CHAPTER 82

A PARAMETRIC HURRICANE WAVE PREDICTION MODEL

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ABSTRACT

A spectral wave model based on a numerical solution of the Radiative Transfer Equation is used to create a synthetic data base on wave conditions within hurricanes. The results indicate that both the velocity of forward movement and maximum wind velocity within the storm play an important role in determining both the magnitude of the waves generated and also the spatial distribution of these waves. An equivalent fetch for hurricane wave generation which is a function of these two parameters is proposed. This concept, together with the standard JONSWAP fetch limited growth relationships, provide a simple means for estimating wave conditions within hurricanes.

INTRODUCTION

Hurricane generated waves play a significant role in the design of almost all coastal and offshore structures in tropical and semi-tropical regions. Despite their obvious importance, the complex processes active in their generation are only beginning to be understood. The physics of the generation process within hurricanes is complicated by the rapidly turning winds which generate cross-seas. The nonlinear interactions within such seas have only recently been investigated (Young et al.,1987). Progress has also been hindered by the lack of reliable field data. Buoy measurements represent only point data in the two-dimensional spatial wave field and only recently have provided directional information. More promising are remote sensing techniques such as Synthetic Aperture Radar (SAR) and Radar Altimeters (ALT) which have provided data from a limited number of hurricanes (King and Shemdin, 1978; Gonzalez et al., 1982; McLeish and Ross, 1983; Beal et al., 1986; Holt and Gonzalez, 1986). Although such instruments represent a significant advance, the small number of hurricanes for which data exists cover only a very limited range of storm parameters.

Recent advances in the physics of numerical wave prediction models (Komen et al., 1984; Hasselmann,S. et al., 1985) have enabled the development of operational hurricane prediction models which yield results consistent with the increasing field data base (Young, 1987c). Due to the complexity of these models they are, however, computationally expensive.

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In order to develop an extensive synthetic data base, the model of Young (1987c) has been run for a wide range of hurricane parameters. The data from these numerical experiments will be used to clarify the wave generation process within hurricanes and to develop a simple parametric model suitable for wave prediction in deep water.

MODEL DESCRIPTION

The model used for the numerical experiments is called ADFA1 (Young, 1987c). It is a Second Generation (SWAMP, 1985) spectral wave model based on a numerical solution of the Radiative Transfer Equation (Hasselmann, 1960). Details of the model have been presented elsewhere (Young, 1987a,c). In particular, the model has a simple but very flexible treatment of the nonlinear source term which is of particular importance under the rapidly turning winds of hurricanes (SWAMP, 1985). An extensive comparison with field data under tropical cyclone conditions off the north-west coast of Australia has been presented by Young (1987b,c). These results clearly validate model performance under such conditions.

The model was used to generate a synthetic data base covering a wide range of hurricane parameters. The three wind field parameters varied were: velocity of forward movement, V_{fm}; maximum wind velocity in storm, V_{max} and radius to maximum winds, R. To cover the three-dimensional parameter space completely would involve a prohibitively large number of runs. It is reasonable to assume that R is simply a scaling parameter and hence for the majority of the experiments was held constant. A total of 43 experiments were conducted, the parameters being shown in Table 1.

Successful numerical modelling of hurricanes represents a conflict of scales. A grid of large geophysical extent is required to ensure all significant atmospheric forcing occurs within the grid and to predict the arrival of remotely generated swell. In order to resolve the eye structure and the associated strong winds, however, a relatively fine grid is required. To accommodate these constraints at acceptable computational expense, ADFA1 uses a system of nested grids.

A course grid with a spatial extent of 750km $\times$ 1050km with a resolution of 30km and a computational time step of 30mins was used to provide boundary conditions to a nested finer grid of extent 360km $\times$ 330km with a 15km resolution and time step of 15mins. Runs were commenced with the hurricane near the southern boundary of the course grid where it was held stationary for a period of two days to enable sea conditions to build up from an initially calm state. The storm was then moved off in a northerly direction at its velocity of forward movement. All results presented are from the finer grid whose south-west corner was located 300km east of the course grid western boundary and 650km north of its southern boundary. In all cases sea conditions had reached steady state by the time the hurricane entered the finer grid.

The hurricane wind field model used for the atmospheric forcing was a slightly modified form of that proposed by Graham and Hudson (1960). The original model had the region of maximum winds in the right rear quadrant whereas the modified form adopted here positions this region in the right forward quadrant, 70° from the direction of forward movement. This modification is consistent with observations from the NOAA hurricane program and has also been adopted in other modelling applications (SWAMP, 1985). In reality, the wind field is almost certainly more complex than the simple model used, with considerable variability between storms. In view of the accuracy with which hurricane parameters can be estimated in practice, however, there is little point in attempting a more sophisticated approach.

