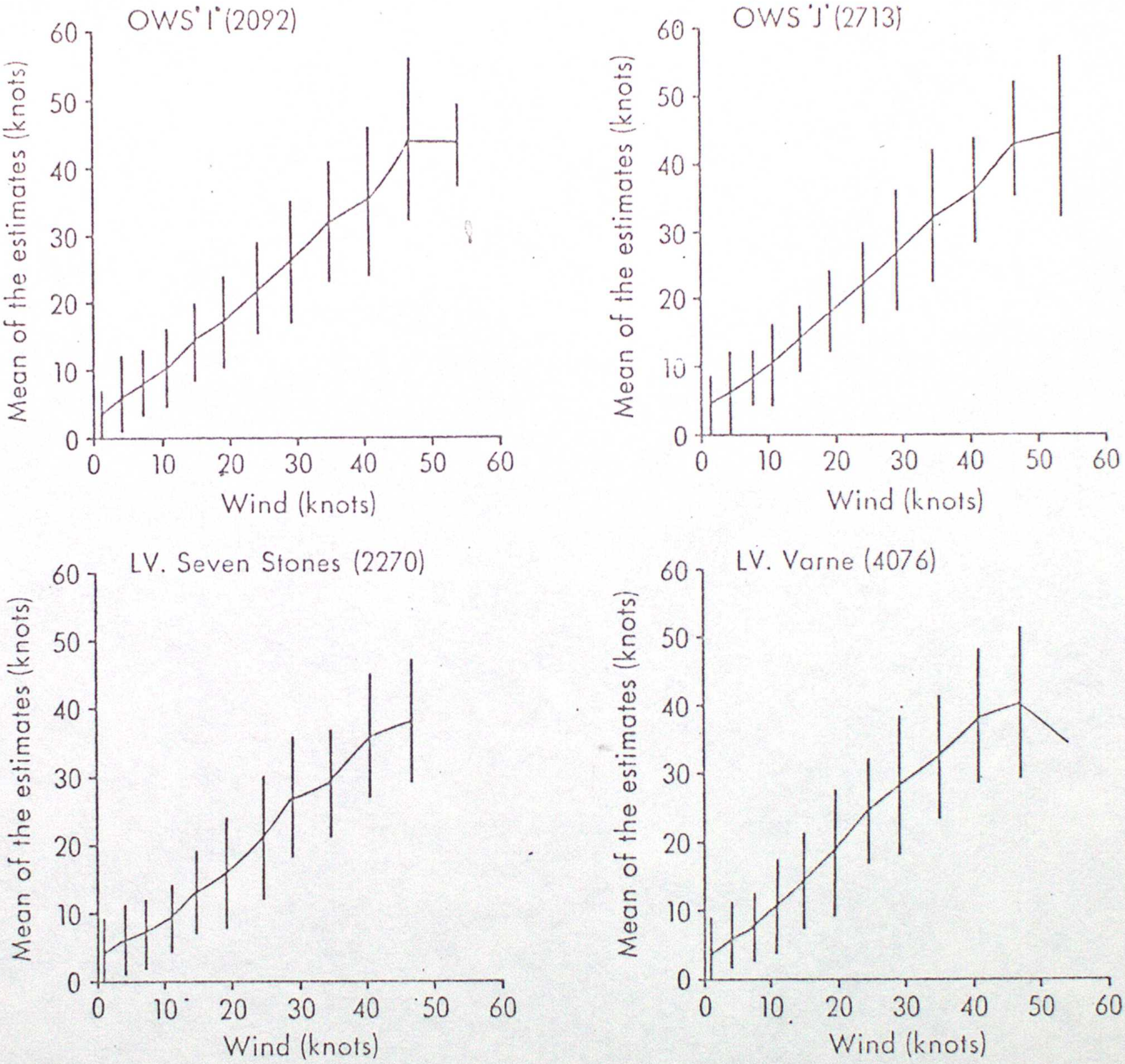
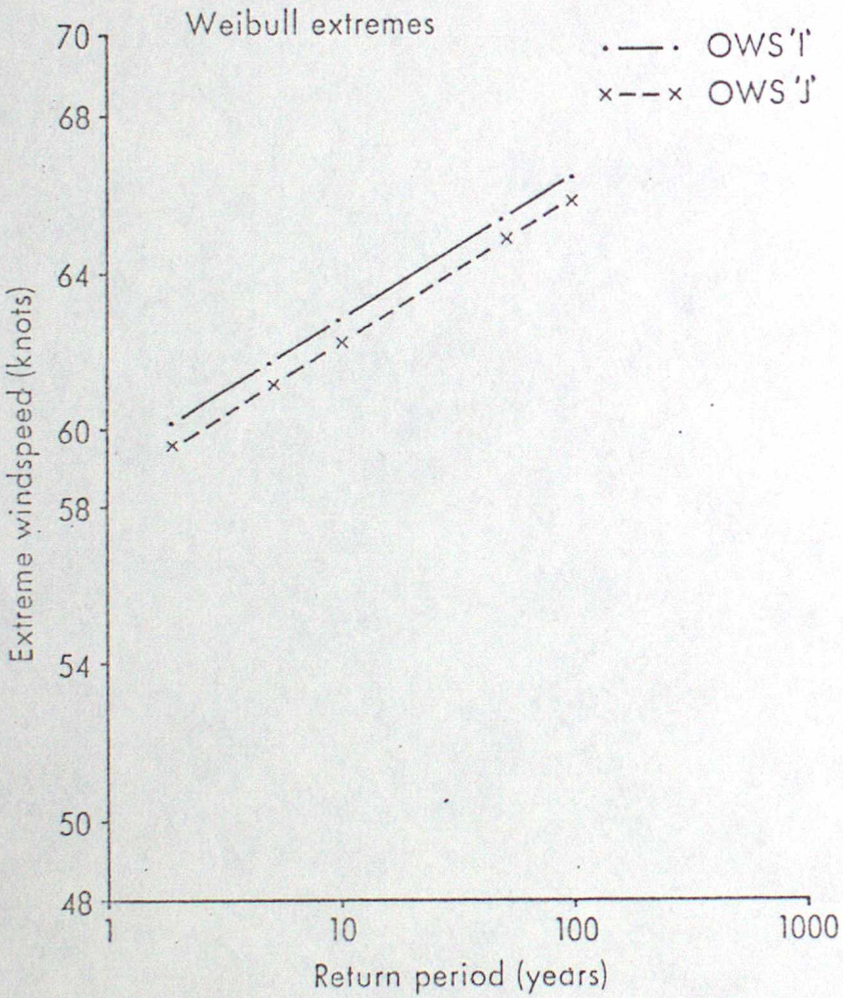
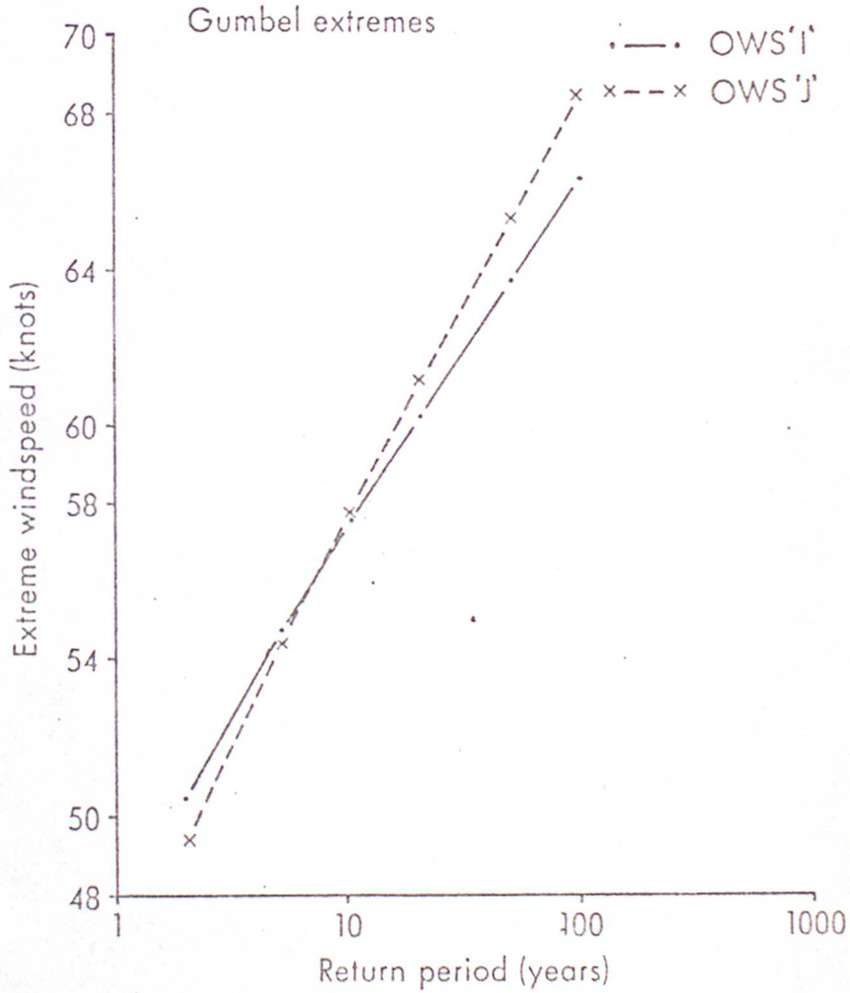


Figure 4. Extreme values of wind speeds for OWS 'I' and OWS 'J' derived from Weibull and Gumbel distributions.





