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A CLIMATOLOGY OF EXTREME WAVE HEIGHTS IN THE AUSTRALIAN TROPICS

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ABSTRACT

The procedure devised by Spillane and Dexter (1976) for determining long-term extreme significant wave heights generated by tropical cyclones in the Australian region has been applied at a number of offshore (deep water) points to obtain a climatology of extreme wave heights, as a function of return period, for this region. Basic input data consist of a Gumbel analysis of annual maximum wind gusts in the tropics, extrapolated to over the sea, cyclone occurrence frequencies, and any geographical fetch restrictions which might be applicable at particular points.

INTRODUCTION

The current and expected future lack of recorded cyclone-associated wave data suitable for the derivation of long-term statistics on extreme wave heights and periods over the whole of the Australian tropical waters has led to the development of a number of methods for estimating these statistics, using the meteorological and other data that are available. One such method, devised by Spillane and Dexter (1976), is based on an analysis of extreme cyclone wind gusts, together with the cyclone track histories of Coleman (1972). In addition, this method makes assumptions about the average radii of cyclone maximum wind bands and average cyclone translation speeds in the Australian region, and uses the latest hurricane wave model published by Bretschneider (1972) in arriving at consistent estimates of extreme wave and wind gust values and their associated return periods.

We consider the Spillane and Dexter approach the most satisfactory for deriving an extreme wave height climatology, since it makes the best and most complete use of relevant reliable data as well as providing estimates of return period - an attribute which the ubiquitous 'design cyclone' completely lacks (cf. Nelson 1971). Consequently, we have employed it in obtaining such a climatology for the Australian tropics.

In order to facilitate computation, the procedure has been rewritten in a form suitable for digital analysis, and the resultant program run for a set of selected deep-water points. In addition, the program is available for extreme wave estimates at any other specified locations. Details of the computational method, wind gust analysis, program, and input data requirements are given in Dexter and Watson (1975).

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ANALYSIS

In general, both the method and equations as programmed by us are those detailed in Spillane and Dexter (1976 hereinafter referred to as SD), and so are omitted from this paper. However, since the approach is somewhat complex, and may appear difficult to apply in practice, we have included as Appendix 2 details of the computation, with intermediate probabilities and tabulations, for a particular point (No 64 in Fig 1) located at 22.0°S 152.4°E. All important features of the method, including geographical fetch restrictions, are evident in this illustration.

Since the SD method allows some flexibility in the choice of statistics for the cyclone parameters extreme wind gust, radius of maximum wind band, and translation speed, comment on the values used in our program is appropriate. Following SD, we assume firstly that the Gumbel (asymptotic extreme-value) distribution is applicable to annual maximum gusts and cyclone maximum gusts in the Australian tropics. We assume also, and more importantly, that the annual maximum gusts are contributed by tropical cyclones in the areas of interest and for return periods greater than about 20 years. These assumptions are discussed in detail in Appendix 1 where it is established that, for the purpose of this study and in the absence of a more precise climatology of cyclone extreme gusts, we may use a generalised gust analysis to predict cyclone extreme gusts for extended return periods.

The development of a meaningful analysis of cyclone radii of maximum wind bands (R) for the Australian region is hampered by a severe lack of data on this parameter for Australian cyclones. To overcome this problem, SD have based their approach on the use of some 'average' radius ($\bar{R}$), and show that their results will be independent of particular cyclone radii provided only that the distribution of actual R is symmetric about $\bar{R}$. They do point out, however, that evidence from United States hurricanes supports the evaluation of average R as a function of latitude (e.g., Shea and Gray 1973). While the limited information available from Australian cyclones (chiefly radar estimates of R obtained over the last five years) does not contradict this, we feel both that the quantity of data is insufficient to determine a functional relationship for this region alone, and that it would be incorrect to transpose US data on R directly. Thus we have decided to follow SD in adopting some average R, and have evaluated the wave climatology for a number of different values of this parameter.

Once again because of data inadequacy, the determination of $\bar{R}$ itself is difficult. Evidence from recent cyclones favours relatively small values, particularly at lower latitudes, and on this basis we have selected $\bar{R}$ = 20 km as a reasonable estimate. However, since it is standard design practice to be conservative where precision is not possible, we also present the climatology for $\bar{R}$ = 30 km. It is obvious from the results in Figs 2 and 3 that extreme wave heights will vary quite significantly with $\bar{R}$ (for given return period), so that some importance must be attached to the determination of more precise estimates of this parameter in the near future.