HURRICANE WAVE GENERATION

The advent of remote sensing techniques and particularly the Synthetic Aperture Radar (SAR) has provided considerable insight into the directional properties of hurricane generated waves. SAR data from a number of hurricanes (King and Shemdin, 1987; Gonzalez et al., 1982; McLeish and Ross, 1983; Beal et al., 1986; Holt and Gonzalez, 1986) consistently shows swell ahead of hurricanes radiating out in a fan shaped pattern from the centre of the storm. The hurricanes investigated by these experiments have all had slow to moderate velocities of forward movement ($V_{fm} = 2.5 - 5ms^{-1}$). King and Shemdin (1978) have, however, speculated that V_{fm} would have a critical role in determining these trends. Figs. 1 show contour plots of directional wave spectra at various points relative to the centre of the hurricane. Plots are presented for a storm with $V_{max} = 40ms^{-1}$ and values of $V_{fm} = 2.5$ and $12.5ms^{-1}$. Each of the contour plots has been normalized such that the spectral peak has a value of one; contours being drawn at 0.9, 0.5, 0.1 and 0.01. The maximum frequency shown on the polar grid is 0.25 Hz. In each of the spectra a relatively high frequency peak with a broad directional distribution centred about the local wind direction can be seen (ie. locally generated wind-sea). In addition, many of the spectra also exhibit a lower frequency swell peak. For the slower moving storm (Fig. 1a), examination of the spectra ahead of the storm centre clearly show swell radiating out from a region to the right of the storm centre in a similar fashion to that reported in the SAR data. Tracing this swell back along wave rays at the appropriate group velocity reveals that it was generated in the intense wind region to the right of the storm. This swell ($f = 0.08Hz$) has a group velocity of $9.8ms^{-1}$ and as such propagates ahead of the storm ($C_g > V_{fm}$). The more rapidly moving storm (Fig. 1b) has a velocity of forward movement, $V_{fm} = 12.5ms^{-1} > C_g$ and consequently no swell is evident ahead of the storm.

This result confirms the speculation of King and Shemdin (1978) as to the importance of V_{fm} in determining the wave field. V_{max} also plays an important role since it can be expected that the peak frequency of the dominant waves will decrease with increasing V_{max} (ie. C_g increases with increasing V_{max}). For a given V_{max}, if V_{fm} is relatively slow, the dominant waves will "outrun" the storm and appear as swell ahead of the storm. Conversely, if V_{fm} is relatively fast, the waves will be left behind the storm and no swell will be present ahead of the storm.

The maximum significant wave height within the hurricane, $H_s(max)$ as a function of both V_{max} and V_{fm} is shown in Fig. 2. For a given value of V_{max}, $H_s(max)$ gradually increases as a function of V_{fm} until a peak is reached, after which the wave height rapidly decreases. The V_{fm} at which this peak occurs increases with V_{max}. The reason for this behaviour is evident in Fig. 3 which shows the group velocity of the spectral peak frequency of the maximum waves in the storm as a function of both V_{fm} and V_{max}. Maximum wave conditions occur when the waves have a group velocity slightly greater than V_{fm}. Bretschneider (1957) proposed that maximum wave conditions would occur when $V_{fm} = C_g(max)$. Under such