PART II

Wave heights estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions.

WAVE HEIGHTS ESTIMATED BY THE VOLUNTARY OBSERVING FLEET COMPARED WITH INSTRUMENTAL MEASUREMENTS AT FIXED POSITIONS

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1. Introduction

For many years estimates of wave conditions at sea have been made by the deck officers of merchant ships. These merchant ships form the Voluntary Observing Fleet (VOF) which provides valuable meteorological and climatological data from the seas and oceans of the world.

In recent years the increase in offshore construction work has produced a need for knowledge of wave conditions including frequency distributions and extremes. Instrumentally measured wave heights are now available from a number of locations around the world, but generally these records are for short and often incomplete periods only and it is still necessary to utilise the many years of estimated data aready archived on a global basis. In order to do this the accuracy of the estimates of wave conditions must be determined by comparison with the measured wave data.

2. Data Sources

Measured wave heights were compared with estimated wave heights from the $2^\circ \times 2^\circ$ areas surrounding each site at which instrumental measurements were made. The positions of these twelve sites are shown in figure 1(a) together with ocean weather stations (OWS) 'I' and 'J'. Figure 1(b) shows the areas around each instrumental site, except for OWS 'L' which is an oceanic site and well exposed from all directions.

The instrumental data were of significant wave heights whereas the visually estimated data comprised wind wave and swell wave heights.

a) Visually estimated wave heights

Visually estimated data were available for the period 1961–1978 and consisted of wind wave and swell wave heights, randomly distributed in space and time throughout the area.

i) Observations of wave heights

The deck officer is required to report estimates of both wind wave and swell wave heights when it is possible to distinguish between the two. The actual instructions for making these estimates can be found in more detail in the Marine observer's handbook, but briefly the estimate should be made from observation of at least 20 waves, the method depending on whether the length of the wave is longer or shorter than the length of the ship. It is noted that in general there is a tendency to overestimate the height of waves with short wavelengths and underestimate those with long wavelengths. At night or in poor visibility the observer has difficulty in reporting wave heights and often will be unable to report at all.

Visual estimates of wave heights are made in the same way by observers on board ships at the OWS. The data sets of wave heights from the OWS consist of regular observations made at the same location. A comparison of such data with the randomly observed data from the VOF was made for the three OWS, 'I', 'J' and 'L'. For OWS 'L' the regularly observed estimates could also be compared with the instrumentally measured wave heights available at that site.

For comparison with the measurements of significant wave heights it is necessary to combine wind wave and swell wave estimates since it is this combination of all wave conditions that equates with the significant wave. An equivalent significant wave height, here called the resultant, R, can then be found using a formula derived by Nordenstrøm (1971):

$$R = 1.68c^{0.75}$$

where

$$c = \sqrt{(\text{wind wave})^2 + (\text{swell wave})^2}.$$

Consequently, only those occasions when both wind wave and swell waves had been reported were used in the analysis.

ii) Coding of wave heights

The observer is required to report the estimated wave height using a code figure. The period covered by the VOF data used in this study was 1961-1978, this period includes a change in the coding practice. On 1 January 1968 the code figures for wave heights changed from those shown in Table I(a) to those in Table I(b). Prior to 1968 the wave heights were reported using code figures 0-9. This required an addition of 50 to the estimation of the wave direction for wave heights greater than four and a half metres.

From the beginning of 1968 code figures from 01-49 were used which did not involve changes to the report of wave direction for any height.

The wind wave and swell wave height distributions were examined for the pre- and post-1968 periods but no evidence was found that there had been a marked reduction in reports of five metre wave heights before the code change compared with those made afterwards. The major difference between the pre- and post-1968 distributions is the lower number of observations in the former period. In ten of the twelve areas the pre-1968 observation count for the resultant wave heights was less than half that post-1968, and just over half for the remaining two. The pre-1968 period covers only seven years whereas eleven years of data were available post-1968. This could account for some but not all of the discrepancy.

Another change in the coding practice was that before 1968 the same code was used for both wind waves and swell. The first group reported referred to the wind waves, and subsequent groups to swell. Since 1968 one code has been used for the wind waves and a different one for swell, with two or more groups being used in the event of more than one swell wave train. This may have encouraged the reporting of a separate swell wave and may account for the increased number of resultant waves in the post-1968 period.

b) Instrumental wave heights

The wave height derived from instrumental recordings is known as the significant wave height, h_s. Originally this was defined as the mean height of the highest one third of waves sampled. It is now defined in terms of the variance of the sea surface elevation, m_o (Tann 1976) such that:

$$h_s = 4\sqrt{m_o}$$

Wave heights can be measured using several kinds of device. Those involved here are the waverider buoy (WRB) and the shipborne wave recorder (SBWR).

The WRB contains an accelerometer which measures vertical displacement as the buoy rides the waves. Thus, it records the variability of the sea surface elevation about the mean-sea level.

The SBWR consists of two pairs of accelerometer and pressure units. These are located one on each side of the ship, approximately on the pitch axis. When the waves are of longer wavelength than the length of the ship the accelerometers measure vertical displacement as in the WRB. For waves with wavelength shorter than the length of the ship, the pressure units detect variations in pressure as the waves pass by.

The precise method of obtaining the significant wave heights from the recording device depends on the agency responsible. As an example, for wave recorders belonging to the Institute of Oceanographic Sciences, the waves are recorded over an approximate 15-minute period every three hours. Significant wave heights are then calculated using the Tucker/Draper method (Tann 1976).

Table II lists the stations with measured wave data together with the period of measurement and number of observations. The corresponding numbers of resultant estimated wave observations for the 18-year period 1961-1978 are also shown.

For three of the sites there are two data sets, one from WRB measurements and one from SBWR measurements. These three sites are Stevenson, FitzRoy and Boyle, manned by ships sponsored by the United Kingdom Offshore Operators Association (UKOOA).

At the South Uist site there are two data sets of WRB measurements, one from a position 10 miles offshore in 42 m of water and the other 5 miles offshore in 14.5 m of water.

3. Analysis of data

a) Distributions of resultant estimated wave heights

As with most meteorological data used for climatological purposes some quality control is necessary. The normal sequential checks and areal comparisons are difficult for ships of the VOF because of their random distribution in space and time. Comparison of the wave heights with the corresponding wind speed estimate provides a rather crude method of quality control, but one which eliminates the more obviously incorrect wave heights.

However, there were still several values in each data set producing a distribution with a long 'tail' of higher wave heights. In each case this tail consisted of resultant wave heights derived from estimates made in the post-1968 period. The most likely reason for this is the larger sample of wave heights present in the longer post-1968 period, allowing a greater likelihood of sampling more high waves.

The percentage frequency distributions of the resultant wave heights for each site are shown in figure 2. With the exception of OWS 'L' with the mode at three metres, all of the distributions have the mode at two metres and contain some zero wave heights.

i) Visual estimates of wave height by OWS observers

There are three data sets available for comparison at the OWS 'L' site; the measured (SBWR) significant waves, the estimates made by the VOF in the surrounding area, and those made by the OWS observers. Figure 2 shows the percentage frequency distributions of the wave heights in these three data sets. The distributions of measured wave heights and the resultant waves derived from the VOF estimates agree reasonably well, but that for the OWS estimates is rather different having a mode of five metres. Visual estimates from OWS 'I' and 'J' were examined to check that the difference was not due to the short period of data available from OWS 'L' (1975-1979). The distributions of resultant wave heights from OWS 'I' and 'J' spanned the period 1961-1975 and the corresponding VOF estimated wave heights the years 1961-1978. Figure 3 shows that for these locations also the OWS mode is higher than that of observations from the VOF. Examination of distributions of simultaneously observed data showed the same difference, thus eliminating the possibility that it is due to the comparison of regularly observed with randomly observed data.