Finally, our choice of average cyclone translation speed is based on an examination of translation speeds for coast crossing cyclones in the northwestern Australian regions over the period 1909 to 1969. This data has been extracted by Lourensz (1975) as part of his major revision of Coleman's (1972) cyclone summary, and consists of average translation speeds during the 24 hours (2300 GMT to 2300 GMT) containing the coast crossing for some 109 crossing occurrences (these being preferred because of the greater reliability of the data in this situation). The resulting average speed for these cyclones was 17.8 km/h, with a standard deviation of 10.5 km/h. Although similar data from other regions are not yet available, we have no reason to expect significant variations from these figures.

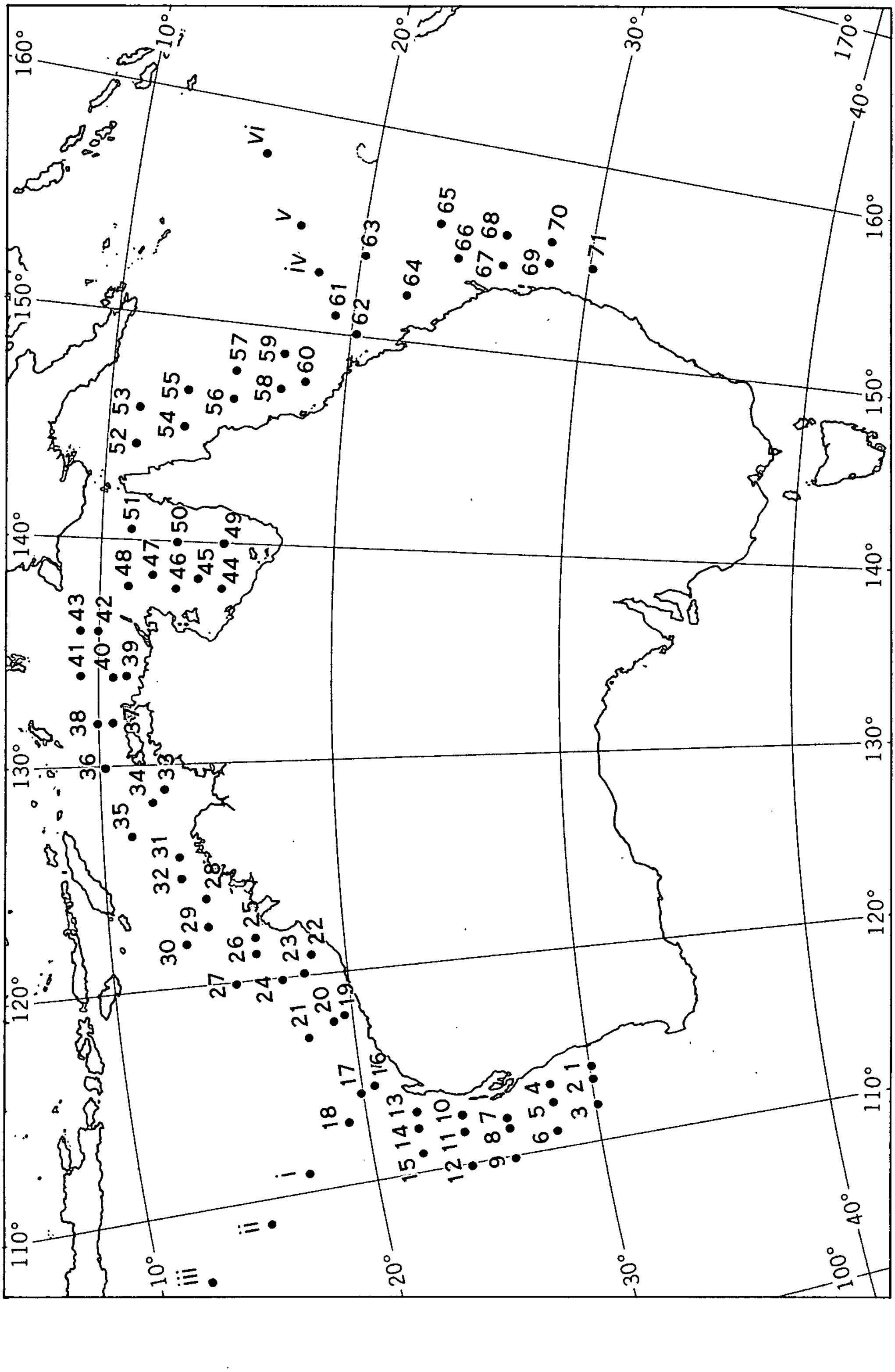

Fig 1 Location map showing points at which extreme wave height computations have been made.