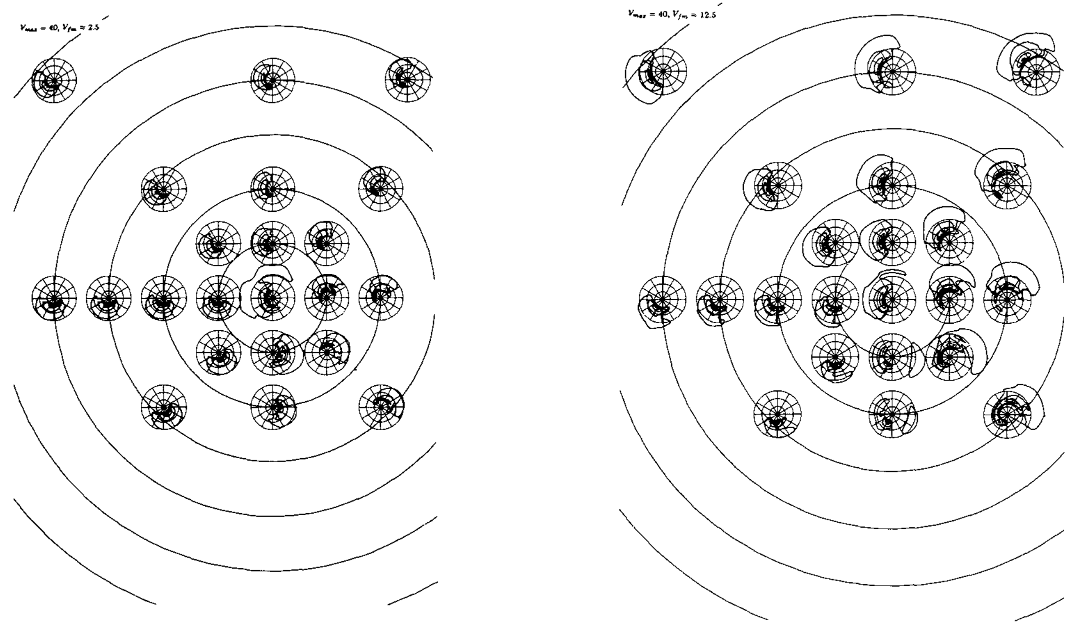

Fig. 1. Contour plots of directional wave spectra at various points within hurricanes with $V_{max} = 40ms^{-1}$ and $V_{fm} = 2.5ms^{-1}$ and $12.5ms^{-1}$. Circular lines are drawn at distance R, 2R, 3R etc. from the storm centre. Note, a southern hemisphere storm is shown.

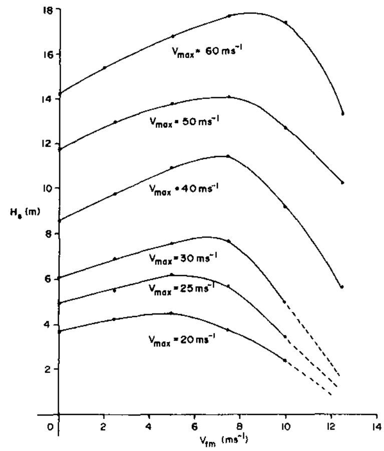

Fig. 2. Maximum significant wave height in a hurricane, $H_s(max)$ as a function of V_{fm} and V_{max}.

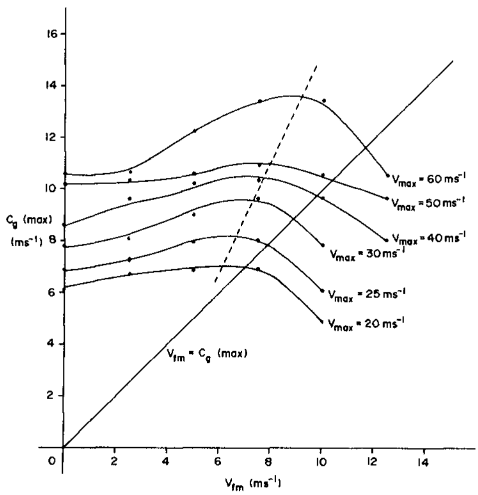

Fig. 3. Group velocity of the maximum waves in a hurricane, $C_g(max)$ as a function of V_{fm} and V_{max}.

a condition waves would move forward with the hurricane and experience an extended fetch. Due to the effect of nonlinear wave-wave interactions, however, there is a continual migration of the spectral peak to lower frequencies (Hasselmann et al., 1973). Consequently, there will be a tendency for the dominant waves to continually move to lower frequencies and "outrun" the storm (King and Shemdin, 1978). Only under fully arisen sea conditions when the peak frequency reaches the Pierson-Moskowitz value (Pierson and Moskowitz, 1958) does the spectral peak migration stop (Komen et al., 1984). As such conditions seldom, if ever, occur in hurricanes, the waves which will dominate are those which remain in the high wind regions for the maximum time.

EQUIVALENT FETCH

Bretschneider (1957) has used the concept of an equivalent fetch within a hurricane to apply fetch limited wave growth relationships to these situations. As already shown, the equivalent fetch must be a function of both V_{max} and V_{fm}.

