PREDICTION OF DOMINANT WAVE PROPERTIES AHEAD OF HURRICANES

by

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ABSTRACT

A method is proposed for predicting properties of dominant waves in the forward region of hurricanes where the waves are found to propagate predominatly in the direction of hurricane forward travel. An extended fetch concept is used in which each wave component is exposed to the action of wind over a fetch length that is determined by wave group speed, hurricane forward speed, and location with respect to eye. Maximum extended fetches are found to the right of the eye (with respect to direction of hurricane travel) in the northern hemisphere. The method correctly predicts dominant wave frequencies and significant wave heights. The prediction method utilizes recently developed concepts in wave generation and energy transfer among wave spectral components; the predicted values are compared favorably with observations

Introduction

There is substantial interest in techiques that can predict properties of waves generated by hurricanes. Considerable damage results in the coastal zone when hurricane-generated waves impact a coast even when the hurricane eye is located far offshore. The damage is most dramatic when the hurricane eye crosses the shoreline (land fall) because of flooding generated by both storm surge and wave-induced set-up. The hurricane windfield is complex but has been successfully described in terms of a translating vortex. For the purpose of this investigation it is assumed that the wind field can be adequately described and that information on the wind field is available as input. This paper outlines a procedure which uses the wind field as input to predict properties of dominant waves which are found ahead of hurricanes (see King and Shemdin, 1978).

Up to 1970 the available hurricane wave measurements were not of sufficient quantity or quality to promote either understanding of the wave generation process or to achieve verification of the empirical predictive techniques available. An organized program was instituted by a consortium of oil companies in the late 60's and early 70's to amend this deficiency (see Ward, 1974). The results were used to develop and verify models that predict the significant wave height (Bea, 1974) and others that provide two-dimensional wave spectral properties (Cardone, Pierson and Ward, 1976).

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Additional valuable data sets on several hurricanes were collected by buoys operated by the NOAA-Data Buoy Office and by our airborne Synthetic Aperture Radar (SAR) which was operated by Jet Propulsion Laboratory (JPL). These data sets were reviewed by King and Shemdin (1979); a condensed summary of measured hurricane parameters is given in Table 1.

The numerical wave spectral model of Cardone, Pierson and Ward (1976) has been shown to predict satisfactorily the significant wave height in hurricanes. Because of the dearth of directional wave measurements the model wave direction predictions have not been verified completely by comparison with measurements. Such measurements have only become available recently through the use of airborne synthetic aperture radars such as discussed by King and Shemdin (1978). Empirical models for predicting the significant wave height have also been advanced by Bretschneider (1972) and Ross (see Cardone and Ross, 1979). The Ross model does not recognize the influence of hurricane forward speed in wave generation and for that reason it is limited in application to very slow moving hurricanes. The Bretschneider model does account for the hurricane forward speed; however, the model is strictly empirical and does not incorporate recent advances in wave generation physics and consequently does not provide insight on the wave generation process in hurricanes.

The purpose of this paper is to propose a method that adequately predicts the frequency and significant wave height of dominant waves which are found in the forward region of the hurricane (ahead of the eye in the direction of forward travel). The model is consistent with known mechanisms of wave generation and incorporates the hurricane foreward speed as a central factor in our ability to correctly predict dominant wave properties in moving hurricanes.

Wave Prediction Model

King and Shemdin (1978) presented SAR images showing waves in different hurricane sectors for several hurricanes. The wave images contained valuable information on dominant wave lengths and directions. A striking asymmetry was observed in the wave field when the wave images were assembled in location with respect to the hurricane eye. The asymmetric wave generation was attributed to two mechanisms: (1) the cyclonic wind speed is greater on the right hand side of a moving hurricane (in the northern hemisphere), and (2) the waves generated on the right side of the moving storm propagate in the same general direction as the storm and therefore remain in the wind generation zone longer than those generated on the left side of the storm. The residence time of a wave component in the wind generation area to the right of the storm is inversely proportional to the difference between the wave group velocity in the direction of hurricane forward travel and the hurricane forward speed. In a wind generation setting various wave frequencies are generated in various directions. The waves which propagate in the same direction as that of hurricanes forward travel are

