CHAPTER 13

HURRICANE WIND AND WAVE FORECASTING TECHNIQUES

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ABSTRACT

Measurements needed to calibrate both significant wave and wave spectrum methods. These concern extreme waves hence related more to design than operations.

Ratio of one-dimensional wave spectrum S(f) as function of wave frequency (f) to that as function of frequency (f_o) of maximum energy density with slope, m + 1 is:

$$\frac{S(f)}{S(f_o)} = e^{\frac{m+1}{m}} \left(\frac{f}{f_o}\right)^{-(m+1)} e^{-\frac{m+1}{m}\left(\frac{f}{f_o}\right)^{-m}}$$

Ratio of period of maximum density (f_o^{-1}) to wind speed (U) in knots with significant wave height (H_s) in feet as a parameter is:

$$\frac{f_o^{-1}}{U} = 0.4 \tanh \left\{ \ln \left[\frac{1+\frac{40\ H_s}{U^2}}{1-\frac{40\ H_s}{U^2}} \right]^{1/2} \right\}^{0.6}$$

and ratio of wind speeds at radial distances r and R in nautical miles from center of <u>stationary</u> hurricane is:

$$\frac{U_r}{U_R} = -\frac{1}{2}\frac{fR}{U_R}\frac{r}{R} + \sqrt{\left[1+\frac{fR}{U_R}\right]\frac{R}{r}e^{(1-R/r)} + \left[\frac{1}{2}\frac{fR}{U_R}\frac{r}{R}\right]^2}$$

Significant wave heights [H_{Rv} and H_{rv}] in hurricane <u>moving</u> at forward speed [V_F] for significant wave heights [H_R and H_r] for <u>stationary</u> hurricane are:

$$H_{Rv} = H_R\left[1+\frac{1}{2}\frac{V_F\cos\theta}{U_{Rs}}\right]^2 \quad \text{and} \quad H_{rv} = H_r\left[1+\frac{1}{2}\frac{V_F\cos\theta}{U_{rs}}\right]^2$$

θ is angle between wind and hurricane forward speed; $H_R = K'\sqrt{R\Delta P}$ and H_r/H_R and K' are functions of fR/UR where f = coriolis parameter = 2x Earth's angular velocity x Sine (average latitude); ΔP = central pressure reduction from normal in inches of mercury; and subscript "s" denotes surface wind speeds.

This technique predicts at one station (N29W89) during Hurricane Camille (11 Aug 69) maximum wave of 42.4 ft compared to 43.1 ft measured and an envelope-of-spectra similar to one from measurements in North Sea (JONSWOP, 15 Sept 68).

Hurricanes in Hawaiian waters have recurrence interval of about 1 in 50 years. One in 1959 [DOT] caused considerable damage especially on island of Kauai.

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FORWARD

The various methods of wave forecasting are summarized briefly including wave spectra and its application to hurricane waves. The latest relationships are presented. Knowledge of the art of forecasting extreme wave conditions is important since tropical cyclones occur in most of the tropical areas of the world, including the Gulf of Mexico and Atlantic Coast of the U.S.A.

WAVE FORECASTING PHILOSOPHIES

Of the various methods of wave forecasting, there are primarily only two concepts: the Significant Wave (Bretschneider, 1970, 72a, 72b) and the Wave Spectrum (Pierson and Moskowitz, 1964; Cordone, Pierson, Ward, 1975).

1. The Significant Wave Concept is a very simple method which forecasts the principle parameters, i.e. the significant wave height, H_S and the significant wave period, T_S, or else the modal period of the frequency spectrum

$$f_o^{-1} = \sqrt[4]{5/4}\ T_s \quad .$$

The normal unit form of the theoretical spectrum can be used to estimate the wave spectrum; and the normal form of the directional spectrum, frequency dependent, can be used to estimate the complete directional spectrum.

2. The Wave Spectrum concept is on reverse to the significant wave method, i.e., the wave spectrum method predicts the directional spectrum, from which the one-dimensional spectrum and the significant wave are determined.

3. In both methods the Rayleigh distribution is used to determine the most probable maximum wave height.

4. Both methods are based upon use of measured wave data for calibration. If the same or similar wave data are used for calibration, then both methods should give essentially the same results in regard to directional spectrum, the one-dimensional spectrum, the significant wave height and period, and the period (f_O^{-1}) of maximum energy density.

5. The significant wave method is easier to use and certainly less costly, whereas the wave spectrum method requires a highly sophisticated and expensive computer program.

6. Both methods are needed to compliment each other, and also serve as calibration techniques for each other.

7. The methods concern only the extreme wave conditions associated with design criteria, and not associated necessarily with the day by day or operational wind and wave criteria.

Presently, there are about seven methods used in wave forecasting and some methods are not better necessarily than others. Wave forecasting, or wave hindcasting as the case may be, is an art as well as a science. The accuracy of any method depends upon practice, experience, verification, and correlation. Both the Significant Wave Method and the Wave Spectrum methods are taught at the University of Hawaii, and it is up to the student to make a choice. These methods are presented in Bretschneider, 1967, 68, 72, 73 and Pierson, Moskowitz, 1964, and Silvester, 1974.

OCEAN WAVE SPECTRUM

ONE-DIMENSIONAL WAVE SPECTRUM.--There is very little that can be added to the state-of-the-art on ocean wave spectrum analytical expressions. Opinions have been generated on what is the best form of the wave spectrum. Only minor details exist between the various semi-empirical methods; none are of any significance to ocean engineering. The problem is to select the design wave spectrum for a particular situation, area of operation, and the recurrence interval. The only thing lacking is data for obtaining statistical extremes in some places.

The generally accepted form of the unit wave spectrum is as follows:

$$S(f) = Af^{-(m+1)}e^{-Bf^{-m}} \qquad (1)$$

where $S(f)$ = energy density, and f = wave frequency in hertz (sec^{-1}). The form of equation (1) is similar to that of the Weibull distribution function (Weibull, 1951) as used in Bretschneider (1959).

There are three parameters involved in equation (1), namely: the coefficients A and B, and the slope (m+1) of the high frequency end of the spectrum. They can be obtained, either by theory, wave forecasting relationships, or by use of measured wave spectrum data.

Based on past experience, enough information is available to postulate the form of equation (1). For example the value of maximum energy $S(f_o)$ and the wave frequency f_o at which it occurs can be determined by performing the following simple operation on equation (1):

$$\frac{d[S(f)]}{df} = 0 \qquad (2)$$

whence

$$B = \frac{m+1}{m} f_o^{m}$$

$$A = S(f_o)\, e^{\frac{m+1}{m}} f_o^{m+1}$$

thus

$$\frac{S(f)}{S(f_o)} = e^{\frac{m+1}{m}} \left(\frac{f}{f_o}\right)^{-(m+1)} e^{-\frac{m+1}{m}\left(\frac{f}{f_o}\right)^{-m}} \qquad (3)$$

Note that when (m+1) = 5, equation (3) becomes:

$$\frac{S(f)}{S(f_o)} = e^{5/4}(f/f_o)^{-5}\, e^{-5/4\,(f/f_o)^{-4}} \tag{4}$$

Equation (4), whose solution is shown in Fig. 1, is a special form of the wave spectrum given in Bretschneider (1959) as is the Pierson-Moskowitz (1964) spectrum. Sometimes engineers prefer the so-called period (T) spectrum, which can be obtained as follows:

$$S(T)\, dT = -S(f)\, df$$

where $$T = f^{-1}$$

and $$dT = -f^{-2}\, df$$

This is a simple operation and leads to:

$$\frac{S(T)}{S(T_o)} = e^{\frac{m-1}{m}} \left(\frac{T}{T_o}\right)^{m-1} e^{-\frac{m-1}{m}\left(\frac{T}{T_o}\right)^{m}} \tag{5}$$

where $S(T_o)$ is maximum with dimension $\ell^2 t^{-1}$ at wave period T_o, and (m-1) is the slope for very low periods of the period-spectrum.

Note that the dimension of S(T) is $\ell^2 t^{-1}$ and S(f) is $\ell^2 t$. When (m-1) = 3, equation (5) becomes:

$$\frac{S(T)}{S(T_o)} = e^{3/4} \left(\frac{T}{T_o}\right)^{3} e^{-3/4\,(T/T_o)^{4}} \tag{6}$$

Equation (6) is a special form of the period spectrum given in Bretschneider (1959); see Fig. 2.

All of the above equations are special forms of the Weibull Distribution function (Weibull, 1951).

Equations (4) and (6) [figures 1 and 2] are related as follows:

$$f_o^{-1} = \sqrt[4]{5/4}\, T_s$$

and $$T_o = \sqrt[4]{3/4}\, T_s$$

or $$f_o^{-1} = \sqrt[4]{5/3}\, T_o$$

$$T_s = \sqrt[4]{4/3}\, T_o \qquad = \sqrt[4]{4/5}\, f_o^{-1} \tag{7}$$

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where T_S is a definite definition of the significant wave period, not necessarily as the characteristic period used in the past.

From actual data on frequency spectrum, the corresponding period spectrum can be obtained by use of two operations:

$$\begin{aligned} S(T) &= S(f)\cdot f^2 && \text{(for the ordinate)} \\ T &= f\cdot f^{-2} && \text{(for the abscissa)} \end{aligned} \qquad (8)$$

The area under the spectrum in either case remains the same.

The design wave spectrum can be obtained by Froude scaling of measured wave spectrum, but with caution. For example:

$$\left.\begin{aligned} S_p(f) &= \lambda^{5/2}\, S_m(f) \\ f_p &= \lambda^{-1/2}\, f_m \end{aligned}\right\} \qquad (9)$$

where λ is the linear scale parameter, and p stands for predicted and m stands for measured. This assumes that ℓ^2 and t are the same from one section of gF/U^2 to the next section, which is not necessarily always true; $g = 32.16$ ft/sec^2, F = fetch (feet), and U = wind speed (ft/sec).