The JONSWAP (Hasselmann et al., 1973) fetch limited growth relationship is

$$\frac{gH_s}{U_{10}^2} = 0.0016 \left(\frac{gF}{U_{10}^2}\right)^{0.5} \tag{1}$$

where U_{10} is the 10m wind velocity and F the fetch length. Replacing U_{10} by V_{max}, which is an appropriate wind scaling parameter for hurricane conditions, Eq. 1 can be written as

$$\frac{gH_s(max)}{V_{max}^2} = 0.0016 \left(\frac{gF}{V_{max}^2}\right)^{0.5} \tag{2}$$

Applying Eq. 2 to the present data and solving for F, yields the equivalent fetch values shown in Table 1. Initially, only the results for the storms with $R = 30km$ will be considered. The fetch dependence on R, however, will be investigated later. A polynomial approximation to the results yields:

$$F_{30} = aV_{max}^2 + bV_{max}V_{fm} + cV_{fm}^2 + dV_{max} + eV_{fm} + f \tag{3}$$

where $a = -6.525 \times 10^1$, $b = 4.518 \times 10^2$, $c = -3.669 \times 10^3$, $d = 6.570 \times 10^3$, $e = 2.021 \times 10^4$, $f = 2.394 \times 10^4$; V_{max}, V_{fm} both have units of $[ms^{-1}]$ and F_{30} is the equivalent fetch for $R = 30km$ (units of [m]). Eq. 3 is presented in graphical form in Fig. 4. It is clear from this figure that for a given V_{max}, there is a value of V_{fm} which will give the maximum equivalent fetch and hence maximum wave conditions. As V_{max} increases, the value of V_{fm} which produces the maximum equivalent fetch also increases. This occurs since higher values of V_{max} will generate waves with high group velocities and hence a more rapidly moving storm is required to maximize the equivalent fetch.

This rather simple model can also be applied to determine the spectral peak frequency of the maximum waves in the storm, $f_m(max)$. Reformulating the JONSWAP result gives

$$\frac{g}{2\pi f_m(max)V_{max}} = 0.045 \left(\frac{gF}{V_{max}^2}\right)^{0.33} \tag{4}$$

Fig. 5 shows a comparison between the values of $f_m(max)$ generated by the wave model and shown in Table 1 with those calculated from Eq. 4 using the values of

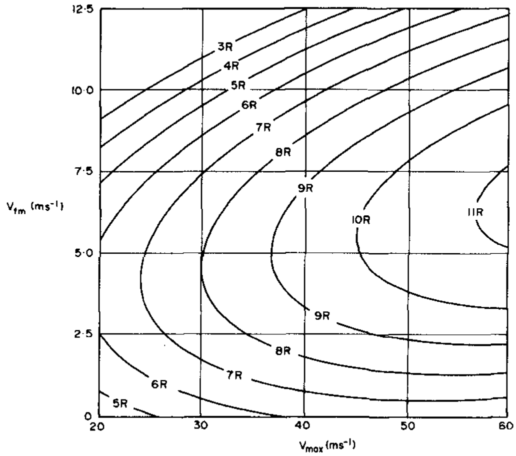

Fig. 4. Contour plot of the equivalent fetch (expressed in terms of R, which equals 30km) as a function of V_{fm} and V_{max}.

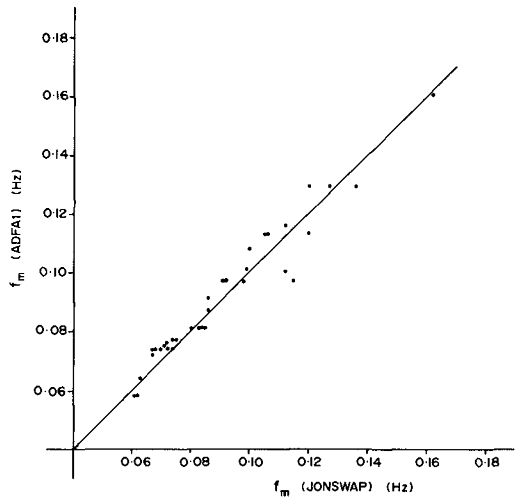

Fig. 5. Peak spectral frequency within the hurricane predicted by the spectral wave model, $f_m(max)$ (ADFA1) verses that predicted by the equivalent fetch assumption, $f_m(max)$ (JONSWAP).