Table 1. Measured Hurricane Parameters

Hurricane	1 f_m (Hz)	2 V (m/s)	3 U_m (m/s)	4 r (km)	5 D (hrs)
PT-35[a]	.067	21	42	16	0
Camille[b,c,d]	.072	5	64	20	24
Eloise[e,f]	.090	6.8	35	27	0
Belle I[f,g]	.075	8.8	31	30	16
Belle II[g]	.075	11.3	27	30	0
Emmy I[h,i]	.077	4.2	22	32	0
Emmy II[h,i]	.085	7.1	24	35	18
Frances[h,i]	.080	5.8	32	40	16
Gloria I[h,i]	.106	3.1	23	35	12
Gloria II[h,i]	.075	7.6	34	35	12
Anita[j]	.090	4.2	37	20	24

a - Arakawa & Suda (1953)

b - Cardone, Pierson and Ward (1976)

c - Patterson (1974)

d - Unpublished data from U.S. Army Corps of Engineers

e - Withee and Johnson (1975)

f - Cardone and Ross (1979)

g - Johnson and Speer (1978)

h - SAR spectral analysis data

i - Unpublished data from NOAA - NHEML

j - Johnson and Renwick (1978)

1. Dominant wave frequency
2. Speed of hurricane forward travel
3. Maximum hurricane wind speed reduced to 10 m elevation
4. Eye radius
5. Duration of linear travel

expected to grow fastest. Of those the wave spectral components which travel slower or equal to the storm forward speed grow rapidly and saturate in the wave generation zone. Very low frequency waves travel faster than the storm and consequently have small residence duration in the wind generation zone. The intermediate wave frequencies which correspond to wave group velocities slightly larger than the hurricane forward speed remain in the wind generation zone long enough to achieve substantial wave heights. These waves eventually overcome the hurricane intense region and appear as dominant waves ahead of the hurricane as shown in the images presented by King and Shemdin (1978). It was shown that these dominant waves have group velocities 1.3 to 2.5 times greater than the hurricane forward speeds.

The above observations also suggest that the dominant waves ahead of the hurricane are primarily generated by a fetch system to the right of the eye that translates with the speed of the storm. In a stationary fetch situation the duration of a wave component in the fetch area is related to the fetch length by the wave group velocity. When a fetch translates in the direction of wave travel the duration of a wave in the fetch area is determined by the difference between the wave group velocity and the forward speed of the fetch.

In a fetch-limited wave generation setting Hasselmann et al (1973) obtained a relationship for the dominant frequency, f_m, in terms of fetch length, X, and wind speed at 10m above the mean sea level, U_{10}, given below:

$$f_m = 3.5\left(\frac{g^2}{X\,U_{10}}\right)^{1/3}, \qquad (1)$$

where g is gravitational acceleration. For the same conditions, they found the mean squared surface displacement, ε, to be:

$$\varepsilon = 1.6 \times 10^{-7}\left(\frac{X\,U_{10}^2}{g}\right), \qquad (2)$$

where ε is related to the significant wave height, H_s, by

$$H_s = 4\sqrt{\varepsilon}\ . \qquad (3)$$

In a translating fetch setting such as in a hurricane the following transformation is proposed:

$$X\,U_{10} = \left(\frac{K\,U_m}{1 - (V/C_g)}\right), \qquad (4)$$

where U_m is the maximum hurricane wind speed reduced to 10m elevation, K is an equivalent fetch which is established empirically, V is the hurricane forward speed and C_g is the wave group velocity in the direction of hurricane forward travel. Substituting Equation (4) into Equation (3) yields:

$$f_m = 3.5\left(\frac{g^2 - 4\pi f_m g V}{K\ U_m}\right)^{1/3} . \qquad (5)$$

King and Shemdin (1979) used the available data, from several hurricanes, on f_m, V and U_m, shown in Table 1, to establish that an equilibrium wave generation condition exists in hurricanes when the hurricane forward travel remains along a linear path over a period specified by time required for waves to propagate through the fetch area. For those hurricanes satisfying the equilibrium condition they empirically determined the equivalent fetch length, K, to be 80 Km. Using this value of K in Equation (5) it was possible to predict f_m from available values of U and U_m. As a test of this procedure, predicted f_m values were compared with observed f_m values as shown in Figure 1. As can be seen the agreement is satisfactory for equilibrium hurricanes and unsatisfactory for non-equilibrium hurricanes.