Informal discussion with observers from the Meteorological Office who have worked on ships manning OWS indicates that the opinion of the deck officer is usually sought when estimating wave height. Consequently, this difference is unlikely to be due to the inexperience of the observers of conditions at sea.

Another possible explanation is that the ships at the OWS do not usually steam in wind speeds below Beaufort force 5. When this wind speed is exceeded the ships need to steam to remain on station. When 'stationary' the ship will be subjected to much more pitching and rolling than when steaming. It is possible that wave heights are overestimated when the ship is stationary and this could explain the low percentages of zero and one metre wave heights and also the shift in the peaks of the distributions. The point at which it becomes necessary to steam to stay on station will vary with the state of the sea, and so Beaufort force 5 is only an estimate. Unfortunately, there is no indication of whether or not the ship was steaming when an observation was made and so this explanation cannot be tested.

ii) Period of VOF data used

The resultant wave height distributions derived from estimates made by the VOF all cover the period 1961-1978. The distributions of measured data with which the resultant waves were to be compared covered varying periods as shown in Table II. Values for Brent B are not shown since the WRB data is still subject to confidentiality rules. Because of the short periods of measured data involved, the number of resultant waves available in the equivalent periods was too small for reasonable comparison, and so for each data set the distribution of waves from the whole period of VOF data was used. The similarity of the wind climatologies at the sites for both the short and long periods indicated that such comparisons were reasonable.

b) Distributions of instrumental significant wave heights

The percentage frequency distributions of instrumentally measured significant wave heights are shown in figure 2. The four light-vessels (LVs) Shambles, Varne, Owers and Mersey Bar have distributions with rather different characteristics from the others. Here the measured data are compared with estimates made over a large area. Many of the estimates will have come from comparatively more exposed positions (see figure 1(b)). The data sets for these LVs cover very short periods, one year for each except Owers which covers almost two years. The other LV, Seven Stones, is in a more exposed position, as are the two South Uist sites, although both are fairly close inshore. The South Uist site five miles from the coast does show a slightly higher percentage of low wave heights as would be expected.

For Seven Stones LV and the two South Uist sites there were no zero wave heights recorded and the mode of each distribution, occurs at two metres. At all sites, except for the four LVs already discussed, no zero wave heights were recorded. The distributions for Famita, Stevenson (WRB) and Boyle (both SBWR and WRB) also have the mode at two metres. Except for OWS 'L', the remaining sites have produced distributions of significant wave height with no clear peaks, but similar percentage frequency of occurrence for wave heights of two and three metres. For OWS 'L' there was a low percentage frequency for wave heights of one metre with the mode at four metres. OWS 'L' is the only oceanic position considered in this study and the higher modal wave height reflects the different regime.

All of these data sets cover only short periods of time. There are only two with more than four years of data; Seven Stones LV, 1968-1978, but with data for the whole of 1970 and twenty other complete months missing; Famita has data covering a period of nine years, but the bulk of the measurements were made during the winter months and only 32 per cent of the possible total number of observations were available.

Figure 2 shows that the distributions of instrumentally measured and visually estimated wave heights differ at all sites. The bulk of the observations agree reasonably well, but large differences occur in the lower and higher ranges. The greatest discrepancies occur at the LVs Shambles, Varne, Owers and Mersey Bar. The VOF data for these locations were taken from the surrounding area, often from more exposed positions some distance from the instrumental site.

c) Extreme-value analysis

For the design and planning of offshore structures it is necessary to have an estimate of the extreme sea conditions likely to be experienced during the expected lifetime of that structure. Extreme values are estimated by fitting a distribution to the available data, and extrapolating the tail of the distribution to the value having a cumulative probability of exceedance corresponding to the return period required. This gives the value expected to be exceeded, on average, once in N-years, where N is the return period.

Many distributions used to estimate the extreme values require the identification of annual maxima. This means that long periods (more than ten years) of regularly observed data are required. Consequently, these methods cannot be used for estimating extreme wave heights from the distributions shown in figure 2 since the measured data available cover only a few years and the estimated data are not regularly observed.

The method used here to estimate extreme wave heights was to fit a three parameter Weibull distribution to the whole spectrum of data.

In practice, when fitting a Weibull distribution to wave heights, it is often necessary to alter subjectively the boundaries of the frequency distribution of the data. This is particularly so when dealing with data collected from the VOF which is random and therefore may give an irregular and unrepresentative distribution in the higher frequency ranges. It has already been noted that, even after some quality control to remove the obviously incorrect wave heights, there is still a long tail of higher wave heights. Where some subjective alteration appeared to be required the estimated extreme values were very similar to those estimated from the unaltered distribution.

This problem did not occur with the distributions of measured wave heights which were quite smooth throughout the ranges used.

4. Results

The 1 in 50-year extremes derived from the significant and resultant wave height distributions are shown in Table III. The whole 18-year period of data was used for the resultant wave height analysis. The extremes estimated from the significant wave heights measured by SBWR were converted to the equivalent WRB height (Graham et al 1979).

The results for the four LVs, Shambles, Varne, Owers and Mersey Bar are not comparable because of the difference in the distributions due to the large area from which the VOF data were taken covering more exposed seas than those at the LV sites. It is probable that the same reason also accounts for the large difference in estimated extremes at the 'inshore' South Uist site.

In every other case the extremes estimated from the distributions of resultant wave heights are higher than those derived from the significant wave heights. The mean difference is five metres. This represents considerable difference in the 1 in 50-year extreme wave height between the resultant wave height distributions and the measured waves. However, it is important to remember that the measured data sets cover only very short periods and it may be that more extreme situations would be sampled over longer periods reducing the apparent over-estimation of the extreme conditions derived from the visual data. The variability of the percentage frequency of occurrence of wave heights is illustrated in figure 4. This figure shows the percentage frequency of occurrence of wave heights in two ranges for 10 years of data from the LV Seven Stones. It is apparent that the choice of data from the years 1972-1974 would indicate different long term characteristics than data from the years 1975-1978.

Extreme values were also derived from the distributions of resultant wave heights obtained from visual estimates made by OWS observers. The 1 in 50-year extremes are shown in Table IV together with the extremes estimated from the corresponding VOF data. Despite the shift to a higher modal wave height the extremes estimated from the OWS resultant wave heights are lower than those from the VOF resultants. The 1 in 50-year extreme value of 17 metres derived from the instrumental data at OWS 'L' indicates that the OWS resultant distribution underestimate the extremes.

5. Conclusion

With a few exceptions, the measured significant wave heights which are available cover very short periods of time and so, despite the high quality of the measurements, their use is limited both climatologically and especially for the estimation of extremes.

The main advantage of the estimated data is that it covers long periods of time and is available for all sea areas. Individually, these data are of much poorer quality being far less accurate than measurements of wave height. However, the bulk of each distribution is probably sufficiently accurate to give an estimate of the overall wave climatology. Unfortunately, because of the difficulties in estimating sea and swell separately many of the resultant wave heights will be incorrect representations of conditions at the time of observation. The distributions are markedly affected in the higher wave height ranges and consequently difficulties are again created in the estimation of extremes.

Obviously, neither the instrumentally measured data available at present, nor the visual estimates are sufficient for current needs if used separately. Where possible both kinds of data should be used to give the most complete overall picture. When the visual estimates of wave height are the only source of information available they should be used with caution, bearing in mind the differences known to exist between estimated and measured data especially with regard to the tail of high wave heights of doubtful accuracy. Instrumental records equally should be used with caution because of the short length of record and their incompleteness.

Earlier work comparing visually estimated wind speeds with instrumental measurements concluded that the winds reported by the VOF can be used with confidence to derive a wind climatology where no reliable measured data are available (Graham, 1982). The National Maritime Institute is developing a wave climate model by combining visually estimated wind speeds and wave heights, together with measured wind and wave data and wind/wave relationships.

However, such a modelled wave climate does not provide a solution to the problem of estimating extreme wave heights. Extremes do not occur in average conditions and, therefore, cannot be described by models based on average relationships.

6. References

Tann, H. M.	1976	The estimation of wave parameters for the design of offshore structures. IOS Report 23, (unpublished manuscript).
Meteorological Office	1977	Marine observer's handbook. London, HMSO.
Graham, C. C., Verboom G., and Shaw, C.J.	1979	Comparison of shipborne wave recorder and waverider buoy data used to generate design and operational planning criteria New York, Amer. Soc. Civil Eng., Proc. 16H. Coast. Eng. Conf. 1, pp. 97-113.
Nordenstrøm, N.	1971	Methods for predicting long-term distributions of wave loads and probability of failure for ships. Part 1. DnV-Report No. 71-2-5, Oslo.
Graham, A. E.	1982	Winds estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions, Meteorol Mag., 111, 312-326.