Run No.	V_{fm} (ms^{-1})	V_{max} (ms^{-1})	R (km)	$H_s(max)$ (m)	F	$f_m(max)$ (Hz)
1	0.0	20	30	3.7	4.4R	0.129
2	0.0	25	30	5.1	5.3R	0.113
3	0.0	30	30	6.1	5.3R	0.101
4	0.0	40	30	8.6	5.9R	0.091
5	0.0	50	30	11.8	7.1R	0.077
6	0.0	60	30	14.3	7.3R	0.074
7	2.5	20	30	4.2	5.6R	0.116
8	2.5	25	30	5.5	6.2R	0.108
9	2.5	30	30	6.9	6.8R	0.097
10	2.5	40	30	9.7	7.5R	0.081
11	2.5	50	30	13.0	8.6R	0.075
12	2.5	60	30	15.4	8.4R	0.074
13	5.0	15	30	3.0	5.1R	0.129
14	5.0	20	30	4.5	6.5R	0.113
15	5.0	25	30	6.2	7.9R	0.097
16	5.0	30	30	7.5	8.0R	0.087
17	5.0	40	30	10.9	9.5R	0.077
18	5.0	50	30	13.8	9.7R	0.074
19	5.0	60	30	16.8	10.0R	0.064
20	7.5	20	30	3.7	4.4R	0.113
21	7.5	25	30	5.7	6.6R	0.097
22	7.5	30	30	7.7	8.4R	0.081
23	7.5	40	30	11.4	10.4R	0.076
24	7.5	50	30	14.1	10.2R	0.072
25	7.5	60	30	17.7	11.1R	0.058
26	10.0	20	30	2.4	1.8R	0.160
27	10.0	25	30	3.4	2.4R	0.129
28	10.0	30	30	5.0	3.6R	0.100
29	10.0	40	30	9.1	6.6R	0.081
30	10.0	50	30	12.7	8.2R	0.074
31	10.0	60	30	17.4	10.8R	0.058
32	12.5	40	30	5.6	2.5R	0.097
33	12.5	50	30	10.2	5.3R	0.081
34	12.5	60	30	13.3	6.3R	0.074
35	5.0	40	15	9.3	13.8R	0.081
36	5.0	40	45	11.8	7.4R	0.074
37	5.0	40	60	12.2	5.9R	0.074
38	5.0	25	15	5.2	11.1R	0.110
39	5.0	25	45	6.4	5.6R	0.097
40	5.0	25	60	6.6	4.5R	0.097
41	5.0	60	15	14.5	14.9R	0.074
42	5.0	60	45	17.1	6.9R	0.064
43	5.0	60	60	18.2	5.9R	0.058

Table 1. The synthetic hurricane data base

F from Table 1. The agreement between the two is very good. This is particularly so when it is considered that estimates of f_m from spectral models such as ADFA1 are not particularly robust due to the discrete frequency resolution of such models.

RADIAL DEPENDENCE

As indicated earlier, it was assumed that the radius to maximum wind, R, was a scaling factor. Runs 35 to 43 were included to investigate this influence. Comparing the equivalent fetch values calculated from these runs, and presented in Table 1, with the values for the equivalent runs with $R = 30km$ shows that the scaling relationship is not linear. (ie. Doubling the radius to maximum winds does not double the equivalent fetch.) Fig. 6 shows the equivalent fetch as a function of radius to maximum winds. In order to collapse the data onto one curve, values have been normalized in terms of the equivalent results for a radius to maximum winds of 30km. (ie. the $R = 30km$ run with the same values of V_{fm} and V_{max}). These results can be approximated quite well by the relationship

$$F/F_{30} = 0.75 log_{10} R/(30 \times 10^3) + 1 \tag{5}$$

where F is the equivalent fetch for a hurricane with a radius to maximum winds, R (units of [m]) and F_{30} is the equivalent fetch for the hurricane with the same values of V_{fm} and V_{max} but with a radius to maximum winds of 30km. In practice, F_{30} can be calculated from Eq. 3.

Eq. 5 provides a means of determining F and hence $H_s(max)$ for any value R. Since F is directly related to H_s for given V_{fm} and V_{max}, it would appear to be a far more appropriate spatial scale parameter than R.

PARAMETRIC MODEL

Applying the results in the previous sections, it is possible to develop a relatively simple yet flexible parametric model for hurricane wave prediction in deep water. Given V_{fm}, $V_{max}$and R, an effective radius R' can be defined from Eq.5

$$R' = 22.5 \times 10^3 log_{10} R - 70.8 \times 10^3 \tag{6}$$

where both R and R' have units of metres. Using R', V_{fm} and V_{max} the equivalent fetch, F is determined from Eq.3

$$F/R' = aV_{max}^2 + bV_{max}V_{fm} + cV_{fm}^2 + dV_{max} + eV_{fm} + f \tag{7}$$

where $a = -2.175 \times 10^{-3}$, $b = 1.506 \times 10^{-2}$, $c = -1.223 \times 10^{-1}$, $d = 2.190 \times 10^{-1}$, $e = 6.737 \times 10^{-1}$ and $f = 7.980 \times 10^{-1}$. Again, all values are in standard S.I. units. The maximum significant wave height and associated spectral peak frequency can be determined from the modified JONSWAP relationships, Eqs. 2 and 4.