The wave prediction model is now extended to predict the significant wave height. Substituting Equation (4) into Equation (2) and adopting a scaling factor, α, between U_{10} and U_m ($U_{10} = \alpha\ U_m$):

$$\varepsilon = 1.6 \times 10^{-7}\left(\frac{\alpha U_m^{\ 2} K}{g - 4\pi f_m V}\right) . \qquad (6)$$

Alternatively, ε may be expressed in terms of the dominant frequency, f_m,

$$\varepsilon = 6.86 \times 10^{-6}\left(\frac{\alpha U_m^{\ 2}\ K}{f_m^{\ 3}}\right) . \qquad (7)$$

Predicted significant wave height, H_s, values derived from Equations (6) and (7) are compared with observed values in the following section.

Comparison with Observations

The comparison between f_m values predicted from the hurricane wind parameters and those observed are shown in Figure 1. The favorable comparison substantiates the relatively simple process with which waves are generated in a translating hurricane wind field. The prediction model extends the usefulness of wave length measurements obtained from airborne SAR images to provide estimates of the significant wave height ahead of the hurricane.

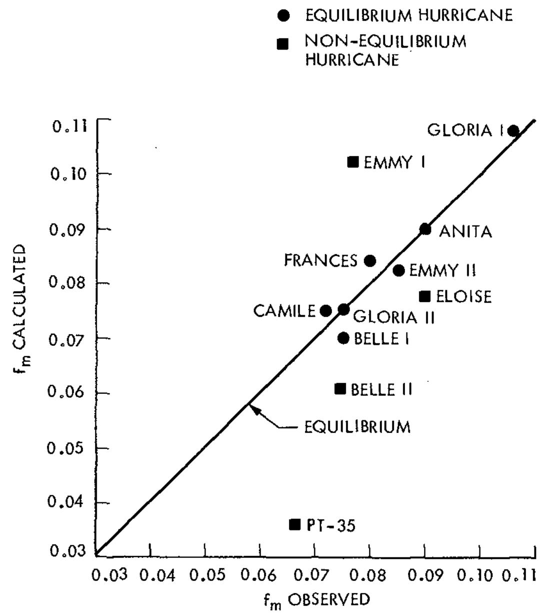

Figure 1. Comparison of observed and predicted f_m values of dominant waves.

The available observations for verifying Equation (7) are summarized in Table 2; only equilibrium hurricanes are included in this table. As shown, significant wave height measurements are available only for three of the seven equilibrium hurricanes listed. The observed wave heights are those measured with NOAA-NDBO buoys. The observed f_m values refer to direct measurements from the buoys or inferred from wave length values in aircraft SAR images. The SAR does not provide wave height measurements. The H_s values predicted with Equation (7) using observed f_m and U_m values are also shown in Table 2. The scaling parameter α was assumed to be one. The H_s comparison is displayed graphically in Figure 2. Because of the limited number of observations no further analysis was pursued to determine the optimum scaling factor α. Clearly, this will become useful as more wave height measurements become available. The favorable comparison shown in Fiqure 2 provides substantiation for the usefulness of the proposed method for predicting the signigicant wave height of the dominant waves ahead of the hurricanes.

Summary and Conclusions

The insight gained from the observed asymmetrical distribution of waves in the various hurricane sectors and the proposed model for describing and predicting the dominant wave properties ahead of hurricanes can be summarized in the following:

1. The dominant and most energetic waves generated in a translating hurricane wind field are found immediately ahead of the storm. These waves propagate in the same general direction as that of hurricane forward travel.

2. The dominant waves are generated by a translating fetch system that is of order 80 km in length and located to the right of the hurricane eye (in the northern hemisphere). The fetch translates with the speed of hurricane forward travel.

3. The hurricane forward travel speed plays a central role in determining the properties of the dominant waves. Fast traveling hurricanes are expected to generate longer and more energetic waves ahead of the hurricane compared to stationary hurricanes.

4. The above description of wave generation is substantiated by favorable comparisons between predicted and measured dominant wave frequencies ahead of hurricanes. The comparisons are only favorable in equilibrium hurricanes.

5. The proposed model predicts the significant wave height, H_s, of dominant waves from either the observed or predicted values of the dominant frequency, f_m. The model is considered valid only for equilibrium hurricanes.

TABLE 2

Comparison of predicted and observed H_s values for equilibruim hurricanes.