Figure 1(a) Positions of fixed stations used in the analysis.

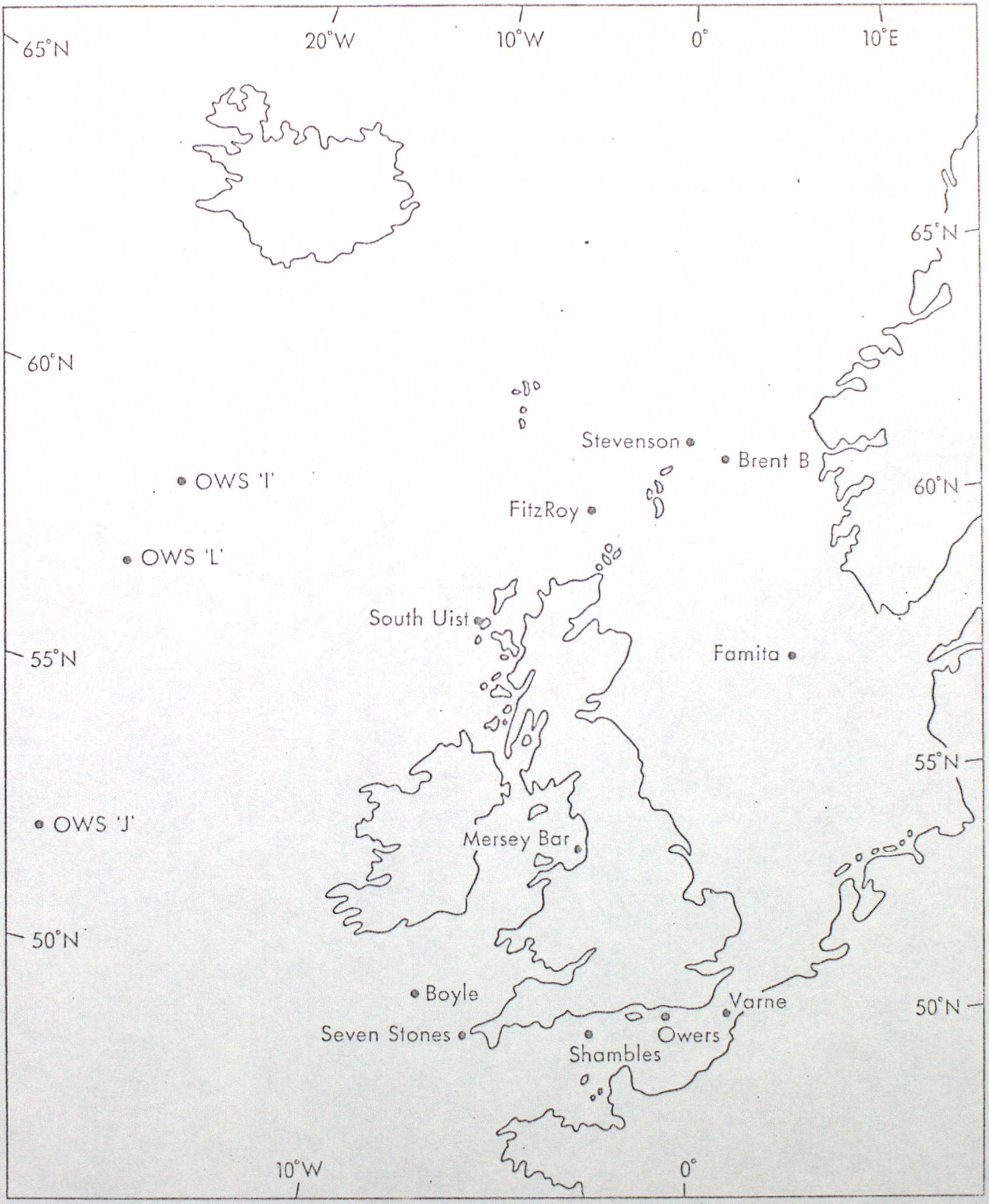


Figure 2(a). Wave-height frequency distribution for LV. Shambles and LV. Owers compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station

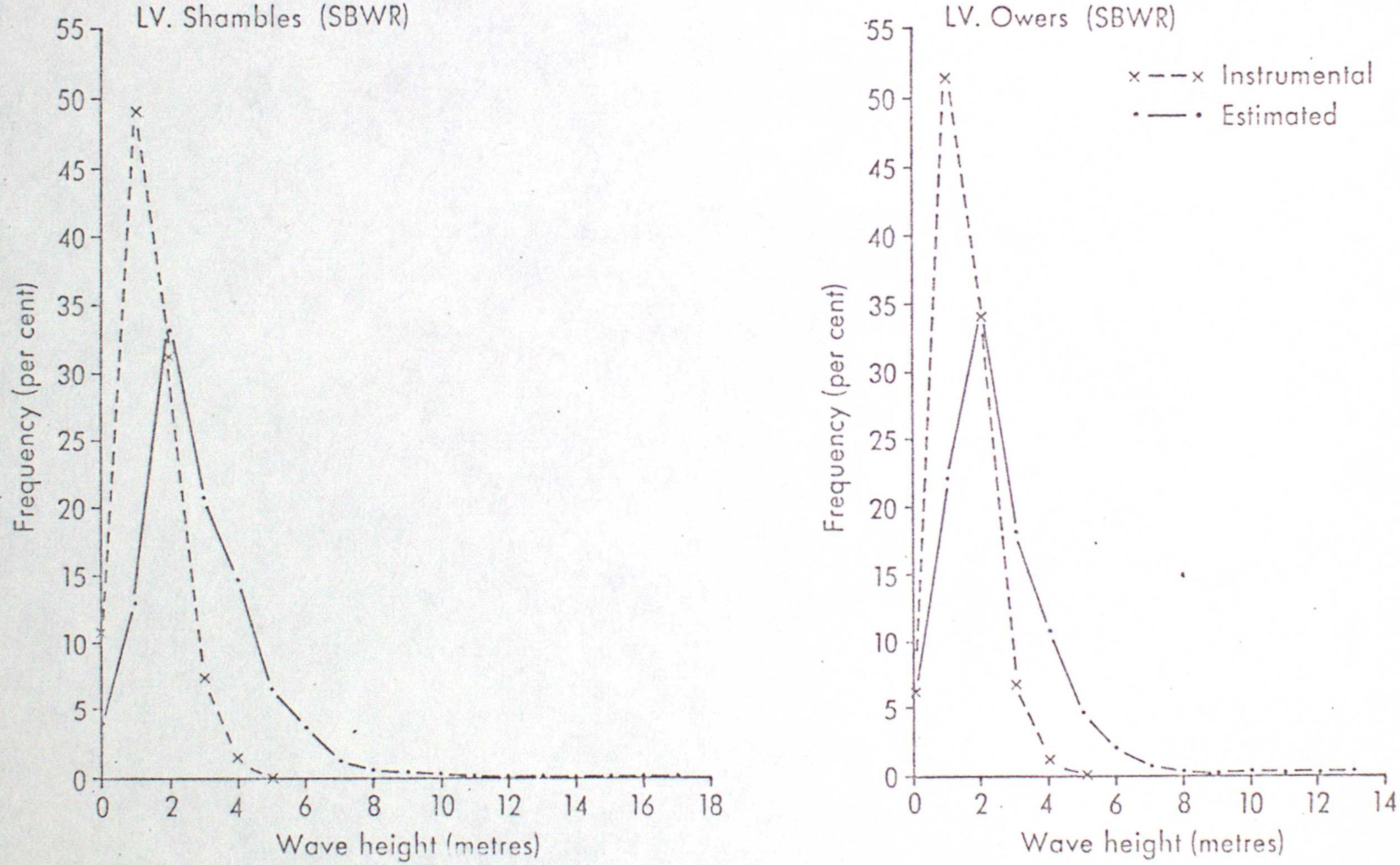
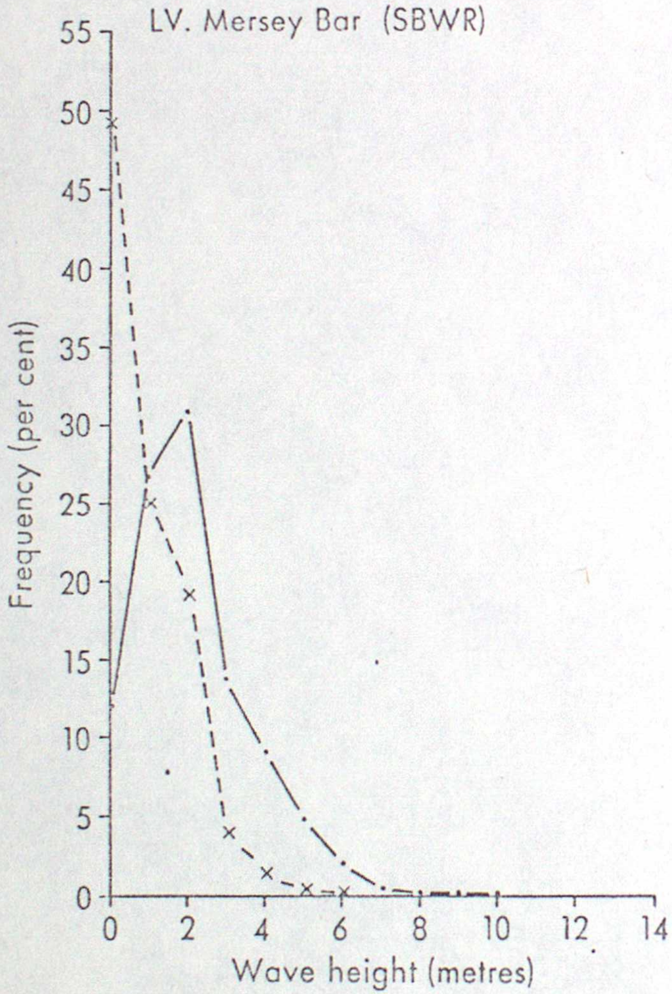
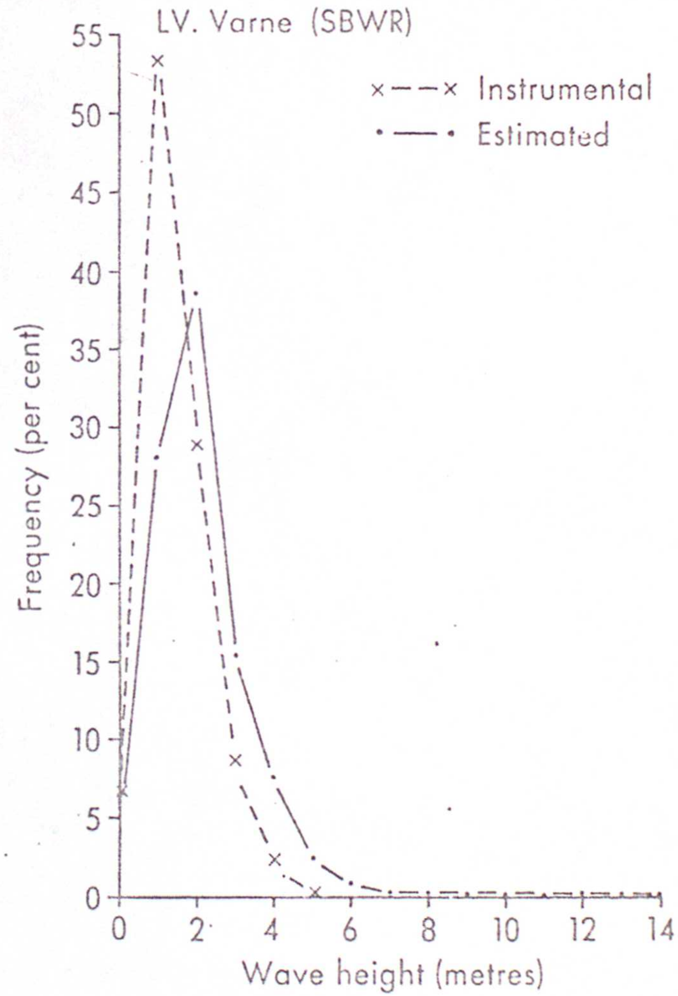