DIRECTIONAL SPECTRUM.—The earliest directional spreading function was the one published by Cote, et al., (1960) as obtained from the Stereo Wave Observation Project (SWOP). Since then, other forms of the directional spectrum have evolved including those by Ou, et al., (1974), Silvester (1974) and Longuet-Higgins, et al., (1963). The choice of the directional spectrum depends upon the engineering solution required. Certainly, more experimental data on the directional spectrum is required especially for engineering problems such as the reaction to wave excitation of ships and of flexible fixed and floating offshore structures. For all practical engineering purposes, it does not seem to make very much difference which of the proposed directional spectrum methods are used. (See Silvester, 1974, Fig. 3.34.)

THE ENVELOPE OF SPECTRA.—The "overshoot" of the high frequency energy during early wave generation has been observed in measurements made in both laboratory and field. The classical field observations were made during JONSWOP, that is the Joint North Sea Wave Project (Barnett, 1972 and Fig. 3), while the classical laboratory observations were made by Mitsuyasu (1968 and Fig. 4). These as well as measurements made on Lake Michigan (Liu, 1971) and on North Atlantic (Miles, 1972) are notable.

The Envelope of Spectra is of the same form as Equation (3) and for demonstration purposes the same as Equation (4), except now the value of maximum energy and the corresponding wave frequency are respectively $S(f_o{}^*)$ and $f_o{}^*$.

The Envelope Spectrum, as discussed by Bretschneider (1975) in fact should be termed "the Envelope of Spectra"; it takes the high frequencies into account and thus includes these "overshoots"

All the spectra under the Envelope of Spectra is preferable to the fully-developed sea spectrum for design purposes because the Envelope of Spectra yields more energy at the high frequencies.

Both the Envelope of Spectra and the fully-developed sea spectrum should be cut off at the particular low frequency defined by the fetch length and wind duration, which limit the length of the wave which can be generated.

As an example, the Envelope of Spectra is superimposed in Fig. 3 on the JONSWOP spectra obtained from measurements at 11 stations situated in the North Sea offshore the Island of Sylt, Germany. The spectra at all stations would be similar if the fetch length at all stations were replaced with the time growth which actually occurred at the station farthest offshore (#11). Thus, the design spectrum should be based on all spectra under the Envelope of Spectra and not on the spectrum at final time of maximum peak. This same effect is apparent in the North Atlantic spectra (Miles, 1972, Figs. 5 and 6). Perhaps a better selection of m would give a better fit, but this demonstration, given of the Envelope of Spectra, seems adequate.

The area under the Envelope of Spectra is considerably more than the area under the fully-developed spectrum $(1/4\, H_S)^2$. This is very important for engineering design purposes. In fact, it is for this reason that small boats are swamped and sunk in small lakes, such as those 2 miles in diameter under 40-knot winds, rather than in the open ocean in the roaring forties. A number of challengers have rowed across the Atlantic and the Pacific Ocean, surviving seas 40-foot high, 12-second period. Many so-called pioneers have drowned trying to get ashore during a gale on a small inland lake with waves 2- to 3-foot high, and 1- to 3-second periods. The Envelope of Spectra supports these conclusions.

DEEP WATER WAVE FORECASTING

EQUATIONS FOR PREDICTION OF DEEP WATER WAVES.--The latest Significant Wave forecasting relationships for constant wind speed and direction are as follows (Bretschneider, 1973):

$$\frac{gH_s}{U^2} = A_1 \tanh \left[B_1 \left(\frac{gF}{U^2}\right)^{m_1} \right] \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

$$\frac{C_o}{U} = \frac{gT_s}{2\pi U} = A_2 \tanh \left[B_2 \left(\frac{gF}{U^2}\right)^{m_2} \right] \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

$$t_{min} = 2 \int_o^{F_{min}} \frac{1}{C_o}\, dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where:

$$A_1 = 0.283 \qquad A_2 = 1.2$$

$$B_1 = 0.0125 \qquad B_2 = 0.077$$

$$m_1 = 0.42 \qquad m_2 = 0.25$$

H_s = significant wave height, feet
T_s = significant wave period, sec
F = fetch length, feet
U = U_s (10-min average surface wind speed), ft/sec at 10-meter water level
t = wind duration, sec
C_o = wave crest speed, ft/sec

The form of these equations was given originally by Wilson (1954); only the coefficients have been changed. Graphical solutions of them are given in Bretschneider (1970) and Shore Protection Manual (1973).

The expression gF/U^2 in equations (10) and (11) can be eliminated, and using the above coefficients and expressing U in knots and g as 32.2 ft/sec^2 the following is obtained:

$$\frac{T_s}{U} = 0.4 \tanh \left[1.07 \left\{ \operatorname{arctanh} \frac{40\, H_s}{U^2} \right\}^{0.6} \right] \qquad (13)$$

REVISIONS OF SIGNIFICANT WAVE PERIOD.--Equation (13) seems to give significant wave periods for high wind speeds about 10% too high. Based on wave spectra measured in the North Atlantic, for example, Fig. 5, from Miles (1972), equation (13) has been changed to read:

$$\frac{f_o^{-1}}{U} = 0.4 \tanh \left\{ \ln \left[\frac{1 + \frac{40\, H_s}{U^2}}{1 - \frac{40\, H_s}{U^2}} \right]^{1/2} \right\}^{0.6} \qquad (14)$$

where f_o^{-1} = sec. = period of maximum energy density, U = knots and H_s = feet and the significant wave period T_s, from equation (7) is $T_s = \sqrt[4]{4/5}\, f_o^{-1}$. Hence, equation (13) is needed no longer. The solution to equation (14) is given in Table I.

Incidentally, the Envelope of Spectra given by equation (4) was applied to the wave spectra measured in the North Atlantic (Miles,

1942) and the results plotted in Figs. 5 and 6. It is interesting to note that the Envelope of Spectra is almost in exact agreement with the +90% confidence limit of the mean International Ship Structures Committee (ISSC) spectrum (Fig. 6).

FORECASTING HURRICANE WIND FIELDS

INTRODUCTION.--A method is presented for determining hurricane wind fields and resulting deep water wave field, as proposed by Bretschneider. A detailed development of the hurricane model is given in Bretschneider, 1972 a and b. The wind field itself is based in part on work by the National Weather Service; see Meyers (1954) and Graham and Nunn (1959).

Graphs, formulae and procedures are presented by Bretschneider (1972-b) which make it possible to calculate the entire deep water wave field from model hurricane wind fields. They have been applied successfully to historical hurricanes along the U.S. East and Gulf of Mexico coasts and to U.S. National Weather Service standard project and probable maximum hurricanes for deep water conditions.

BASIC RELATIONSHIPS FOR STATIONARY HURRICANE WIND FIELD.--The balance of the pressure gradient, Coriolis, and centrifugal forces of the equation of motion leads to the non-dimensional stationary hurricane wind field, which is given as:

$$\frac{U_r}{U_R} = -\frac{1}{2}\frac{fR}{U_R}\frac{r}{R} + \sqrt{\left(1 + \frac{fR}{U_R}\right)\frac{R}{r}\,e^{(1-R/r)} + \left(\frac{1}{2}\frac{fR}{U_R}\frac{r}{R}\right)^2} \qquad (15a)$$

where U_r and U_R are the wind speeds at radial distance r and R (radius of maximum winds) from the hurricane center, $f = 2\omega \sin\phi$ (coriolis parameter) $\omega = 7.29 \times 10^{-5}$ rad/sec (angular velocity of earth), and ϕ is the latitude.

$$P = P_o + (P_N - P_o)\, e^{-R/r} \qquad (15b)$$

where P = atmospheric pressure at radial distance r, P_o = central pressure, P_N = normal pressure = 29.92 inches of mercury, and R = radius to maximum wind.

Figure 7 gives the non-dimensional solution for equation (15a) for values of $r/R \geq 1.0$ vs fR/U_R. Note that r/R did not necessarily occur where U_r/U_R is a maximum. Graham and Nunn (1959) recognized this shortcoming and made modifications based in part on experience and data. The significant change is their recommendation of a single relationship as shown in Figure 7 for $r/R \leq 1.0$. The example which follows utilizes The Graham and Nunn model for $r/R \leq 1.0$ and the National Weather Service model given by equation (15a) for $r/R \geq 1.0$ (Fig. 7).

The maximum sustained wind speed will occur at R, radius of maximum wind, and refers to a value, averaged over a time of 10-20 minutes, and reduced to the 10-meter elevation above mean sea level. The geostrophic wind speed U_R is given by:

$$U_R = K\sqrt{\Delta P} - 0.5\ fR \tag{16}$$

where U_R is in knots, $\Delta P = P_N - P_O$ is the central pressure reduction from normal in inches of mercury, and the constant K varies with latitude from 67 at 20-25°, to about 63 at 45° latitude (see Table II).

The 10-minute average wind speed, U_{RS}, at the 10-meter reference level is given by:

$$U_{RS} = k^* \ U_R \tag{17}$$

where $k^* = .865$ for all U.S. East Coast and Gulf Coast Zones A and C, and $k^* = .886$ for Gulf Coast Zone B [see Graham and Nunn (1959) for zone designations].