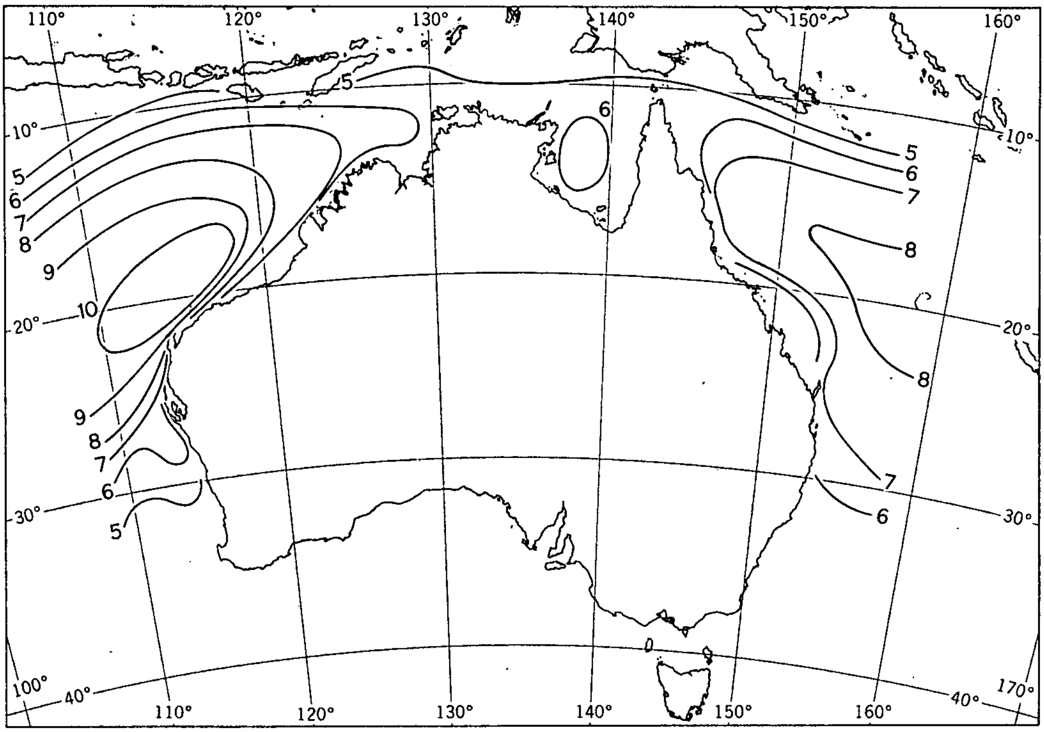

Fig 2(a) Isopleths of extreme significant wave height (m) for return period 50 years and average cyclone radius of 20 km.