Figure 2(b). Wave-height frequency distribution for LV. Mersey Bar and LV. Varne compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station





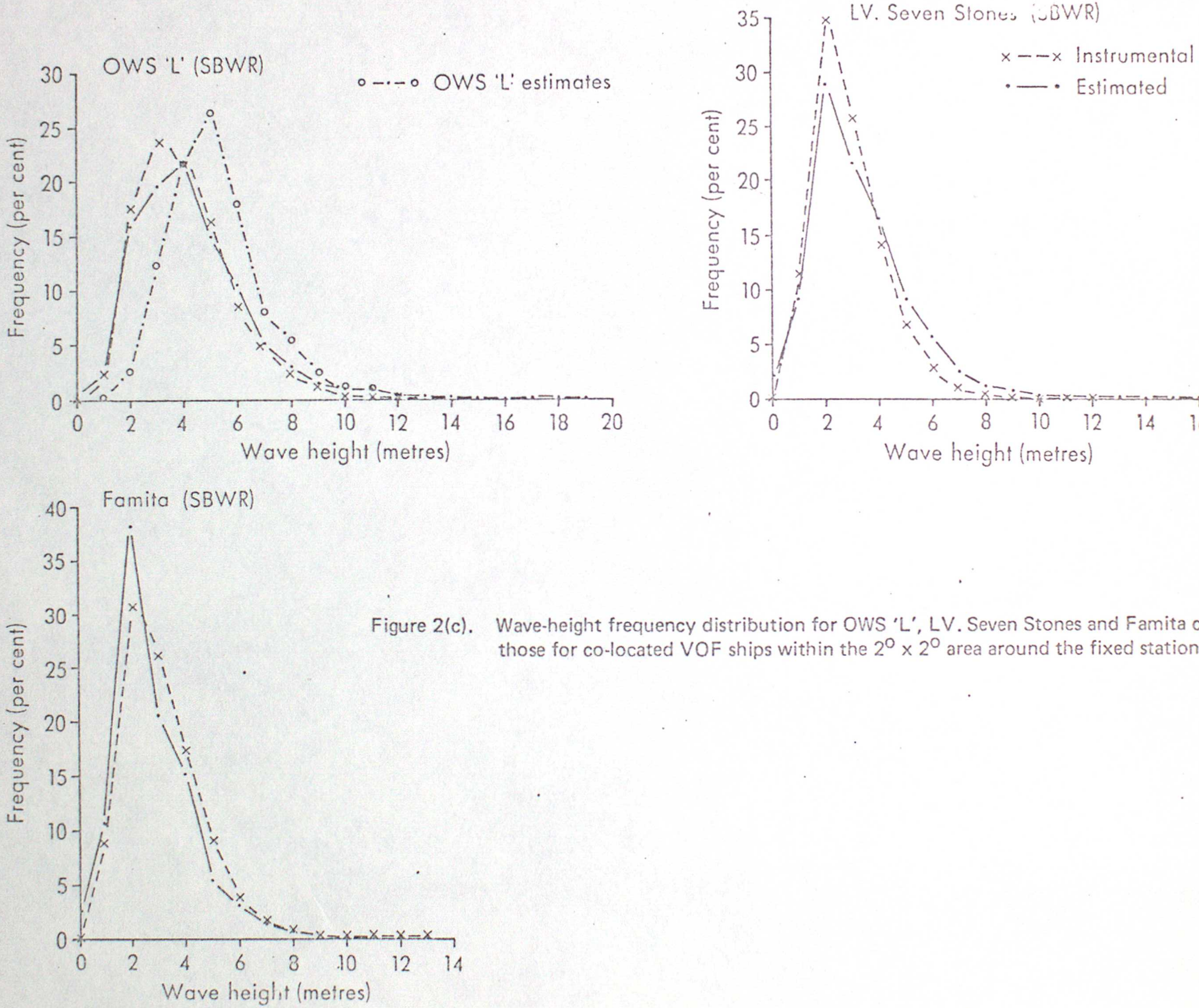


Figure 2(c). Wave-height frequency distribution for OWS 'L', LV. Seven Stones and Famita compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station

Figure 2(d). Wave-height frequency distribution for Stevenson and Boyle compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station