CORRECTION DUE TO FORWARD MOTION OF HURRICANE.--The stationary model hurricane wind field is coupled directly to the corresponding model hurricane wind field. Thus, any change in the wind field will result in a directly related change in the wave field. For a moving hurricane, the change in the wind speed component is:

$$\Delta U = \frac{1}{2} V_F \cos \theta \tag{18}$$

thus

$$U_{RS}^{*} = U_{RS} + \Delta U \tag{19}$$

where θ is the angle of wind deflected from the direction of the incurvature angle of the wind speed and V_F is average forward speed of the hurricane.

Hurricanes moving faster than the critical forward speed are not considered herein. This condition needs further study.

EXAMPLE CALCULATIONS FOR 1969 HURRICANE CAMILLE.--The following are some simple sample calculations for Camille according to parameters obtained from Cordone, Pierson & Ward (1975).

R = radius of maximum wind = 10 nautical miles
ΔP = atmospheric pressure reduction at hurricane center from normal = 105 milli-bar = 3.1" mercury
V_F = average forward speed of hurricane = 10 knots (this increased as Camille moved inland)
ϕ = approximate average latitude for maximum wave generation = 29°
f = .525 sin ϕ = coriolis parameter = .255 radians/hour
β = 25° incurvature angle for stationary hurricane

Determinations of maximum sustained wind speed at R

$K = 66$ (from Table II)
$U_R = K\sqrt{\Delta P} - 0.5\ fR = 114.9$ knots
$U_{RS} = .886\ U_R = .886(114.9) = 102$ knots

This is for the stationary hurricane and U_{RS} is the 10-minute average wind speed at the 10-meter anemometer level above mean sea level.

WIND FIELD FOR CAMILLE MOVING AT 10 KNOTS.—1. The change in wind components, ΔU, due to the moving hurricane for radii at 20° incremental angles is:

$$\Delta U = 5 \cos \theta$$

2. Thus, the 10-minute average wind speed at 10-meter level (U_{RS}*) for a moving hurricane is:

$$U_{RS}^* = U_{RS} + \Delta U = .886\ U_R + \Delta U = 102 + 5 \cos \theta$$

3. Various values for the isotachs were chosen (U_{rs} = 20, 40, 50, 60, 70, 80, 90, 100 knots), and the parameter U_{rs}/U_{RS}^* calculated for each U_{RS}^* .
4. From Fig. 7 the corresponding values of r/R were determined for the calculated parameter $fR/UR = 0.022$.
5. The wind field was then constructed for the values of U_{rs} and their corresponding radius (Fig. 8).

FORECASTING HURRICANE DEEP WATER WAVES

STATIONARY MODEL HURRICANE WAVE FIELD.—Relationships have been developed in Bretschneider (1972) for obtaining the model hurricane wave field:

$$H_R = K' \sqrt{R\Delta P} \tag{20}$$

where R and ΔP have been defined and K', a function of fR/U_R, can be obtained from Table III.
The general relationships for the entire stationary hurricane wave field, where H_r/H_R = function of fR/U_R, is shown in Fig. 9.

FORWARD MOTION OF A HURRICANE.—

$$H_{Rv} = H_R \left[1 + \frac{1}{2} \frac{V_F \cos\theta}{U_{Rs}}\right]^2 \tag{21}$$

$$H_{rv} = H_r \left[1 + \frac{1}{2} \frac{V_F \cos\theta}{U_{rs}}\right]^2 \tag{21A}$$

where H_R is obtained by use of equation (20), H_r is obtained by use of Figure 9, H_{RV} and H_{rV} are a result of the forward speed, V_F, and the direction of wind in relation to direction of forward speed as given by the angle θ. The limitation of equation (21) is that $V_F \leq V_C$, where V_C is the critical forward speed.

CAMILLE DEEP WATER WAVES

FOR SIGNIFICANT WAVES.--Calculate $fR/U_R = .255\,(10)/114.9 = 0.0222$. From Table III, $K' = 6.64$, R = radius at maximum wind.

FOR THE STATIONARY HURRICANE.--$H_R = k'\sqrt{R\Delta P} = 6.64\sqrt{31} = 37.0$ feet. Calculate

$$\frac{40\ H_R}{U_{RS}^{\ 2}} = \frac{40\ (37.0)}{(102)^2} = 0.142$$

From Table I [or equation (14)], $f_o^{-1}/U = 0.121$. Therefore, f_o^{-1} = period of maximum energy = 12.34 sec. And, T_s = significant period = $\sqrt[4]{4/5}\ f_o^{-1} = 11.67$ sec.

HURRICANE MOVING AT FORWARD SPEED, $V_a \leq V_C$ WHERE V_C = CRITICAL FORWARD SPEED.--The modified significant wave height for actual forward speed is:

$$H_a = H_R \left[1 + \frac{1/2\ V_F}{U_{RS}}\right]^2 = 37.0 \left[1 + \frac{5}{102}\right]^2 = 40.7 \text{ feet}$$

The wave period f_o^{-1} may be found by first calculating:

$$\frac{40\ H_a}{(U_{RS} + 1/2\ V_F)^2} = \frac{40(40.7)}{(107)^2} = 0.142$$

From Table I (or equation 14), $f_o^{-1}/U = 0.121$. Therefore, f_o^{-1} = .121 x (107) = 12.95 sec. And, $T_s = \sqrt[4]{4/5}\ f_o^{-1} = 12.25$ sec.

Similarly the critical forward speed, V_c in knots can be calculated from $V_F = V_c = 1.515\ T_c$.

Table IV summarizes the results of the above calculations.

SIGNIFICANT WAVES AT $r/R = 1.8$ TO 2.0.--Refer to figures 7 and 9. The maximum value of the significant wave does not occur at R = radius of maximum wind, but at 1.8 to 2.0 R, where $H_{2R} = 1.04\ H_R$ = 37 x 1.04 = 38.5 feet and $U_{2RS} = 0.9\ U_{RS} = 0.9\ (102) = 91.8$ knots.

$$\frac{40\ H}{U^2} = \frac{40\ (38.5)}{(91.8)^2} = 0.182$$

$$\frac{f_o^{-1}}{U} = 0.139$$

$$f_o^{-1} = 0.139\ (91.8) = 12.76\ \text{sec}$$

$$T_s = 12.76\ \sqrt[4]{4/5} = 12.07\ \text{sec}$$

For a hurricane moving at 10 knots:

$$U_{2RS} = 91.8 + 5 = 96.8\ \text{knots}$$

$$H_{2RS} = 38.5\left[1 + \frac{5}{91.8}\right]^2 = 42.8\ \text{feet}$$

$$\frac{f_o^{-1}}{U} = 0.139$$

$$f_{o\ (2R)}^{-1} = 0.139\ (96.8) = 13.46\ \text{sec}$$

$$T_s = 13.46\ \sqrt[4]{4/5} = 12.73\ \text{sec}$$

A summary of the above calculations for r = 2R is given in Table V.

CAMILLE DEEP WATER WAVES AT "2R"

The path of Hurricane Camille and the location of the six wind and wave measuring stations are shown in Fig. 10 taken from Cordone, et al. (1975) as part of the Ocean Data Gathering Program (ODGP) of the Shell Development Co.

The height of the maximum significant wave corrected for a moving hurricane was determined for each ΔU corresponding to radii at 20° incremental angles according to:

$$H_{Rv} = H_R\left[1 + \frac{1}{2}\,\frac{V_F\ \cos\theta}{U_{RS}}\right]^2 = 36.97\left[1 + \frac{\Delta U\ \cos\theta}{101.8}\right]^2$$

Values of H_r/H_{RV} were determined for the parameter $fR/U_R = 0.022$ and set values of r/R using Fig. 9.

The values of H_r corresponding to the given radius r were then calculated for each H_{RV} and the results plotted in Fig. 11.

The wave field was then constructed for chosen values of H_r (in this example, $H_r = 10, 15, 20, 30, 35, 40$ feet) using Fig. 11.

The results of the above wave predictions are shown in Figure 8, superimposed on the wind field. A comparison is made in Figure 12 between these predictions and measurements made at six stations off the Louisiana coast as part of the ODGP.

In order to make the comparison between the predicted and the measured significant wave heights at the ODGP stations, the predicted wind and wave field was placed along the storm track with forward direction 10° W of N and centered at time 1800 CDT. The predicted significant wave heights are for an instantaneous wave field. The comparison made here is not absolute since the wave heights will change as a function of time with the moving hurricane. The maximum measured significant wave height was 43.13 feet compared to 42.4 feet predicted in the field generally and not necessarily at one of the stations.

A comparison between the measured spectrum (Cordone, et al., 1975) and two predicted spectrum (Cordone, et al., 1975 and Bretschneider, 1970) at ODGP Station 1 at 1600 hours CDT, August 11, 1969, is presented in Fig. 13. Both predictions are well within the measured ±90% confidence limit (Fig. 10 of Cordone, et al., 1970). Fig. 13 includes the Envelope of Spectra (equation 4) based on the measured values (at the maxima where $f_o^{-1} = 14.3$ seconds, $S(f_o) = 4{,}030$ ft^2 sec $= 374.4$ m^{2}sec) in contrast to the predicted spectra which are based upon predicted values of the wave height. This Envelope of Spectra is very similar to that from the JONSWOP measurements (Fig. 3). For example, if Camille were a design hurricane, the design spectrum would be all the spectra under the Envelope of Spectra as shown in Fig. 13 rather than the actual measured spectrum, in order to account for the "overshoot" of early wave generation in time, fetch, and wind speed. Some other value of m might be more appropriate in equations (3) and (4) and thus might fit better the measured spectra.

The purpose was not to determine the proper value of m for the Envelope of Spectra, but was to illustrate the importance of the "overshoot". There is need for more research in this area.