SPATIAL DISTRIBUTION

The model presented in the previous section provides a means for determining the maximum significant wave height and its associated spectral peak frequency but no insight into the spatial distribution of these quantities within the storm. As with $H_s(max)$, the spatial distribution of significant wave heights is also a function of both V_{fm} and V_{max}. Hence it is not possible to present simply one spatial distribution diagram in a manner similar to that of Bretschneider (1957). Due

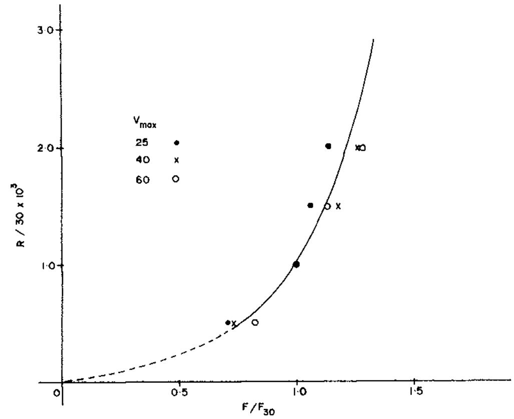

Fig. 6. Dependence of the equivalent fetch, F, on the radius to maximum winds, R. Values are presented in terms of the equivalent fetch for a hurricane with R=30km. The solid line is Eq. 5.

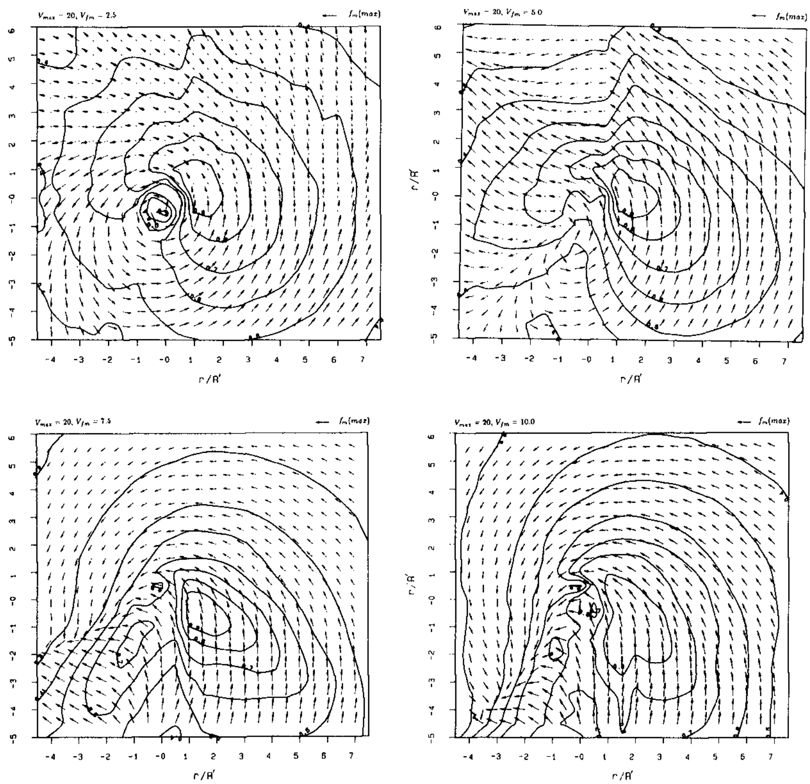

Fig. 7(i). Contour plot of $H_s/H_s(max)$ for hurricanes with $V_{max} = 20ms^{-1}$. Vectors indicate mean direction of wave propagation. Vector lengths are directly proportional to $T_m = 1/f_m$. Scale is shown at top right.

to space limitations, the spatial distributions for all the runs cannot be presented here. Due to the importance of such results for design purposes, however, as many as is practical appear in Figs. 7. A more complete set of such figures has been presented by Young (1988). Figs. 7 show contours of significant wave height; the values being normalized such that $H_s(max)$ has a value of one. Spatial distances have also been presented in a nondimensional form in terms of r/R', where r is the distance from the storm centre and R' the effective radius to maximum winds, as defined by Eq. 6. Superimposed on the plots are vectors; the direction being the mean wave direction obtained by integrating the directional spectrum and the length being proportional to the wave period of the spectral peak ($T_m = 1/f_m$).