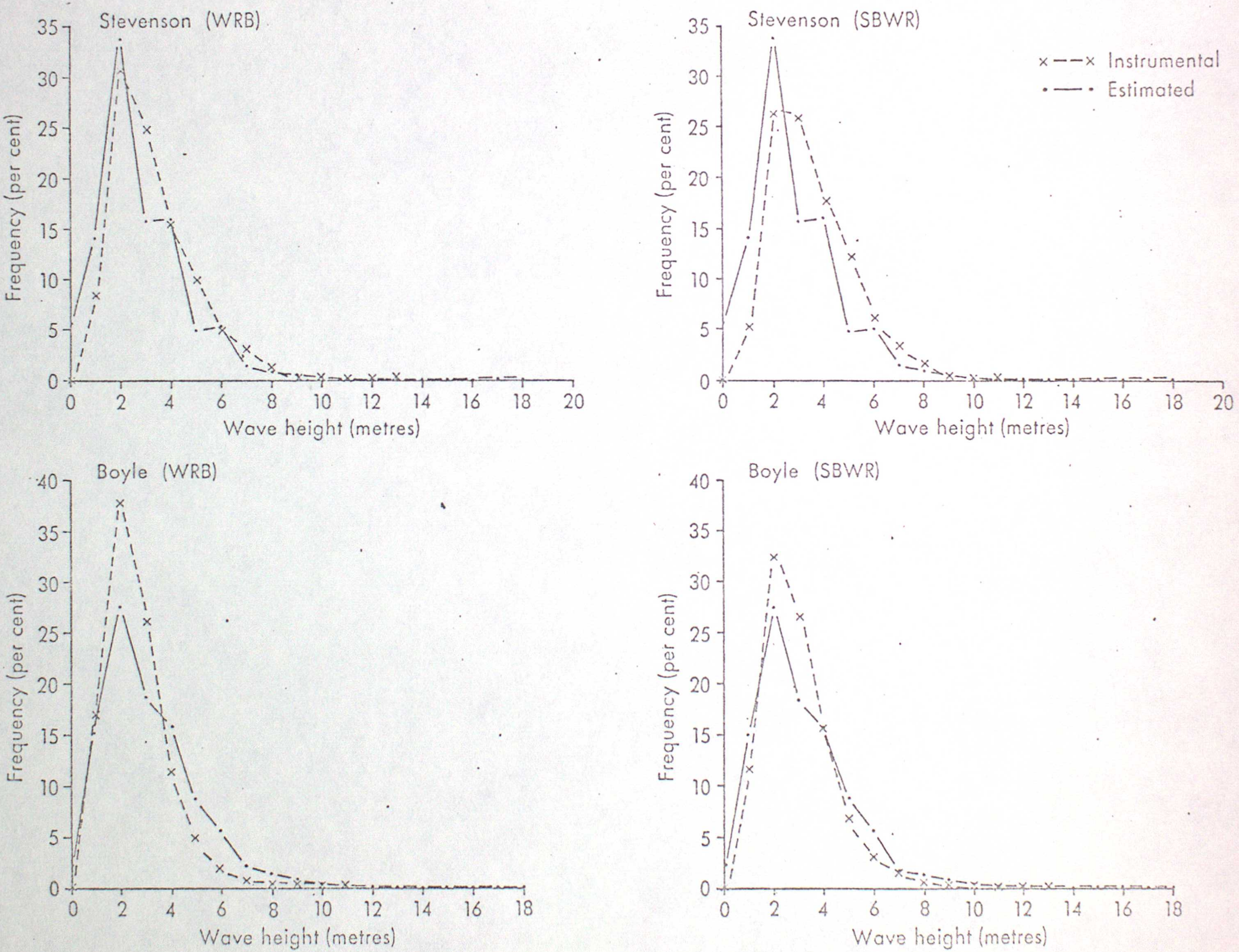


Figure 2(e). Wave-height frequency distribution for Fitzroy compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station

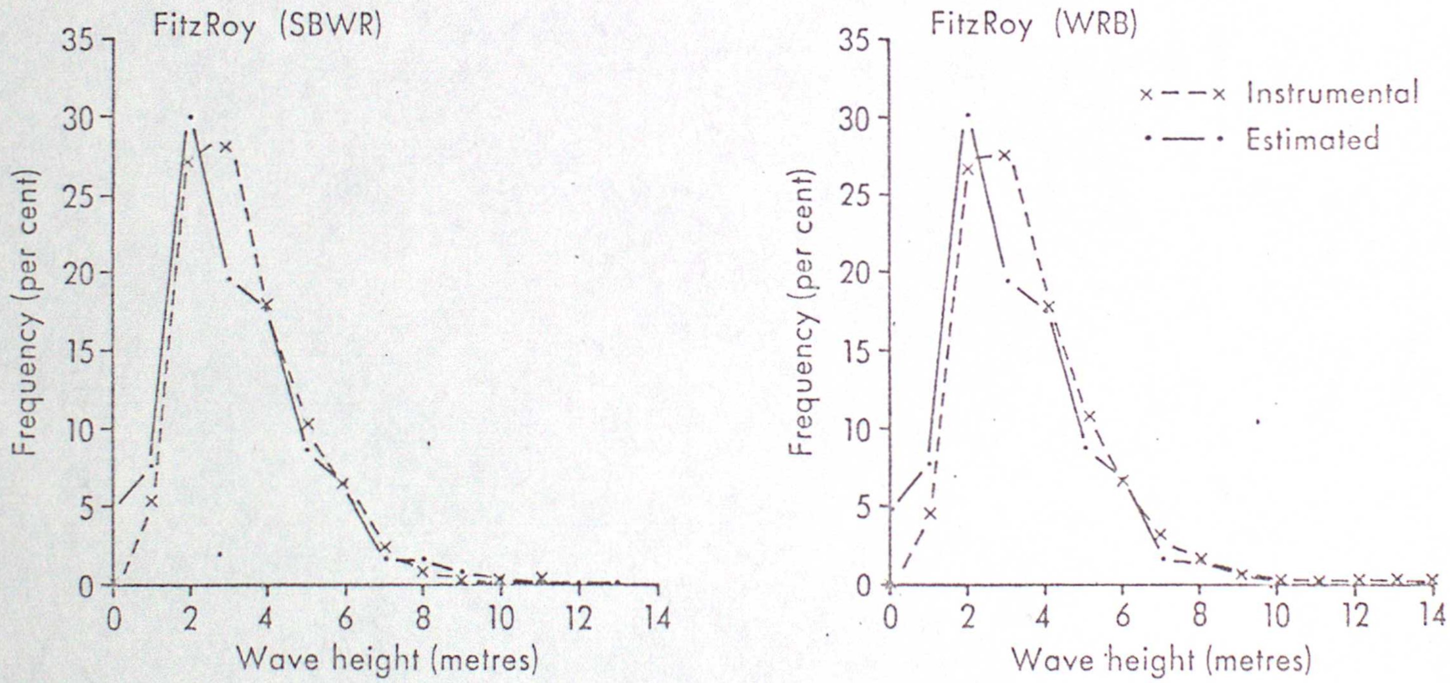


Figure 2(f). Wave-height frequency distribution for South Uist compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the fixed station