HAWAIIAN DEEP WATER WAVES

The tracks of the major hurricanes near Hawaii for the period 1950-1974 are shown in Figure 14. They include DOT (1959), NINA (1957) and HIKI (1950).

Note that most hurricanes approach the Islands from either the east or south. Although most have done little or no damage, a few have been devastating such as Hurricane DOT (1959) which did over 5.5 million dollars worth of damage to crops and buildings on the island of Kauai with gusts over 100 mph recorded at Kilauea Point Lighthouse and $150,000 in damage on the Islands of Oahu and Hawaii. In 1972 Hurricane DIANA generated waves estimated to be 30 feet high along the SE (Puna) coast of the Island of Hawaii.

Using the technique described in "Wind Field for Camille" a graphical presentation was prepared (Fig. 15) which when applied to Figure 14 provides predictions of the wind and wave field that may be expected to occur in the open ocean during a hurricane off the Hawaiian Islands. Its recurrence interval is estimated to be once in fifty years.

As a hurricane approaches the land, the winds are reduced by 1% per mile within 10 miles of the coast and correspondingly the waves are decreased in height, except very close to shore where the waves begin to break. However, the effect of the Islands is fairly negligible since their extent is small compared to that of the hurricane. Therefore, it is reasonable to expect significant waves of up to 30 feet and greater in height with 60 knot (69 mph) winds. In addition, instantaneous gusts of 84 knots (97 mph) may occur, and individual maximum waves could exceed 50 feet in height. Winds in the usually windy Pali (cliff) on the Island of Oahu can be expected to exceed 87 knots (100 mph).

DISCUSSION AND SUMMARY

There is an abundance of information available for calculating in deep water (1) the standard project and probable maximum hurricane wind and wave fields as verified adequately by use of the Ocean Data Gathering Project measurements (2) the maximum sustained wind speed, U_R, and maximum significant wave height, H_R, at radius of maximum wind, R, as applied successfully to historical hurricanes along the U.S. East and Gulf of Mexico coasts and to the standard project and probable maximum hurricanes of the U.S. National Weather Service (Bretschneider, 1972-b). The method is limited to a hurricane moving at speed equal to or less than its critical forward speed. Those faster need further study.

Winds and waves due to a hurricane moving over the Continental Shelf and the Coastline are modified by bottom friction percolation, refraction, shoaling, breaking, and water depth change caused by storm surge and/or tide. These must be taken into account.

ACKNOWLEDGEMENT

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NOTE CONCERNING FIG. 4: "D" is wind damper opening in percent and "F" is the fetch in meters. Thus, the index 15-8 denotes a fetch of 8 meters subject to a wind generated when damper is 15% open.

APPENDIX I.--REFERENCES

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LIST OF SYMBOLS

ΔH	Change in significant wave height due to a change in wind speed and fetch length, moving hurricane
H_r	Significant wave height at r, stationary hurricane
H_R	Significant wave height at R, stationary hurricane
H_{Rv}	Significant wave height at R due to change in wind speed, moving hurricane
H_x	Component of H along x-axis
H_y	Component of H along y-axis
K	Coefficient used in expression for U_R
K'	Coefficient used in expression for H_R
k^*	Coefficient used in expression for U_{RS}
ΔP	Central pressure reduction from normal, inches mercury
r	Radial distance from center of hurricane
R	Radius of maximum wind
s	A subscript to denote surface wind speed
ΔU	Change in wind speed due to moving hurricane
U_r	Geostrophic wind speed at distance r from hurricane center, stationary hurricane
U_s	10-minute average surface wind speed at 10 meters above water surface
U_R	Geostrophic wind speed at distance r from hurricane center, stationary hurricane
U_{rs}	Surface wind speed at distance r from hurricane center, stationary hurricane
U_{RS}	Surface wind speed at distance R from hurricane center, stationary hurricane
U_{RS}^*	Surface wind speed at distance R from hurricane center due to change in wind speed, moving hurricane
V_F	Forward speed of hurricane
β	Incurvature angle of wind vector
θ	Angle of the radius measured counterclockwise from the x-axis
ϕ	Latitude
ω	Angular velocity of earth
P	Atmospheric pressure at radial distance r
P_o	Central pressure
P_N	Normal pressure = 29.92 inches H_g
ℓ	Length
t	Time
T	Wave period in general
T_s	Significant wave period
T_c	Critical period
f_o^{-1}	Period of maximum energy density
f	Wave frequency; also Coriolis parameter
f_o	Frequency of maximum energy density
f_o^*	Frequency of maximum energy density for the Envelope Spectrum

TABLE I

$$\frac{f_o^{-1}}{U} \quad \text{vs} \quad \frac{40\ H}{U^2}$$

f_o^{-1} = sec U = knots H = feet

$\frac{40\ H}{U^2}$	f_o^{-1}/U	$\frac{40\ H}{U^2}$	f_o^{-1}/U
0.0	0.0	0.510	0.24383
0.010	0.02521	0.520	0.24638
0.020	0.03814	0.530	0.24892
0.030	0.04856	0.540	0.25143
0.040	0.05760	0.550	0.25393
0.050	0.06572	0.560	0.25641
0.060	0.07317	0.570	0.25888
0.070	0.08010	0.580	0.26133
0.080	0.08661	0.590	0.26377
0.090	0.09276	0.600	0.26619
0.100	0.09860	0.610	0.26861
0.110	0.10419	0.620	0.27101
0.120	0.10955	0.630	0.27340
0.130	0.11470	0.640	0.27579
0.140	0.11966	0.650	0.27817
0.150	0.12446	0.660	0.28054
0.160	0.12911	0.670	0.28291
0.170	0.13362	0.680	0.28528
0.180	0.13800	0.690	0.28764
0.190	0.14226	0.700	0.29000
0.200	0.14642	0.710	0.29237
0.210	0.15047	0.720	0.29473
0.220	0.15442	0.730	0.29710
0.230	0.15828	0.740	0.29948
0.240	0.16206	0.750	0.30186
0.250	0.16576	0.760	0.30426
0.260	0.16938	0.770	0.30666
0.270	0.17293	0.780	0.30908
0.280	0.17642	0.790	0.31151
0.290	0.17984	0.800	0.31397
0.300	0.18320	0.810	0.31644
0.310	0.18650	0.820	0.31895
0.320	0.18975	0.830	0.32148
0.330	0.19295	0.840	0.32405
0.340	0.19610	0.850	0.32665
0.350	0.19920	0.860	0.32931
0.360	0.20225	0.870	0.33202
0.370	0.20526	0.880	0.33479
0.380	0.20823	0.890	0.33763
0.390	0.21116	0.900	0.34056
0.400	0.21405	0.910	0.34359
0.410	0.21691	0.920	0.34675
0.420	0.21973	0.930	0.35005
0.430	0.22252	0.940	0.35356
0.440	0.22528	0.950	0.35731
0.450	0.22801	0.960	0.36140
0.460	0.23071	0.970	0.36599
0.470	0.23338	0.980	0.37139
0.480	0.23603	0.990	0.37844
0.490	0.23865	0.999	0.39082
0.500	0.24125	1.000	0.

TABLE III

K' vs fR/U_R

[Reproduced from Bretschneider(1972-a)]

fR/U_R	K'	fR/U_R	K'
0	7.50	0.15	4.50
.005	7.25	0.16	4.42
.010	7.05	0.17	4.34
.015	6.85	0.18	4.28
.020	6.70	0.19	4.18
.025	6.55	0.20	4.10
.030	6.40	0.21	4.03
.035	6.25	0.22	3.97
.040	6.10	0.23	3.91
.045	5.95	0.24	3.85
.050	5.80	0.25	3.80
.055	5.70	0.26	3.75
.060	5.60	0.27	3.70
.065	5.49	0.28	3.65
.070	5.42	0.29	3.60
.075	5.34	0.30	3.55
.080	5.27	0.31	3.50
.085	5.20	0.32	3.45
.090	5.13	0.33	3.40
.095	5.06	0.34	3.35
.100	5.00	0.35	3.30
.110	4.88	0.36	3.26
.120	4.76	0.37	3.23
.130	4.66	0.38	3.20
.140	4.57	0.39	3.17
.150	4.50	0.40	3.15

TABLE II

K and f vs ϕ
(Reproduced from Bretschneider, 1972a)

ϕ Deg. Lat.	20	22.5	25.0	27.5	30.0
K	67	67	67	66	66
f(hours)$^{-1}$	0.18	0.20	0.22	0.24	0.26
ϕ Deg. Lat.	32.5	35.0	37.5	40.0	42.5
K	66	66	65	64	63
f(hours)$^{-1}$	0.28	0.30	0.32	0.34	0.36

TABLE IV

SUMMARY OF HINDCAST OF SIGNIFICANT WAVES AT R FOR CAMILLE

	Stationary Hurricane	Actual Forward Speed	Critical Forward Speed
V_F (knots)	0	10	20.6
H_s (feet)	37.0	40.7	44.8
f_o^{-1}(sec)	12.34	12.95	13.58
T_s (sec)	11.67	12.25	12.84
U_{Rs} (knots)	102	107	112.3