A number of consistent trends are clear in the spatial distributions as a function of V_{fm} and V_{max}. Typical distributions are characterized by a crescent shaped region to the right of the storm as reported by numerous other authors. This region occurs since the wind velocity is a maximum here and also because the wind direction is approximately parallel with the storm track. Hence, waves generated in this region move forward with the hurricane and maximize the time for which they experience strong winds. The actual position of the crescent shaped region varies with V_{fm}. For slowly moving storms the region is in the right front quadrant. As V_{fm} increases and the hurricane "outruns" the waves it generates, the region moves into the right rear quadrant. The mean wave direction also varies with V_{fm}. As mentioned earlier, for slowly moving storms, swell radiating out from the storm centre dominates the wave field ahead of the storm. As V_{fm} increases, the storm "outruns" the swell and the waves ahead of the storm are entirely locally generated and in the local wind direction. A similar situation occurs in the left rear quadrant. Waves generated ahead of, but close to the storm centre, will be moving to the left. For a slowly moving storm these waves will have had sufficient time to propagate out of the region by the time the storm centre passes over the area. Therefore, waves in the left rear quadrant of slowly moving storms are largely locally generated. For rapidly moving storms, however, waves generated directly ahead of the storm have not had sufficient time to propagate away from the region before the storm moves forward. As a result, conditions in the left rear quadrant are extremely confused with swell moving to the left and locally generated waves moving to the lower right. This is consistent with the SAR data of King and Shemdin (1987) which shows swell in this quadrant propagating in opposition to the wind for Hurricane Gloria which had $V_{fm} = 8.3ms^{-1}$.

The rate of decrease in H_s with distance from the centre of the hurricane varies with V_{max}. This occurs since the relationship between wind speed and wave height is not linear. The result being that there is a more gradual decline in relative wave height with distance from the storm centre for the more intense storms.

Although presented in terms of the non-dimensional spatial scale, r/R', Figs. 7 all correspond to a value of $R = R' = 30km$. The validity of scaling spatial distributions in terms of R' and hence using these diagrams for other values of R was tested using Runs 35-43 which have a variety of values of R. Due to space limitations, results are not presented here but can be found in Young (1988). These results show that, not only the equivalent fetch, F but also the spatial distribution can be scaled in terms of R'.

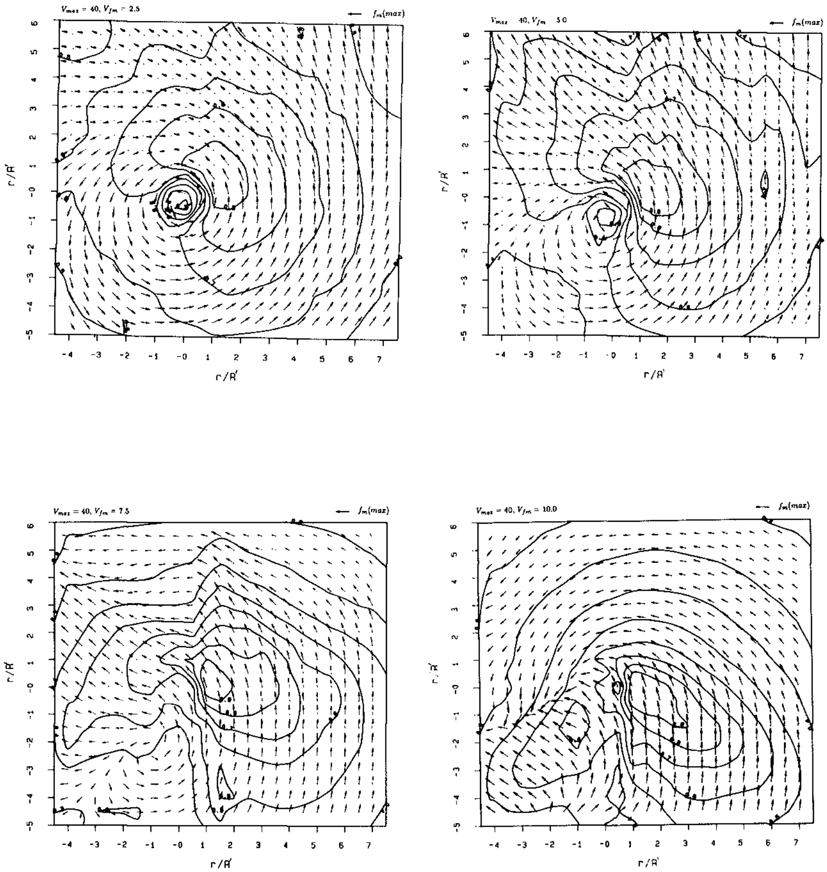

Fig. 7(ii). Contour plot of $H_s/H_s(max)$ for hurricanes with $V_{max} = 40ms^{-1}$. Vectors indicate mean direction of wave propagation. Vector lengths are directly proportional to $T_m = 1/f_m$. Scale is shown at top right.