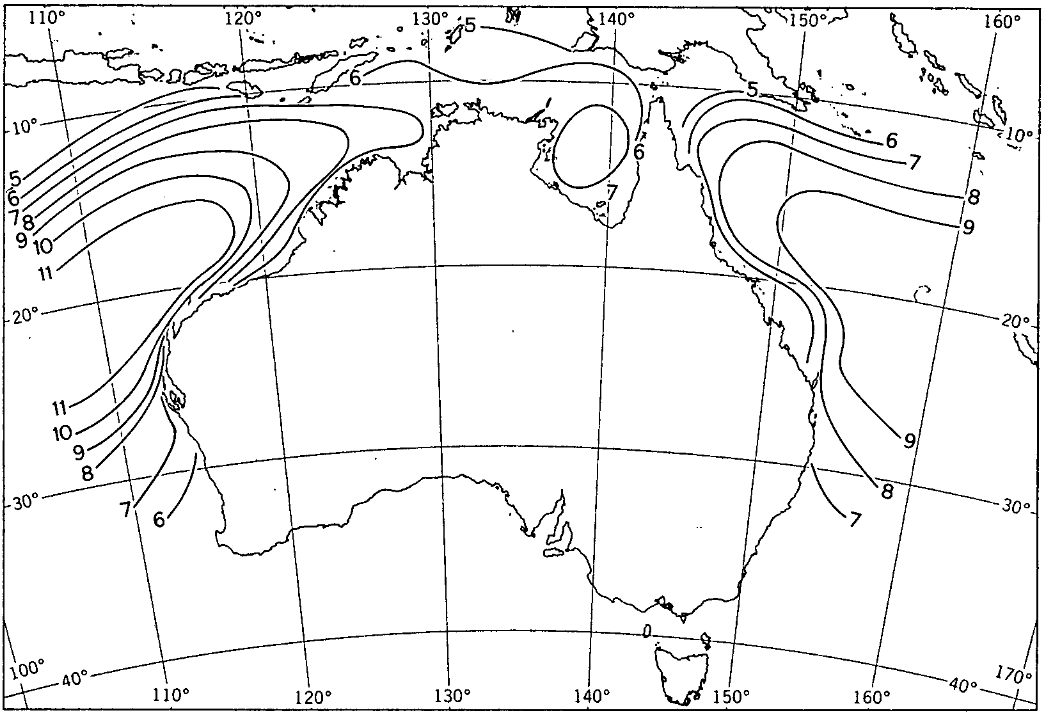

Fig 2(b) Isopleths of extreme signifcant wave height (m) for return period 50 years and average cyclone radius of 30 km.

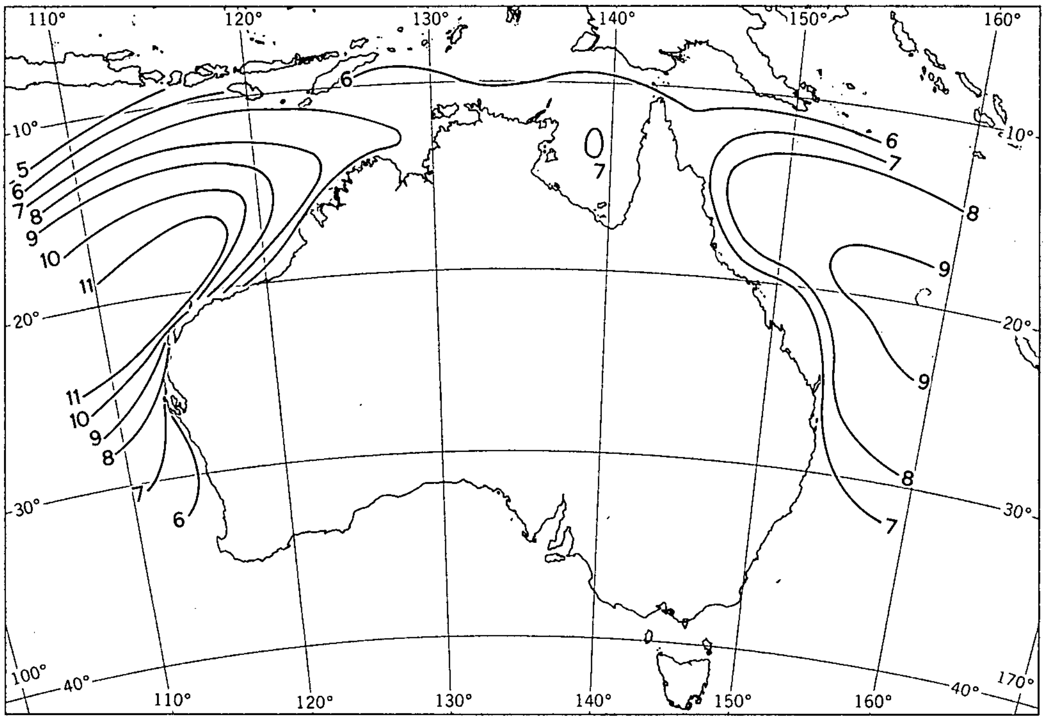

Fig 3(a) Isopleths of extreme significant wave height (m) for return period 100 years and average cyclone radius of 20 km.