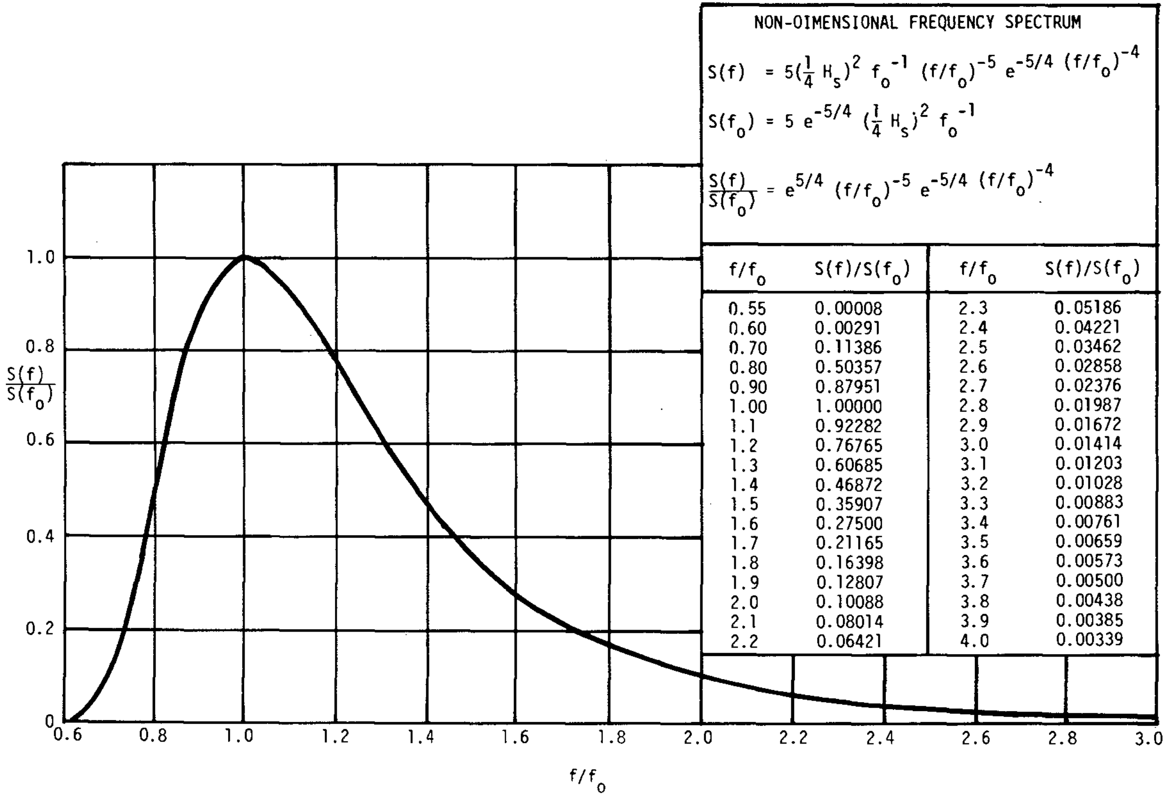
TABLE V

SUMMARY OF HINDCAST OF SIGNIFICANT WAVES AT r = 2R FOR CAMILLE

	Stationary Hurricane	Actual Forward Speed	Critical Forward Speed
V_F (knots)	0	10	21.7
H_s (feet)	38.5	42.8	48.14
f_o^{-1} (sec)	12.76	13.46	14.26
T_s (sec)	12.07	12.73	13.49
U_{Rs} (knots)	91.8	96.8	102.7

Note: For Tables IV and V, U_{Rs} is the 10-minute average at 10 meter elevation.

Fig. 1	Non-Dimensional Wave Frequency Spectrum
Fig. 2	Non-Dimensional Wave Period Spectrum
Fig. 3	Spectra of Waves Generated in North Sea by Winds offshore Island of Sylt, Germany on 15 Sept. 1968 during Joint North Sea Wave Observation Project (Barnett, 1972) with the Envelope of Spectra added
Fig. 4	Spectra of Waves Generated in Kyushu University Laboratory by Wind (Mitsuyasu, 1968) with Envelope of Spectra added. See "note concerning Fig. 4" preceding "References" .
Fig. 5	Spectra of Waves Measured in 1954-67 in North Atlantic Ocean (station India at about N59 W20) with significant height [H_S] of 25-35 ft compared to spectrum of Intern. Ship Structures Comm [ISSC] for H_S of 29.42 ft and 9.14 sec. period (Miles, 1972). The Envelope of Spectra is added.
Fig. 6	Spectrum of Waves with Significant Height of 35-45 ft and its standard deviation as measured in 1954-67 in North Atlantic Ocean at about N59 W20 and as predicted by ISSC (Miles, 1972). The Envelope of Spectra is added.
Fig. 7	Ratio of Wind Speed, U_r, at Radial Distance, r, to Speed, U_R, at Radial Distance, R, of Maximum Wind versus r/R with the Coriolis (f) Function, fR/U_R, as a Parameter. For $r/R \geq 1$ use equation (15) and for $r/R \leq 1$ use Graham and Nunn (1972).
Fig. 8	Wind and Wave Field Predicted for Hurricane Camille (1969)
Fig. 9	Ratio of Significant Wave Height, H_r, at Radial Distance, r, from center of a stationary hurricane to that, H_R, at Radial Distance, R, of Maximum Wind Speed with Coriolis (f) Function, fR/U_R, as a Parameter
Fig. 10	Path of Hurricane Camille (1969) thru Six Measuring Stations of Shell's Ocean Data Gathering Program in the Gulf of Mexico
Fig. 11	Predicted Height of the Significant Wave Generated by Hurricane Camille (1969) at Various Distances from its Center. Angles are measured clockwise from true North to the particular station.
Fig. 12	Predicted and Measured Height of the Significant Wave Generated in the Gulf of Mexico at Six Different Measuring Stations of Shell's Ocean Data Gathering Program by Hurricane Camille, 1969. Values estimated from Fig. 11.
Fig. 13	Spectrum of Waves Generated by Hurricane Camille at ODGP-Station 1 (N29-05 W88-44) on 17 August 1969 at 1600 h CDT and those hindcast by the Significant Wave and Wave Spectrum methods with the Envelope of Spectra added.
Fig. 14	Tracks of Hurricanes and Tropical Storms in the Vicinity of the Hawaiian Islands for the period 1950-1974 [from National Weather Service of NOAA]
Fig. 15	Hurricane Wind and Wave Field Model for use with Fig. 14 hence it should be to same scale as Fig. 14. Place on Fig. 14 to obtain wind-wave field in area selected.



NON-OIMENSIONAL FREQUENCY SPECTRUM

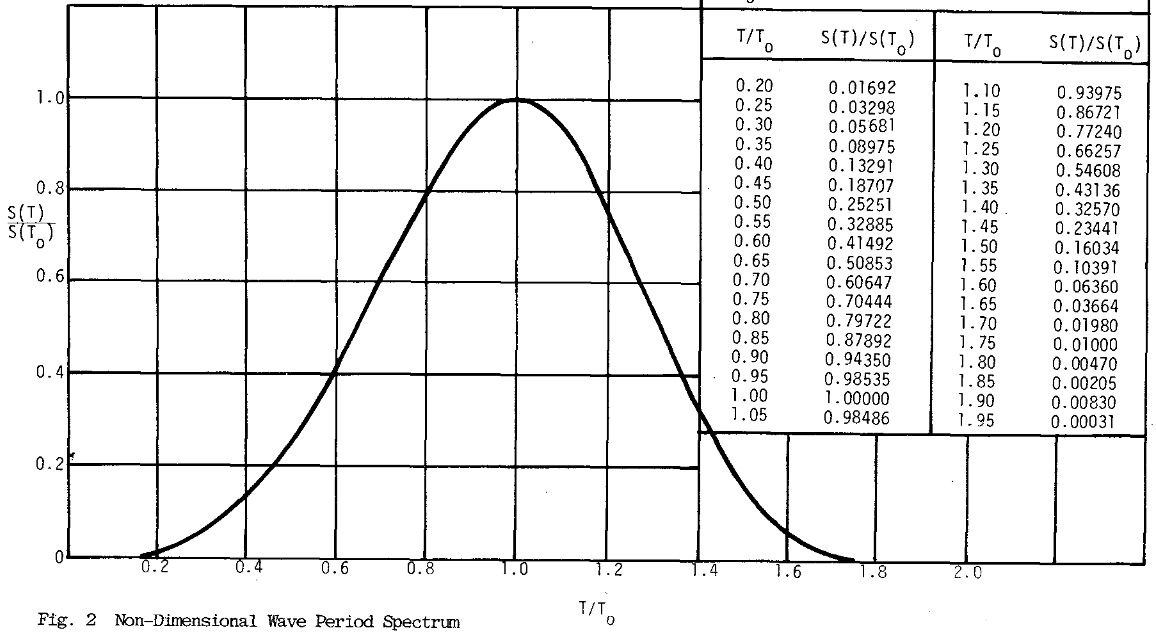
$$S(f) = 5(\tfrac{1}{4} H_s)^2 f_o^{-1} (f/f_o)^{-5} e^{-5/4 (f/f_o)^{-4}}$$

$$S(f_o) = 5 e^{-5/4} (\tfrac{1}{4} H_s)^2 f_o^{-1}$$

$$\frac{S(f)}{S(f_o)} = e^{5/4} (f/f_o)^{-5} e^{-5/4 (f/f_o)^{-4}}$$

f/f_o	$S(f)/S(f_o)$	f/f_o	$S(f)/S(f_o)$
0.55	0.00008	2.3	0.05186
0.60	0.00291	2.4	0.04221
0.70	0.11386	2.5	0.03462
0.80	0.50357	2.6	0.02858
0.90	0.87951	2.7	0.02376
1.00	1.00000	2.8	0.01987
1.1	0.92282	2.9	0.01672
1.2	0.76765	3.0	0.01414
1.3	0.60685	3.1	0.01203
1.4	0.46872	3.2	0.01028
1.5	0.35907	3.3	0.00883
1.6	0.27500	3.4	0.00761
1.7	0.21165	3.5	0.00659
1.8	0.16398	3.6	0.00573
1.9	0.12807	3.7	0.00500
2.0	0.10088	3.8	0.00438
2.1	0.08014	3.9	0.00385
2.2	0.06421	4.0	0.00339