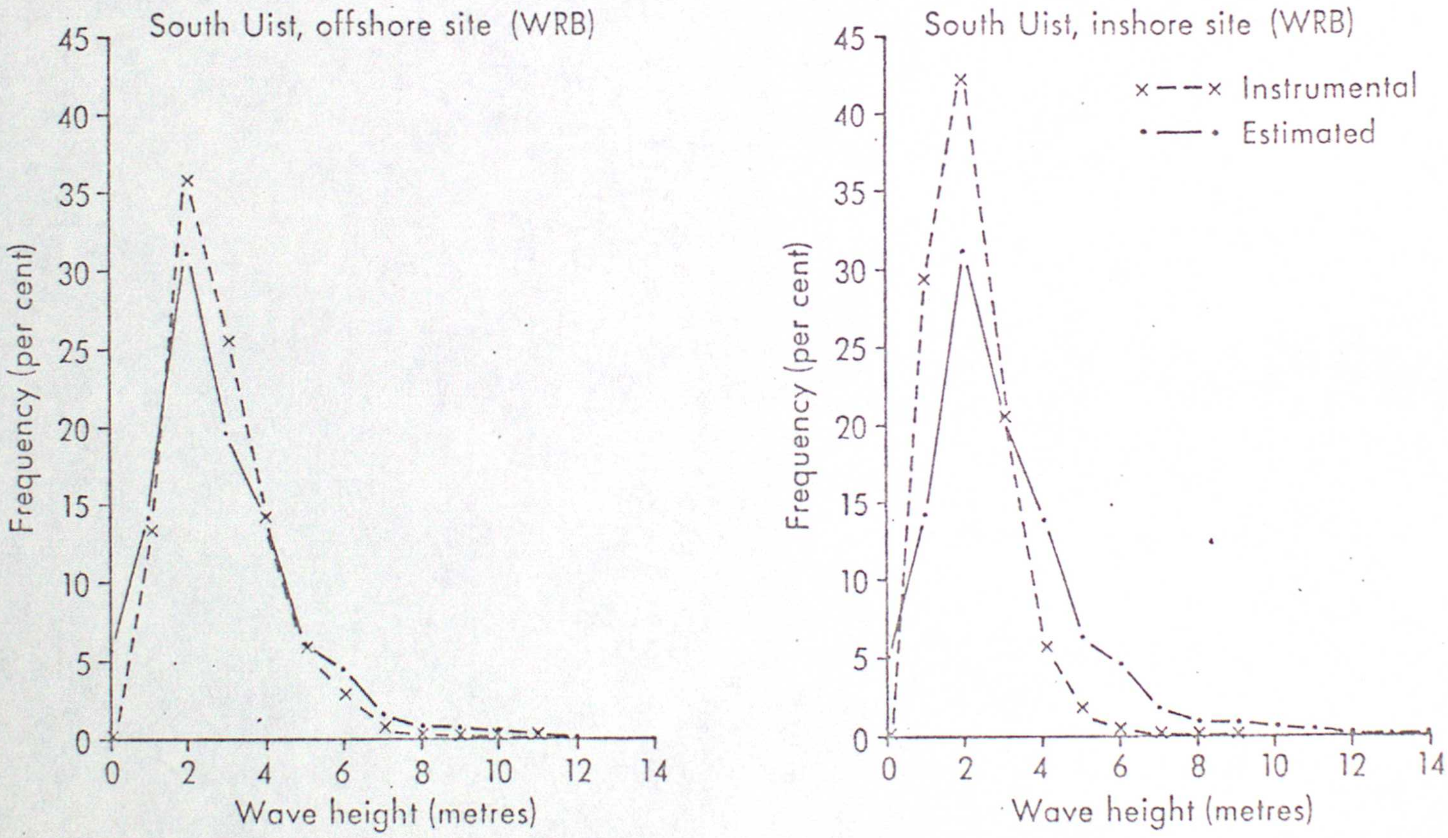
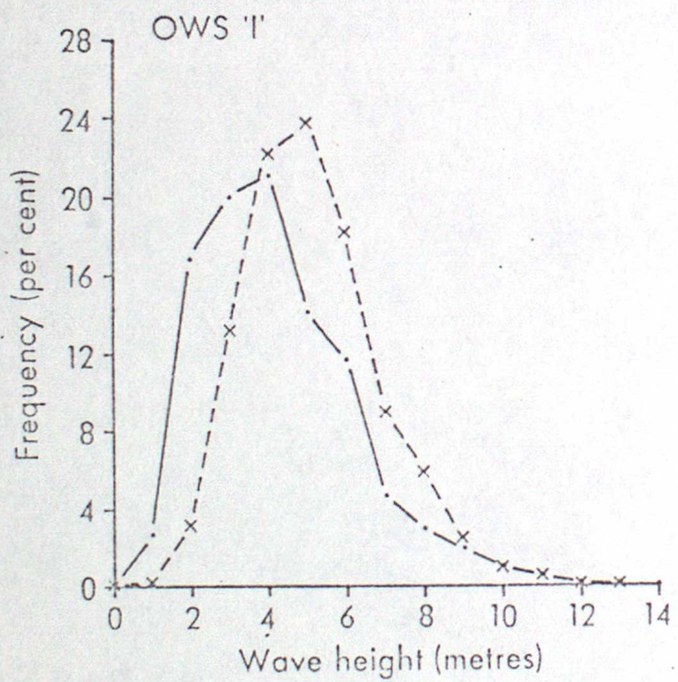


Figure 3. Wave-height frequency distribution for OWS 'I' and OWS 'J' compared with those for co-located VOF ships within the $2^{o} \times 2^{o}$ area around the OWS



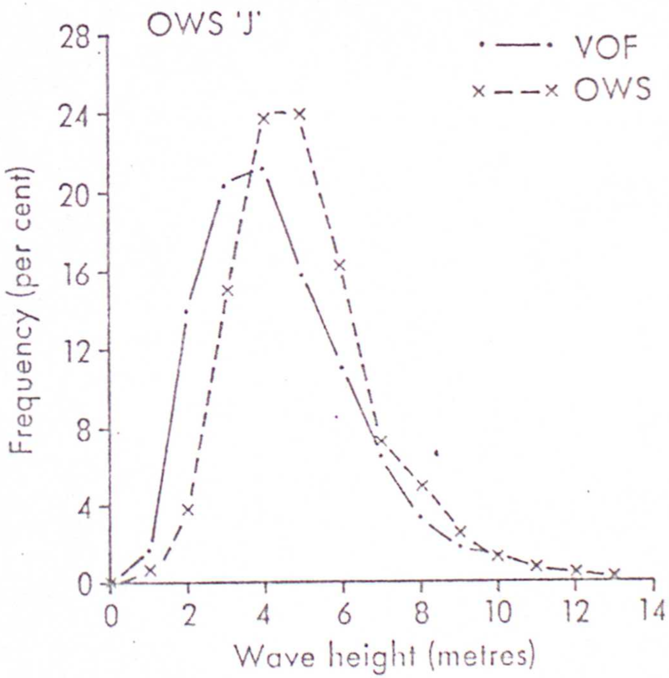


Figure 4. Percentage frequency of waves in each year at LV. Seven Stones for wave heights 2.5 – 4 m and 4.5 – 6 m inclusive

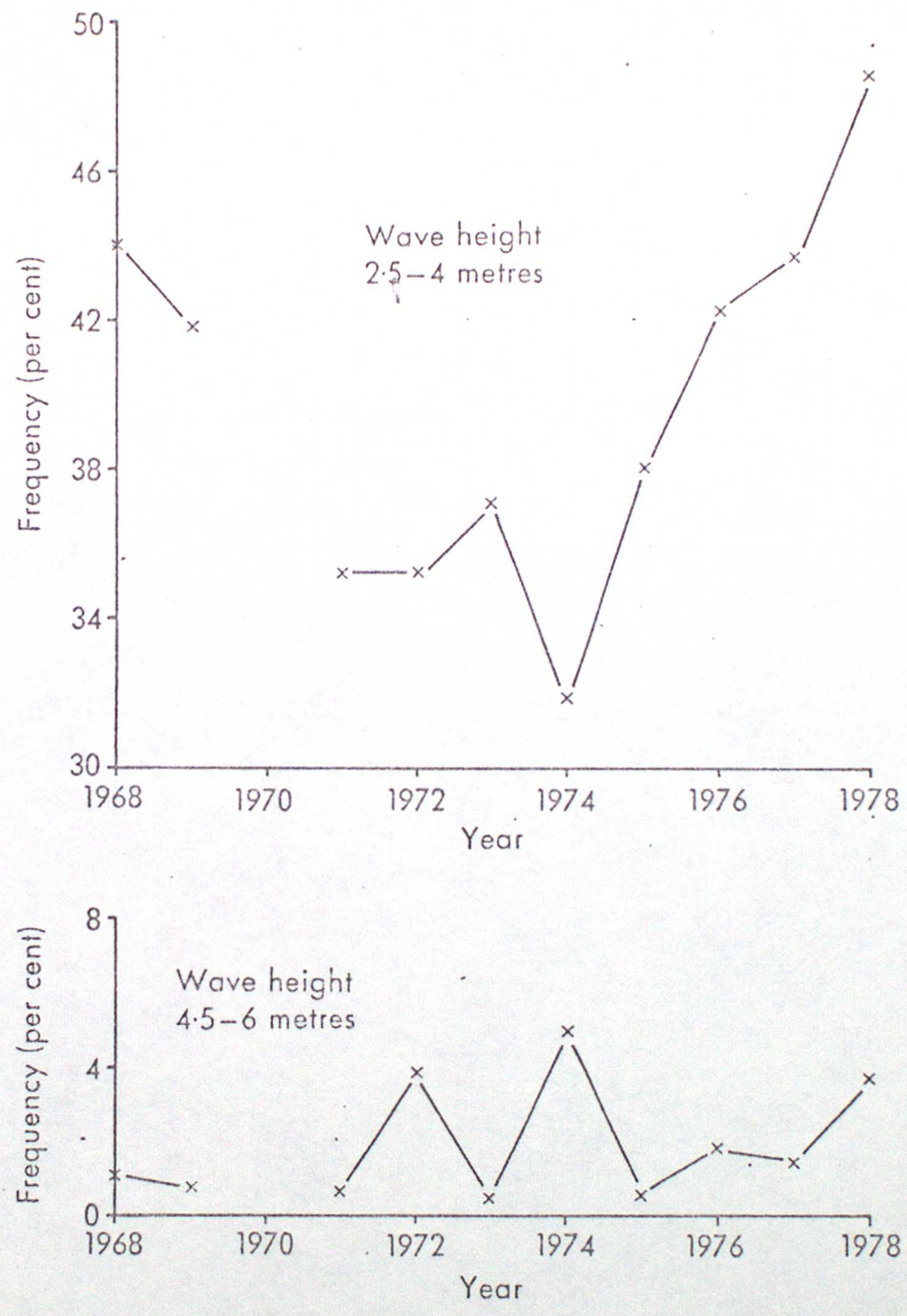


Figure 1(b). Positions of fixed stations and areas from which the VOF data were taken