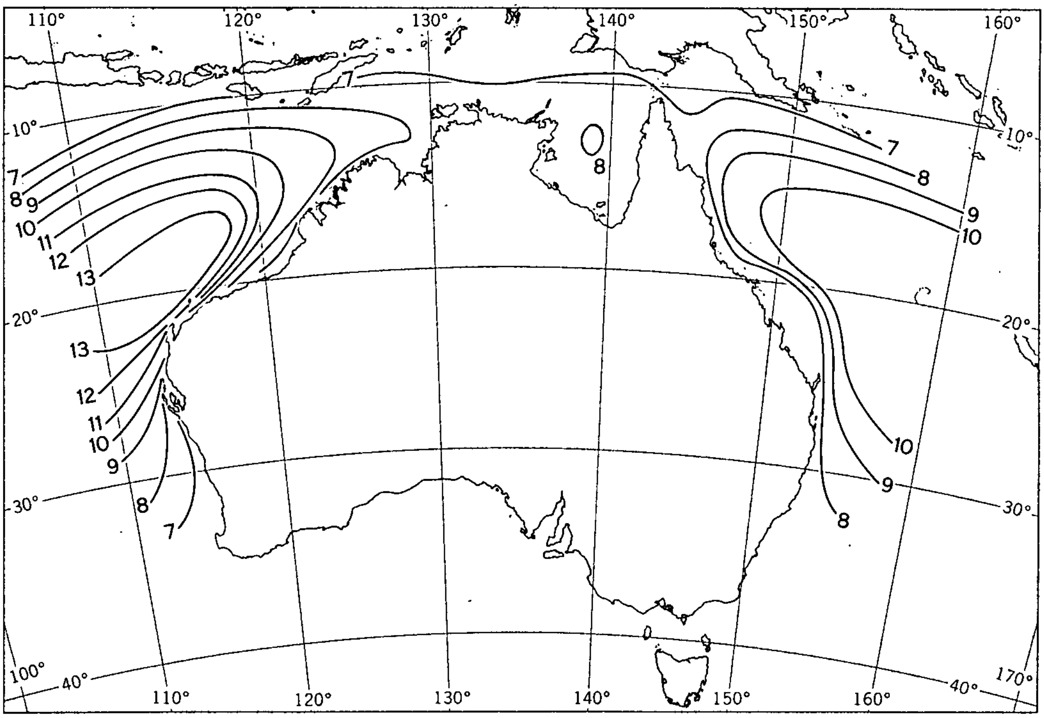

Fig 3 (b) Isopleths of extreme significant wave height (m) for return period 100 years and average cyclone radius of 30 km.

Sensitivity tests with our extreme wave height model indicate that a variation in average translation speed of 10 km/h will cause less than 5 per cent variation in wave height. In addition, this variation is nearly symmetrical about the average value, and we have some confidence in the extreme wave heights determined using this average translation speed. As pointed out in SD, the average translation speed and $\bar{R}$, together, thus result in an *average* extreme significant wave height appropriate to any particular return period.

RESULTS

Our programmed model has been run to determine extreme significant wave heights, and associated wave periods, as a function of recurrence interval in years for a total of 71 selected points off the Australian tropical coasts. The positions and numbers assigned to these points are shown in Fig 1. All points are located in effectively deep water, while remaining over or near to the continental shelf. The innermost points have been placed at a minimum distance of 120 km from shore, in order to ensure both that they are in deep water and that fetch restrictions imposed by the presence of the coastline are negligible.

Within the Great Barrier Reef region off the northeast coast, however, geographical fetch lengths will often be affected by the presence of reefs, islands, and cays. The points for which some restrictions apply are Nos 52, 54, 56, 58, 60, 62, 64, and E-values (SD, Appendix) for these have been derived individually and introduced into our program as input data.

In addition to the selected points above, results have also been computed for the six supplementary points i to vi shown in Fig 1. These are all located off the continental shelf, but results for them have been included to facilitate the contouring of wave heights in adjacent areas.

Extreme significant wave heights are presented in this paper as contoured fields in Figs 2 and 3, for recurrence intervals of 50 and 100 years and average cyclone radii of 20 and 30 km. More detailed results, including a tabulation of wind gust distribution parameters and wave height and period for each computation point, are available in Dexter and Watson (1975).

Points within the Barrier Reef area, detailed above, have been included in the contour fields of Figs 2 and 3, despite the fetch restrictions, both for completeness and because these restrictions generally appear to have only a minor effect on wave heights. Although these points are probably representative of the region in general, the fact that they have fetch restrictions should be considered when assessing wave height contours. Indeed, any other specific points within the reef should be treated individually, and the program is readily available for this purpose.

It can be seen that the maxima in wave height contours generally follow the maxima in track frequencies and wind gust parameters as expected. Peak values appear reasonable in the light of available observations on cyclone-generated waves obtained elsewhere (e.g., Arakawa and Suda 1953, Earle 1975), and the extreme-value distributions of wave heights presented by Thom (1971). Finally, it should be remembered (from SD) that the wave heights presented here are average values of extreme significant wave heights for the particular return periods - they are equalled or exceeded on average once in every two such return periods.

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APPENDIX 1

The Estimation of Extreme Cyclone Wind Gusts from Annual Maximum Gust Statistics

The question that inevitably arises in assessing the value of this climatology concerns the assumption that the generalised gust statistics in the Australian tropics may be used to represent cyclone gusts in the same region. While it is true that this assumption can never be completely justified, we believe that it may be shown to be sufficiently realistic for the purpose of this study, in view of either the inaccuracy or complete absence of other relevant data.