Fig. 1 Non-Dimensional Wave Frequency Spectrum



NON-DIMENSIONAL PERIOD SPECTRUM

$$S(T) = 3(\tfrac{1}{4} H_s)^2 \, T_o^{-1} \, (T/T_o)^3 \, e^{-3/4 \, (T/T_o)^4}$$

$$S(T_o) = 3 \, e^{-3/4} \, (\tfrac{1}{4} H_s)^2 \, T_o^{-1}$$

$$\frac{S(T)}{S(T_o)} = e^{3/4} \, (T/T_o)^3 \, e^{-3/4 \, (T/T_o)^4}$$

T/T_o	$S(T)/S(T_o)$	T/T_o	$S(T)/S(T_o)$
0.20	0.01692	1.10	0.93975
0.25	0.03298	1.15	0.86721
0.30	0.05681	1.20	0.77240
0.35	0.08975	1.25	0.66257
0.40	0.13291	1.30	0.54608
0.45	0.18707	1.35	0.43136
0.50	0.25251	1.40	0.32570
0.55	0.32885	1.45	0.23441
0.60	0.41492	1.50	0.16034
0.65	0.50853	1.55	0.10391
0.70	0.60647	1.60	0.06360
0.75	0.70444	1.65	0.03664
0.80	0.79722	1.70	0.01980
0.85	0.87892	1.75	0.01000
0.90	0.94350	1.80	0.00470
0.95	0.98535	1.85	0.00205
1.00	1.00000	1.90	0.00830
1.05	0.98486	1.95	0.00031

Fig. 2 Non-Dimensional Wave Period Spectrum

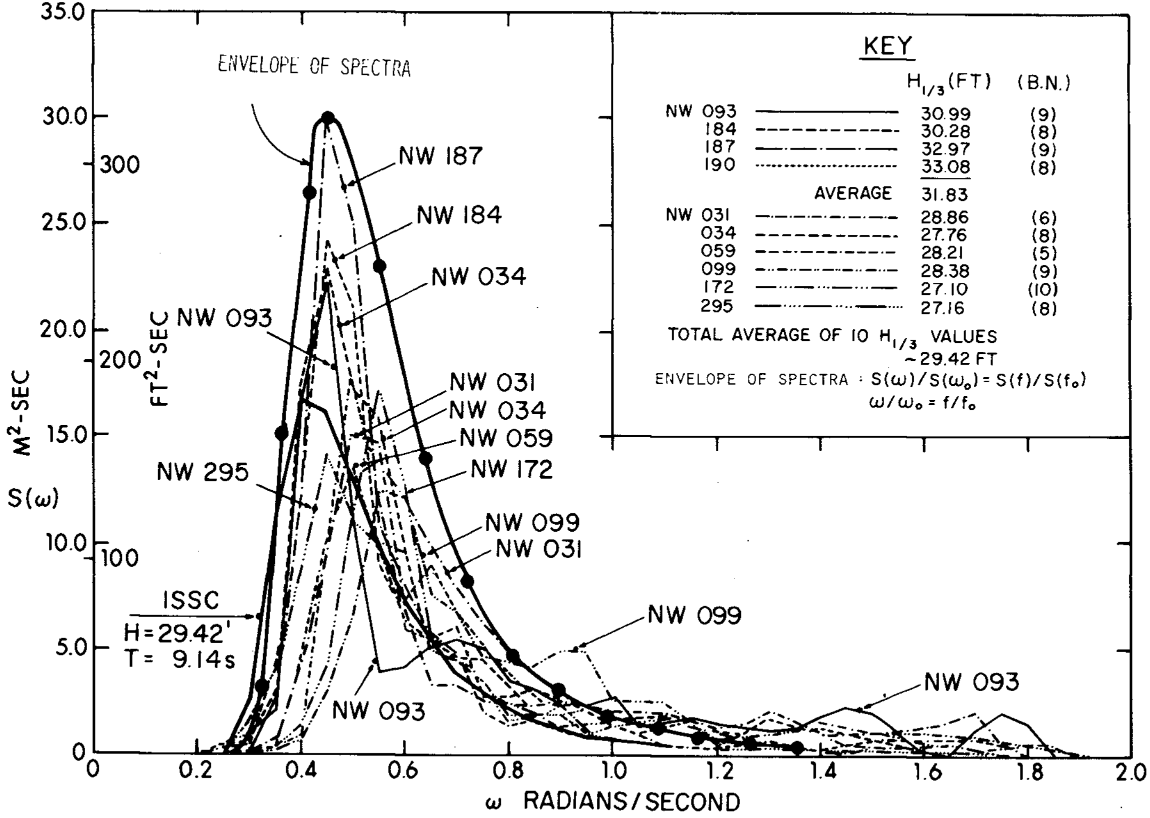


Fig. 5 Spectra of Waves Measured in 1954–67 in North Atlantic Ocean (station India at about N59 W20) with significant height [H_S] of 25–35 ft compared to spectrum of Intern. Ship Structures Comm [ISSC] for H_S of 29.42 ft and 9.14 sec. period (Miles, 1972). The Envelope of Spectra is added.

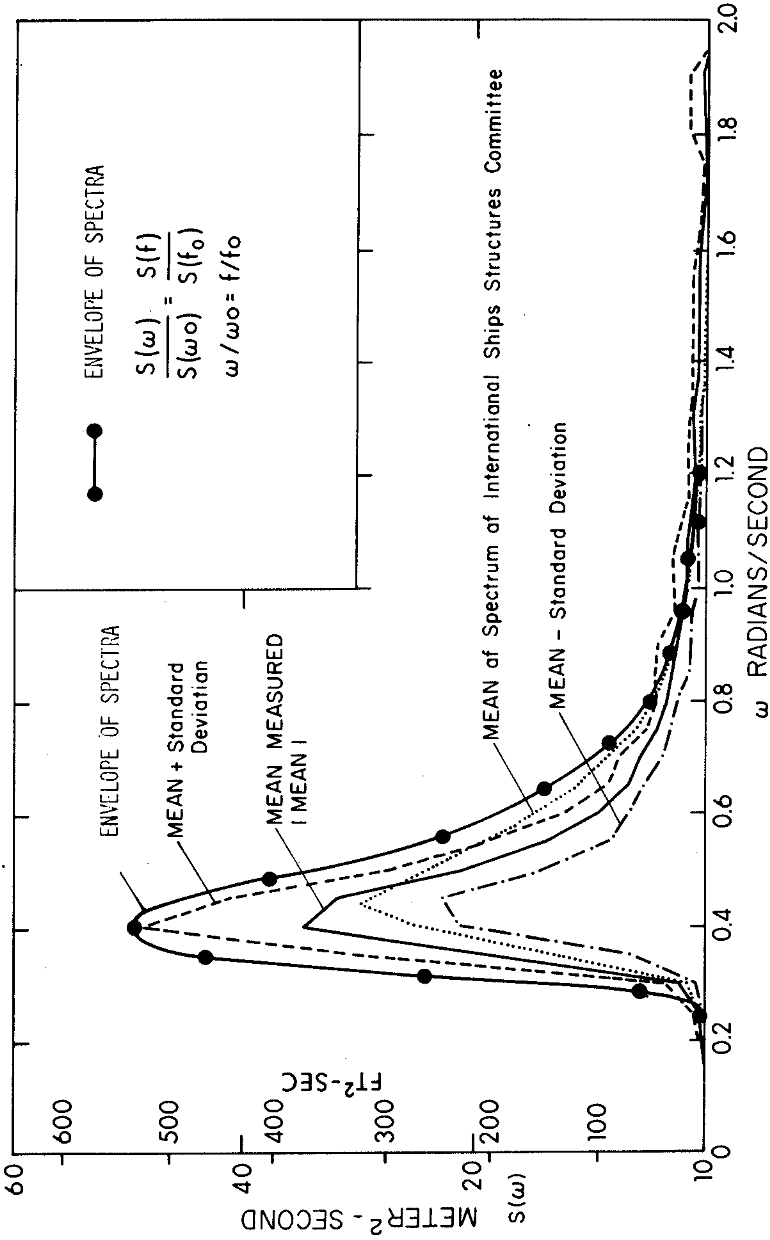


Fig. 6 Spectrum of Waves with Significant Height of 35–45 ft and its standard deviation as measured in 1954–67 in North Atlantic Ocean at about N59 W20 and as predicted by ISSC (Miles, 1972). The Envelope of Spectra is added.