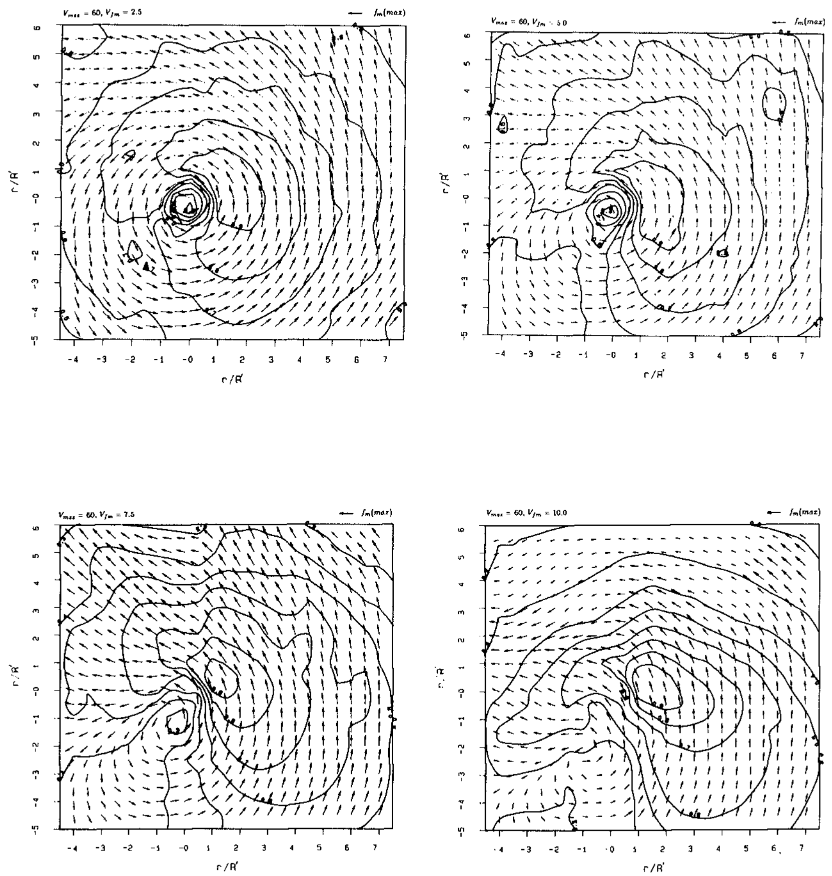

Fig. 7(iii). Contour plot of $H_s/H_s(max)$ for hurricanes with $V_{max} = 60ms^{-1}$. Vectors indicate mean direction of wave propagation. Vector lengths are directly proportional to $T_m = 1/f_m$. Scale is shown at top right.

CONCLUSIONS

An extensive set of numerical experiments have been conducted to determine the influence of the hurricane wind field parameters V_{fm}, V_{max} and R in determining the wave field. V_{fm} and V_{max} play a duel role in determining the maximum significant wave height within the storm, $H_s(max)$, the spatial distribution of waves and the directional properties. This is explained using the concept of an equivalent fetch. For slowly moving storms, waves generated in the intense wind regions to the right of the storm have group velocities greater than V_{fm}, propagate ahead of the storm and experience only a relatively short equivalent fetch. The opposite situation occurs for rapidly moving storms with the waves being left behind the storm. For an optimum combination of V_{fm} and V_{max} waves spend maximum time in the intense wind region, have the maximum equivalent fetch and consequently produce the greatest values of $H_s(max)$. The third parameter, R, acts as a nonlinear spatial scaling parameter.

Based on the concept of the equivalent fetch and the standard JONSWAP fetch limited growth relationships, a simple parametric model has been developed for the maximum significant wave height within the storm, $H_s(max)$ and its associated spectral peak frequency, $f_m(max)$. The spatial distribution of H_s and f_m can be found in terms of the maximum values using a series of field plots expressed in terms of the nondimensional distance parameter r/R'.

The model has a significant advantage over other simple parametric models (Bretschneider, 1957; Ross, 1976) in that it recognizes the important role played by both V_{fm} and V_{max} in determining the spatial distribution of wave parameters within a hurricane. Obviously the model is limited to deep water conditions and cases where the hurricane wind field parameters are relatively constant. For more involved cases the added expense of a full spectral wave model is required.

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