In particular, if we can show (a) that the longer return period extreme gust values along the tropical coasts are all attributable to tropical cyclones, and (b) that the data set containing all gusts irrespective of origin is a good predictor of those long-period extremes, then this will provide strong circumstantial evidence to support the retention of this assumption. Point (b) will follow if we can establish simply that the distribution of annual maximum gusts attributable to tropical cyclones is homogeneous with that of gusts from all other sources.

Our investigation of these points involved two steps. First, the annual maximum gust figures for all available years of record for six tropical coastal anemometer stations (Townsville, Cairns, Willis Island, Broome, Port Hedland, and Onslow) were examined to determine which gusts could be attributed to cyclones. This was done simply on the basis of the presence or absence of a tropical cyclone within 300 km of the anemometer site at the date and time of occurrence of the annual maximum gust. Those gusts for which the cyclone was within 110 km of the site were also noted.

Second, all gust values were transformed so that the ordered sets of gust figures for all stations fitted Gumbel distributions with the same mode and slope. This was done so that the gusts from all stations could be plotted on the same graph, and would have the same best fit Gumbel line. Thus, if we choose mode = 1, slope = 1 as the fixed values, where the actual mode, slope for a particular station are M, S, then the gusts for that station are transformed according to

$$V' = \left(\frac{V}{S} - \frac{M}{S}\right) + 1,$$

where V', V are the transformed and original gust values respectively.

With this transformation, the ordered gusts for each site were plotted on extreme-value probability paper in the usual manner, i.e., according to the relation

$$V' = 1 + y,$$

where y = reduced variate = $-\log_e(-\log_e P)$, P being cumulative probability.

The principal advantage of this approach is that it enables the gusts from any number of sites to be plotted together, thus considerably increasing the available data points, and facilitating the comparison of cyclone and other gusts. Results for the six stations mentioned earlier are shown in Fig 4, where the solid squares represent cyclone gusts with the cyclone within 110 km of the anemometer, the open circles other cyclone gusts, and the dots are all remaining gusts due to non-cyclone events. The straight line is the best-fit Gumbel line for unit mode and slope.