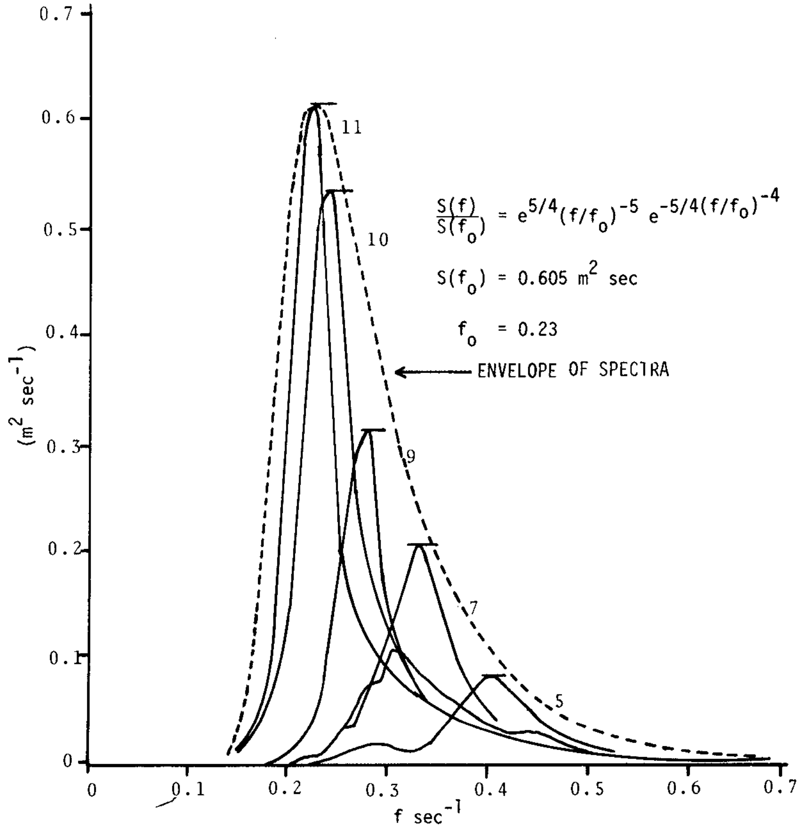


Fig. 3 Spectra of Waves Generated in North Sea by Winds offshore Island of Sylt, Germany on 15 Sept. 1968 during Joint North Sea Wave Observation Project (Barnett, 1972) with the Envelope of Spectra added

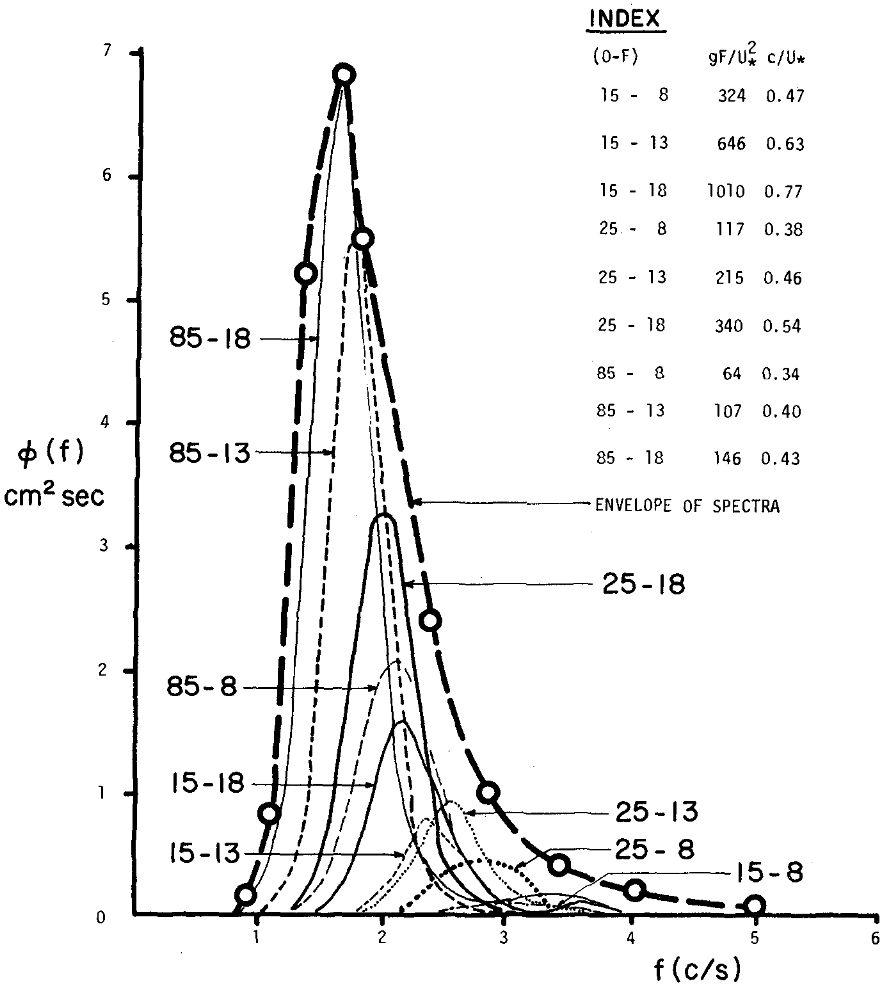


Fig. 4 Spectra of Waves Generated in Kyushu University Laboratory by Wind (Mitsuyasu, 1968) with Envelope of Spectra added. See "note concerning Fig. 4" preceding "References".

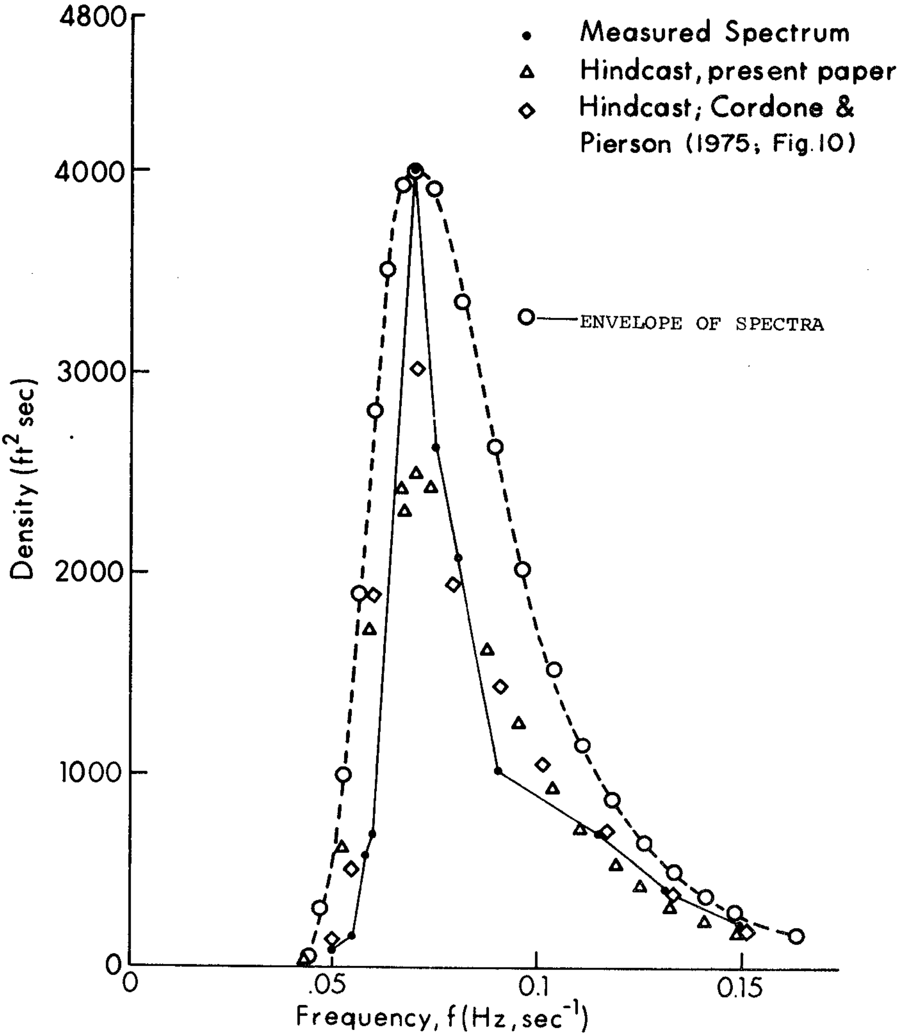


Fig. 13 Spectrum of Waves Generated by Hurricane Camille at ODGP-Station 1 (N29-05 W88-44) on 17 August 1969 at 1600 h CDT and those hindcast by the Significant Wave and Wave Spectrum methods with the Envelope of Spectra added.

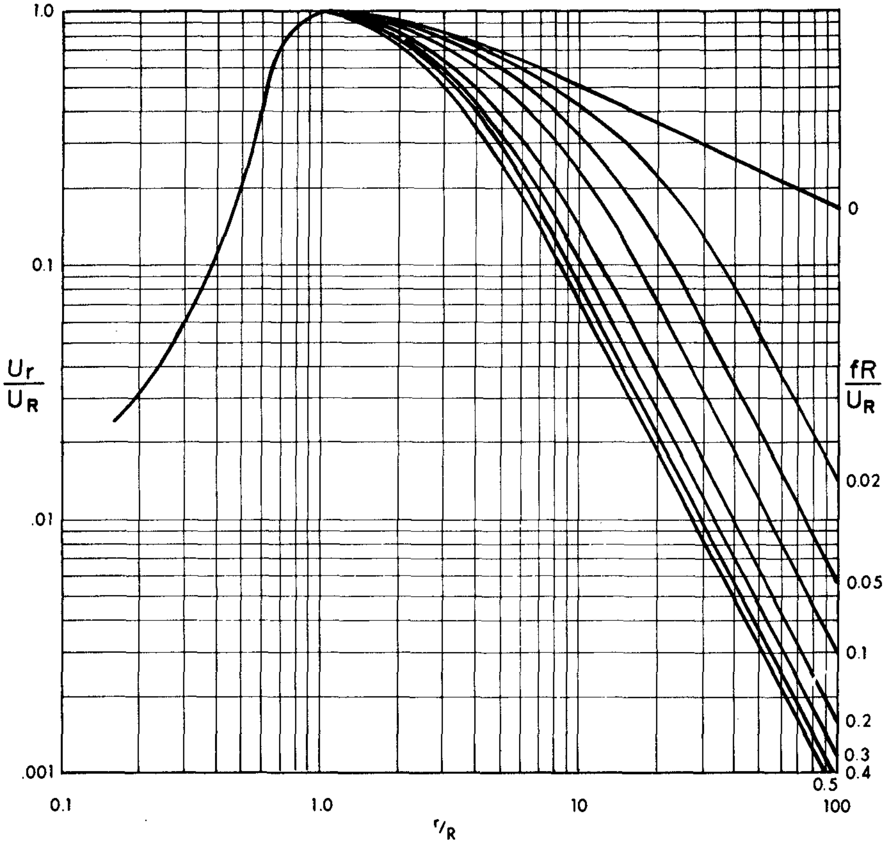


Fig. 7 Ratio of Wind Speed, U_r, at Radial Distance, r, to Speed, U_R, at Radial Distance, R, of Maximum Wind versus r/R with the Coriolis (f) Function, fR/U_R, as a Parameter. For $r/R \geq 1$ use equation (15) and for $r/R \leq 1$ use Graham and Nunn (1972).