Hurricane	Observed Values $f_m(H_z)$	U_m(m/s)	H_s(m)	Predicted H_s(m) from Eq. (7)*
Camille	0.072	64	13.8	13.6
Belle I	0.075	31	7.5	8.9
Emmy II	0.085	24		6.5
Frances	0.080	32		8.2
Gloria I	0.106	23		4.6
Gloria II	0.075	34		9.3
Anita	0.090	37	6.7	7.4

* α = 1 assumed in these calulations.

6. The proposed model is suitable for statistical studies of dominant wave properties in hurricanes. It can be applied productively when complex and costly numerical procedures are not needed such as in predicting H_s or f_m values of dominant waves. Detailed directional wave properties in various sectors of the hurricane require detailed numerical procedures, however.

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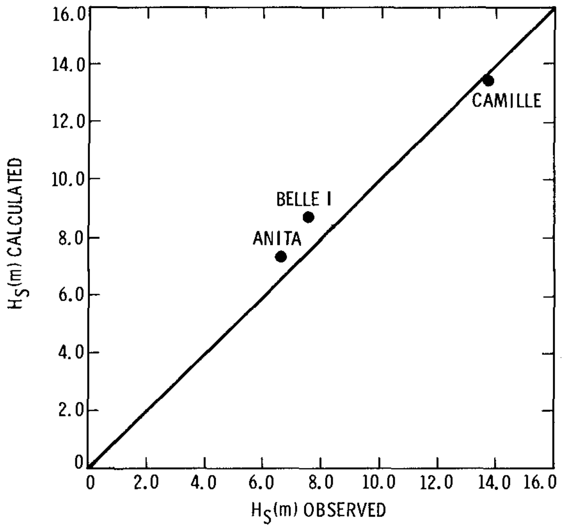

Figure 2. Comparison of observed and predicted H_s values for dominant waves.

REFERENCES

Arakawa, H. and K. Suda, Analysis of Wind Waves and Swill over the Sea to the East of Japan during the Typhoon of September 16, 1935, Monthly Weather Review, Vol. 81, no. 2, 31-37, 1953.

Bea, R. G., Gulf of Mexico Hurricane Wave Heights, Proc. of 6th Annual Offshore Technology Conf., Houston, Texas, 1974.

Bretschneider, C. L., A Non-dimensional Stationary Hurricane Wave Model, Proc. of 4th Annual Offshore Technology Conf., Houston, Texas, 1972.

Cardone, V. J., W. J. Pierson and E. G. Ward, Hindcasting the Directional Spectra of Hurricane Generated Waves, J. of Petroleum Tech., 28, 385-394, 1976.

Cardone, V. J. and D. B. Ross, State-of-the-Art Wave Prediction Methods and Data Requirements, Ocean Wave Climate, edited by M. D. Earle and A. Malahoff, Plenum Publishing Corp., 1979.

Hasselmann, K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselmann, P. Kruseman, A. Meerburg, P. Muller, D. J. Olbers, K. Richter, W. Sell, and H. Walden, Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP), Deutsche Hydrogr. Zeits., Reihe A (B^o), Nr. 12, Hamburg, 1973.

Johnson, A., and G. A. Speer, Data Report: Buoy Observations During Hurricane Belle, August 1976, Report from the NOAA Data Buoy Office, National Space Technology Laboratories, NSTL Station, Mississippi 39529, 1978.

Johnson, A., and S. M. Renwick, Data Report: Buoy Observations During Hurricanes Anita and Babe, 1977, Report from the NOAA Data Buoy Office, National Space Technology Laboratories, NSTL Station, Mississippi, 39529, 1978.

King, D. B. and O. H. Shemdin, Radar Observations of Hurricane Wave Directions, Proc. of 16th International Conference on Coastal Engineering, Hamburg, Germany, 1978.

King, D. B. and O. H. Shemdin, Equilibrium Wave Generation in Hurricanes, submitted to JGR, 1979.

Patterson, M. M., Oceanographic Data from Hurricane Camille, Proc. of 6th Annual Offshore Technology Conf., Houston, Texas, 1974.

Ward, E. G., Ocean Data Gathering Program - An Overview, Proc. of 6th Annual Offshore Technology Conf., Houston, Texas, 1974.

Withee, G. W. and A. Johnson Jr., Data Report: Buoy Observations During Hurricane Eloise (September 19 to October 11, 1975), report from the NOAA Data Buoy Office, Environmental Sciences Division, Bay St. Louis, Mississippi 39520, 1975.