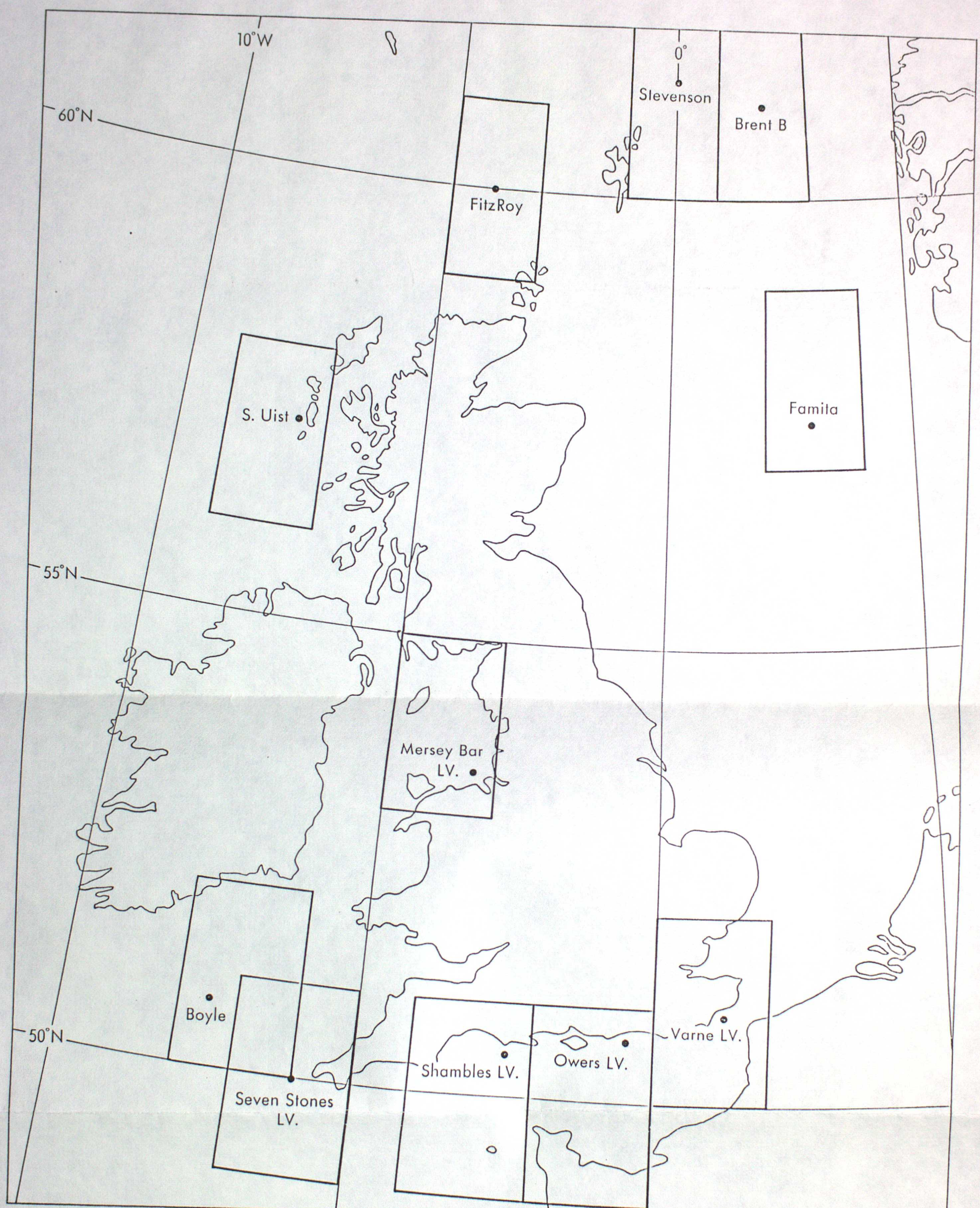


Table I(a) Wave height code table pre-1968

Code figure	Height in feet	Height in metres	Code figure (50 added to wave direction)	Height in feet	Height in metres
0	< 1	< 0.25	0	16	5
1	1.5	0.5	1	17.5	5.5
2	3	1	2	19	6
3	5	1.5	3	21	6.5
4	6.5	2	4	22.5	7
5	8	2.5	5	24	7.5
6	9.5	3	6	25.5	8
7	11	3.5	7	27	8.5
8	13	4	8	29	9
9	14	4.5	9	30.5	9.5

Table 1(b) Wave height code table post-1968

Code figure	Height in metres	Height in feet	Code figure	Height in metres	Height in feet
1	0.3	1	25	12.5	41
1	0.6	2	25	12.8	42
2	0.9	3	26	13.1	43
2	1.2	4	27	13.4	44
3	1.5	5	27	13.7	45
3	1.8	6	28	14.0	46
4	2.1	7	29	14.3	47
5	2.4	8	29	14.6	48
5	2.7	9	30	15.0	49
6	3.1	10	30	15.2	50
7	3.3	11	31	15.5	51
7	3.7	12	32	15.8	52
8	4.0	13	32	16.1	53
9	4.3	14	33	16.5	54
9	4.6	15	34	16.8	55
10	4.9	16	34	17.1	56
10	5.2	17	35	17.4	57
11	5.5	18	35	17.7	58
12	5.8	19	36	18.0	59
12	6.1	20	36	18.3	60
13	6.4	21	37	18.6	61
13	6.7	22	38	18.9	62
14	7.0	23	38	19.2	63
15	7.3	24	39	19.5	64
15	7.6	25	40	19.8	65
16	7.9	26	40	20.1	66
16	8.2	27	41	20.4	67
17	8.5	28	41	20.7	68
18	8.8	29	42	21.0	69
18	9.1	30	43	21.3	70
19	9.5	31	43	21.6	71
19	9.7	32	44	21.9	72
20	10.1	33	45	22.3	73
21	10.4	34	45	22.6	74
21	10.7	35	46	22.9	75
22	11.0	36	46	23.2	76
23	11.3	37	47	23.5	77
23	11.6	38	48	23.8	78
24	11.9	39	48	24.1	79
24	12.2	40	49	24.4	80

Table II. Availability of measured wave data and estimated data which were used in the analysis.

Station	Type of Measurement	Period of Measured Data	Number of measured observations	Number of estimated observations during 1961-78
Famita	SBWR	69 - 77	8566	8183
Lima	SBWR	75 - 77	5188	2835
Seven Stones	SBWR	68 - 78	24369	11899
Mersey Bar	SBWR	65 - 66	2919	1475
Shambles	SBWR	68 - 68	2920	12302
Varne	SBWR	65 - 66	3146	9465
Owers	SBWR	68 - 70	4426	10535
Stevenson	WRB	73 - 76	6028	5520
Stevenson	SBWR	73 - 76	5370	"
Fitzroy	WRB	73 - 76	4589	2972
Fitzroy	SBWR	73 - 76	5008	"
Boyle	WRB	74 - 77	7175	6032
Boyle	SBWR	74 - 77	7029	"
South Uist (Offshore)	WRB	78 - 80	9342	1665
South Uist (Onshore)	WRB	78 - 80	3714	"

Table III. Once in 50 year extreme values for all datasets of measured wave heights and the corresponding VOF resultant wave heights.

Station	Extremes derived from significant waves	Extremes derived from resultant waves
	metres	
Famita	13	16
Lima	17	19
Seven Stones	12	17
Mersey Bar	8	12
Shambles	5	17
Varne	5	16
Owers	5	15
Stevenson (WRB)	14	21
Stevenson (SBWR)	13	21
Fitzroy (WRB)	14	16
Fitzroy (SBWR)	14	16
Boyle (WRB)	12	20
Boyle (SBWR)	12	20
South Uist (Offshore)	11	15
South Uist (Onshore)	9	15

Table IV. 1 in 50 year extreme values for OWS and VOF resultant waves.

Station	Extremes derived from OWS resultant wave heights	metres	Extremes derived from VOF resultant wave heights
OWS 'L'	15		19
OWS 'I'	15		19
OWS 'J'	14		19