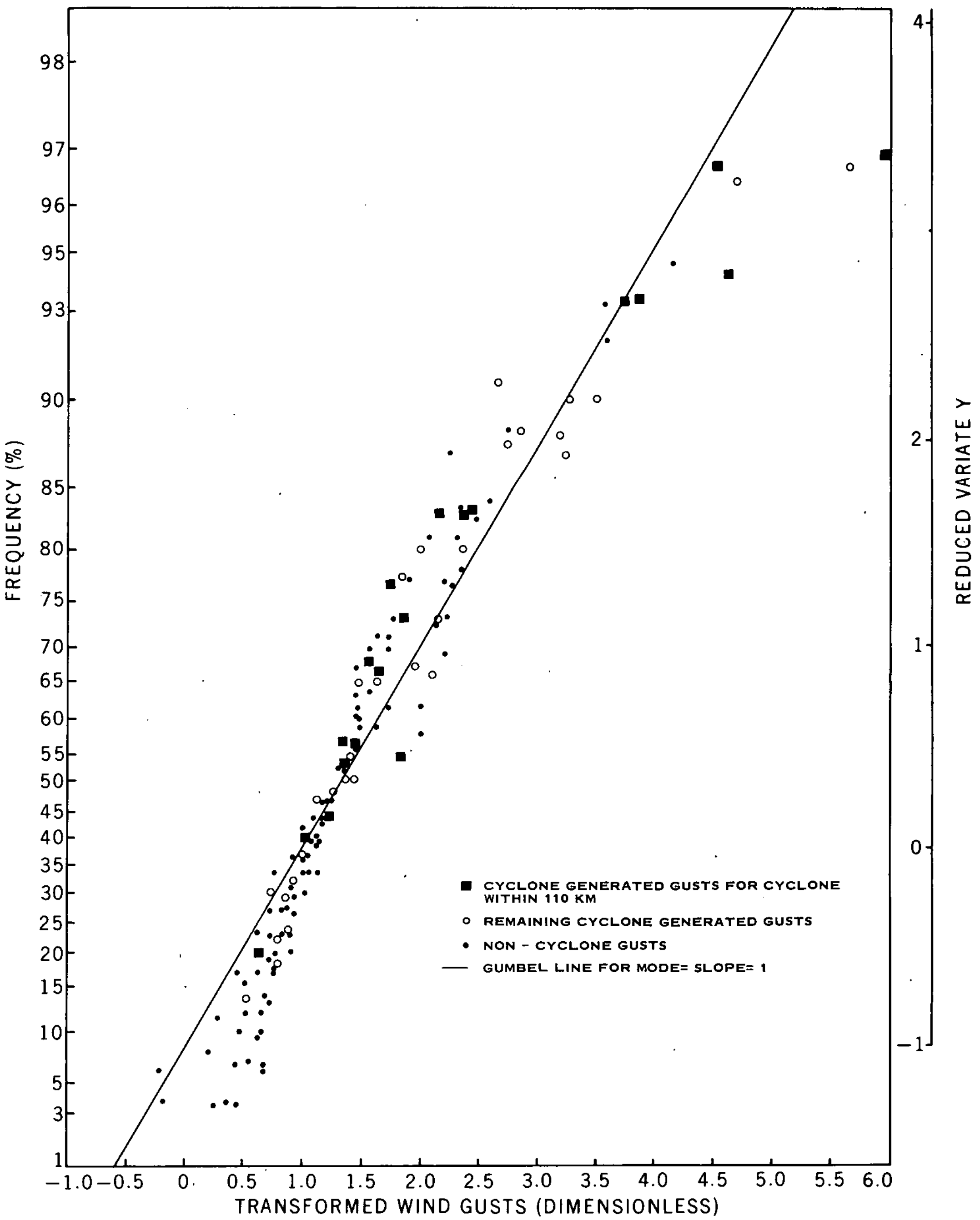

Fig 4 Gumbel plot of transformed annual maximum wind gusts for six tropical coastal anemometer stations.

From the point of view of this study, the following conclusions are immediately apparent:

(i) cyclone gusts are generally located above the mode, with non-cyclone gusts being near to or below this value;

(ii) the highest five, seven of the highest 10, and 14 of the highest 20 gusts are cyclone-generated;

(iii) in the area of overlap, the distributions of cyclone and non-cyclone gusts appear quite homogeneous - all gusts fit the same distribution, irrespective of origin.

Thus our final conclusion in this regard must be that we are quite justified in using all available gust data in predicting extreme cyclone gusts, certainly for return periods greater than 10 years (the highest 10 per cent of gusts).

The other interesting feature of Fig 4 is the fact that although all gusts appear to fit the same distribution, this is most likely *not* a Gumbel distribution. From the apparent slope of the empirical distribution of gusts when plotted on extreme-value probability paper as seen in Fig 4, it would seem that an appropriate distribution might be of the single exponential (e.g., Fréchét, as used by Thom 1968), rather than double exponential form. In any event, this feature should certainly be the subject of further study. For the present, however, principally because of its current wide acceptance and usage, we have continued to employ the Gumbel distribution as a predictor of extreme gusts for cyclone wave computations.

APPENDIX 2

Illustration of Procedure at a Specific Point

To assist in clarifying the generalised procedure of Spillane and Dexter (1976), details of our computations are given here for a particular point (No 64 in Fig 1), located at 22.0°S, 152.4°E. The notation is that employed by Spillane and Dexter, and the equation numbers relate to equations in that reference also. Steps in the procedure are performed as follows:

(i) Input data. These consist essentially of three quantities: frequencies of occurrence of tropical cyclones within a distance of 110 km of the point, as a function of direction of movement, in a 60-year period (F_B); mode (M) and slope (S) parameters of the extreme wind gust distribution at the point; and fetch restrictions, expressed as E-values, for the point, determined as outlined in the Appendix of SD. For point 64, the input data are Tables 1 and 2, and M = 91.0 km/h, S = 30.0 km/h.

(ii) The expected frequencies of cyclone maximum wind bands passing over the point in 60 years are first computed directly from the frequencies of Table 1, and assumed average radii ($\bar{R}$) of maximum wind, and are shown in Table 3.

(iii) Using Table 3 and the input wind gust parameters (M,S), the average number of cyclones (of average radii $\bar{R}$) needed to produce an extreme gust equal to or greater than a certain value in a particular return period may be computed. Thus the last two columns of Table 4 are obtained from Table 3 using Eqn 14, while the maximum mean winds corresponding to various return periods are derived from the extreme gust data by way of Eqns 16 and 17.

The reciprocals of the average numbers of cyclones are the probabilities that any particular cyclone will have a maximum wind equal to or exceeding those given in Table 4. This is expressed analytically in Eqn 18 of SD.

(iv) In determining the return periods of significant wave heights at a point, the contribution from storms of greater extreme, at greater distances, must be considered. This is done using the E-values of Table 2, which represent the probabilities that a cyclone moving towards a particular direction will produce significant wave heights $\geqslant FH_o$, where the fetch restrictions for point 64 apply from 045° through 360° to 225°.

We next compute the average number of times in 100 years (say) that storms of average radius $\bar{R}$ will cause waves $\geqslant FH_o$ in height at the point (Table 5). This is done by substituting values of F_B (Table 1) and E (Table 2) into Eqn 24.

(v) From the frequencies of storms of various $\bar{R}$ and F from Table 5, the expected maximum wind speed that would occur on average once in each random sample of such storms may be determined in Table 4. Then, corresponding to each value of $\bar{V}_{max}$ for such samples, the associated $H_{o\ max}$ is computed using Bretschneider's (1972) hurricane wave model, Eqns 19, 20, 21. Thus Table 6, for point 64, is derived from three sources: Table 5 for cols 1 and 2, Table 4 for col 3, and the hurricane wave model for col 4.

(vi) From Table 6, the maximum significant waveheight values expected to be equalled or exceeded, on average, once in every two design return periods of 100 years at point 64 are selected as the maxima of the $FH_{o\ max}$ for each radius. These are, with their corresponding wave periods, given in Table 7. Values of H_s similar to those in Table 7 are used in determining the contoured wave height fields of Figs 2 and 3.

Table 1 Directional frequency of cyclone passage within 110 km of site 64

Direction towards	N	NE	E	SE	S	SW	W	NW	Total
F_B	0	3	2	16	4	5	2	1	33

Table 2 E-values for site 64, derived according to the procedure in the Appendix of Spillane and Dexter (1976)

Cyclone motion towards	F 0.95	 0.90	 0.85	 0.80	 0.75	 0.70	 0.60	 0.50
N NW W	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
NE SW		0.33	0.75	1.25	1.75	2.25	3.25	4.25
S E					0.2	0.5	1.2	1.6
SE							0.6	1.0

Table 3 Frequency of occurrence of cyclone maximum wind bands (for different average cyclone radii) intersecting site 64, in Y years, and corresponding return periods per event

Average R	F_Y (Eqn 12)	T_Y (Eqn 13)
km		years
20	6.0	10.0
30	9.0	6.67

Table 4 The average number of cyclones, of average R, which are available to contribute the various maximum mean wind speeds which will be received at the site in each return period.

Average return period	Maximum mean wind	Average number of cyclones of average R	
		20 km	30 km
years	km/h		
30	134.6	3.0	4.5
50	145.5	5.0	7.5
70	152.6	7.0	10.5
100	160.1	10.0	15.0
200	174.7	20.0	30.0
300	183.3	30.0	45.0

Table 5 Frequency of occurrence in 100 years of waves ≥ FH_o intersecting the site as a function of average cyclone radius.

	F							
	0.95	0.90	0.85	0.80	0.75	0.70	0.60	0.50
Sum over all directions	$0.010\bar{R}$	$0.039\bar{R}$	$0.073\bar{R}$	$0.111\bar{R}$	$0.158\bar{R}$	$0.208\bar{R}$	$0.381\bar{R}$	$0.518\bar{R}$
$\bar{R}$ = 20 km	0.205	0.779	1.458	2.221	3.163	4.168	7.621	10.37
$\bar{R}$ = 30 km	0.308	1.168	2.187	3.332	4.745	6.253	11.43	15.55

Table 6 For each given sample of cyclones, of average radius $\bar{R}$, the expected maximum mean wind, corresponding significant wave height, and expected maximum significant wave height at the site, in each 100 years. The desired extreme wave height is the maximum of all the $FH_{o\ max}$ at each $\bar{R}$.

	$\bar{R}$ = 20 km				$\bar{R}$ = 30 km			
F	No of storms	V_{max}	$H_{o\ max}$	$FH_{o\ max}$	No of storms	V_{max}	$H_{o\ max}$	$FH_{o\ max}$
		km/h	m	m		km/h	m	m
0.5	10.4	160.7	10.1	5.1	15.5	160.7	11.8	5.9
0.6	7.6	154.1	9.6	5.8	11.4	154.1	11.3	6.8
0.7	4.2	141.1	8.9	6.2	6.3	141.1	10.4	7.3
0.75	3.2	134.7	8.4	6.3	4.7	134.7	9.8	7.4
0.8	2.2	128.5	8.0	6.4	3.3	128.5	9.4	7.5
0.85	1.5	120.0	7.4	6.3	2.2	120.0	8.6	7.3
0.9	0.8	104.2	-	-	1.2	104.2	7.5	6.8
0.95	0.2	-	-	-	0.3	-	-	-

Table 7 Extreme significant wave heights and corresponding wave periods, as a function of selected average cyclone radius for a return period of 100 years.

$\bar{R}$ (km)	20	30
H_s (m)	6.4	7.5
T_s (sec)	9.8	10.6