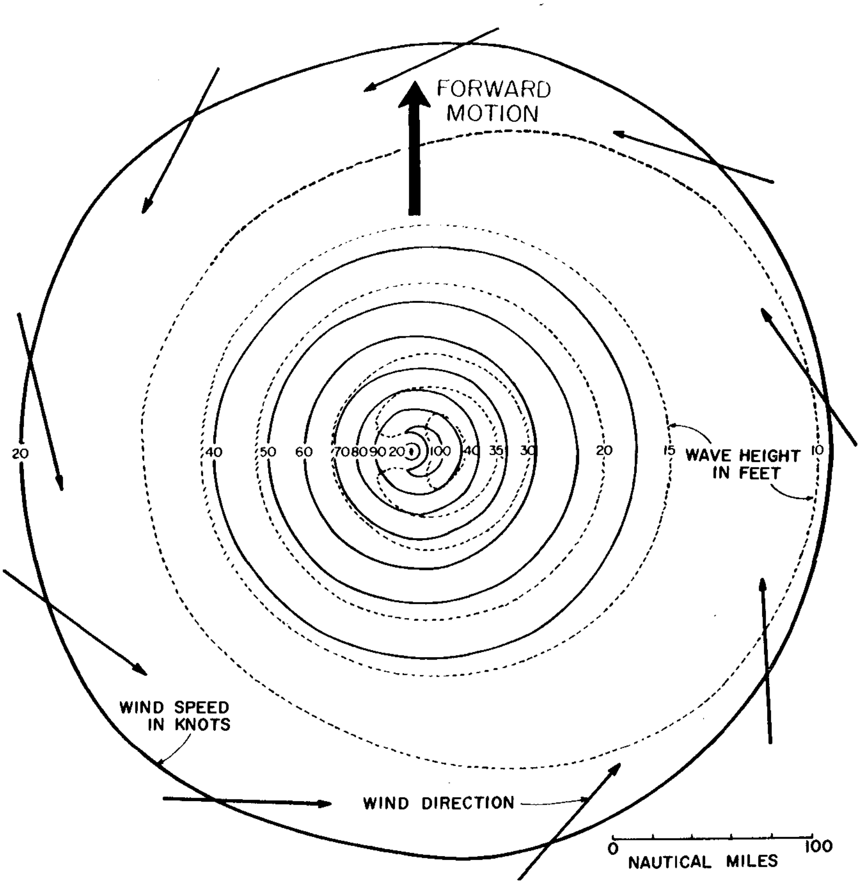


Fig. 8 Wind and Wave Field Predicted for Hurricane Camille (1969)

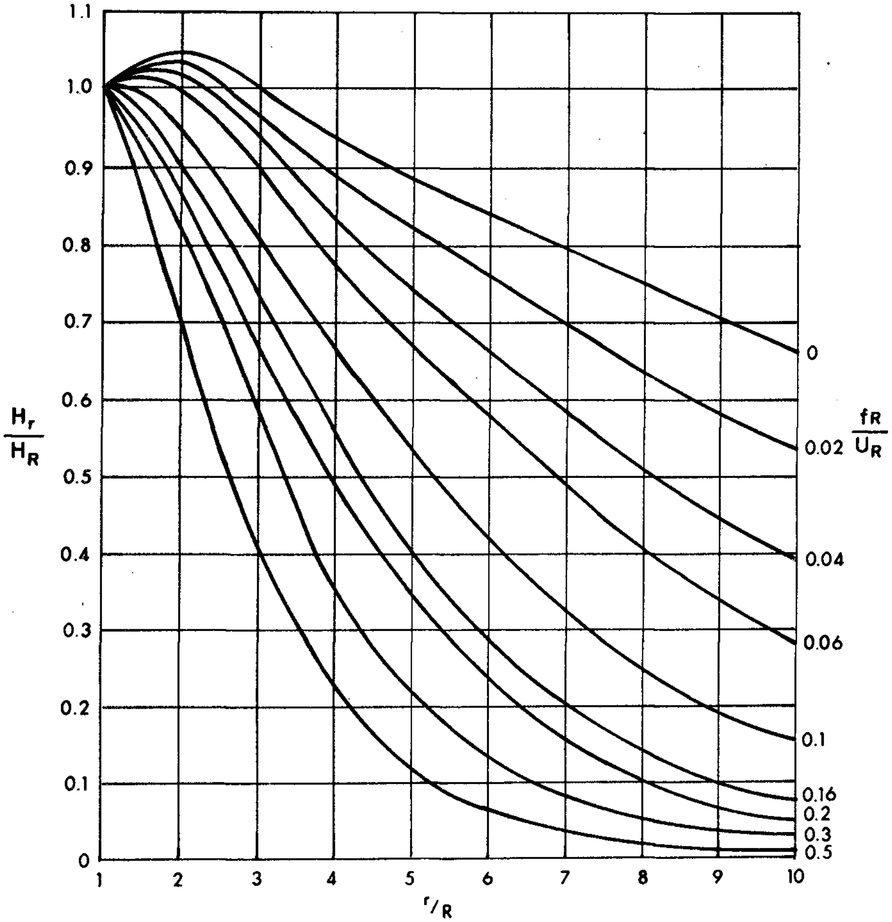
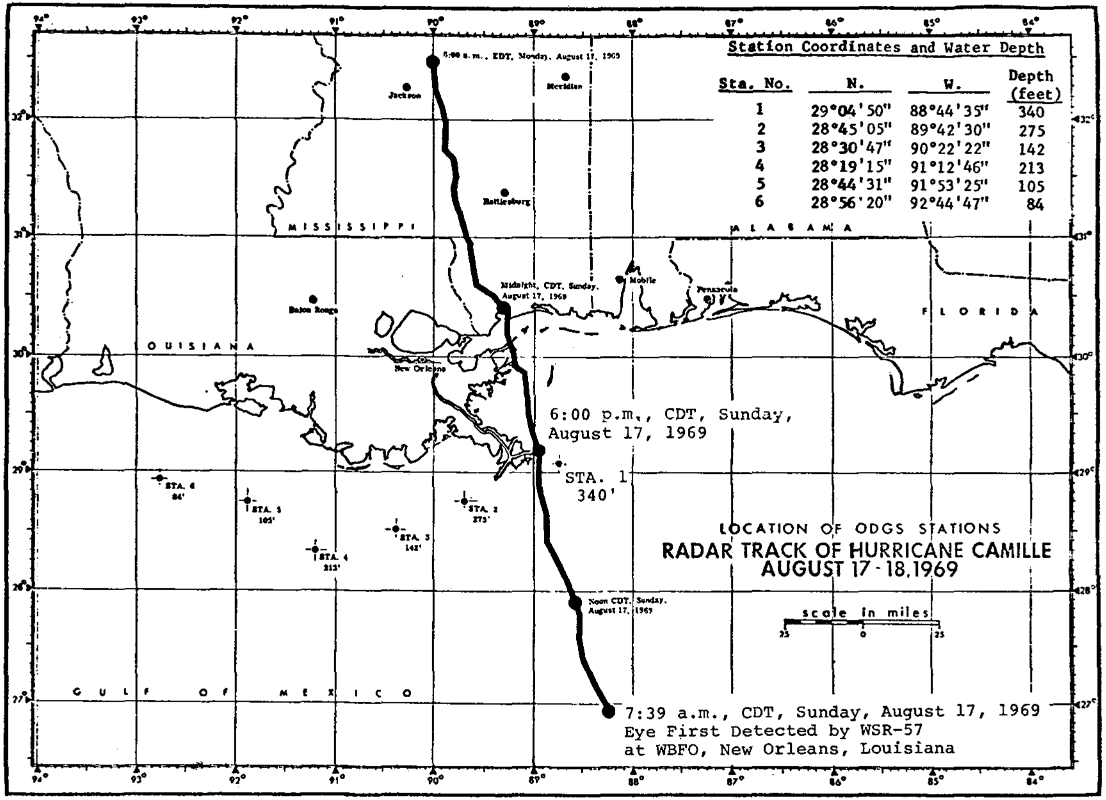


Fig. 9 Ratio of Significant Wave Height, H_r, at Radial Distance, r, from center of a stationary hurricane to that, H_R, at Radial Distance, R, of Maximum Wind Speed with Coriolis (f) Function, fR/U_R, as a Parameter



Station Coordinates and Water Depth

Sta. No.	N.	W.	Depth (feet)
1	29°04'50"	88°44'35"	340
2	28°45'05"	89°42'30"	275
3	28°30'47"	90°22'22"	142
4	28°19'15"	91°12'46"	213
5	28°44'31"	91°53'25"	105
6	28°56'20"	92°44'47"	84

Fig. 10 Path of Hurricane Camille (1969) thru Six Measuring Stations of Shell's Ocean Data Gathering Program in the Gulf of Mexico

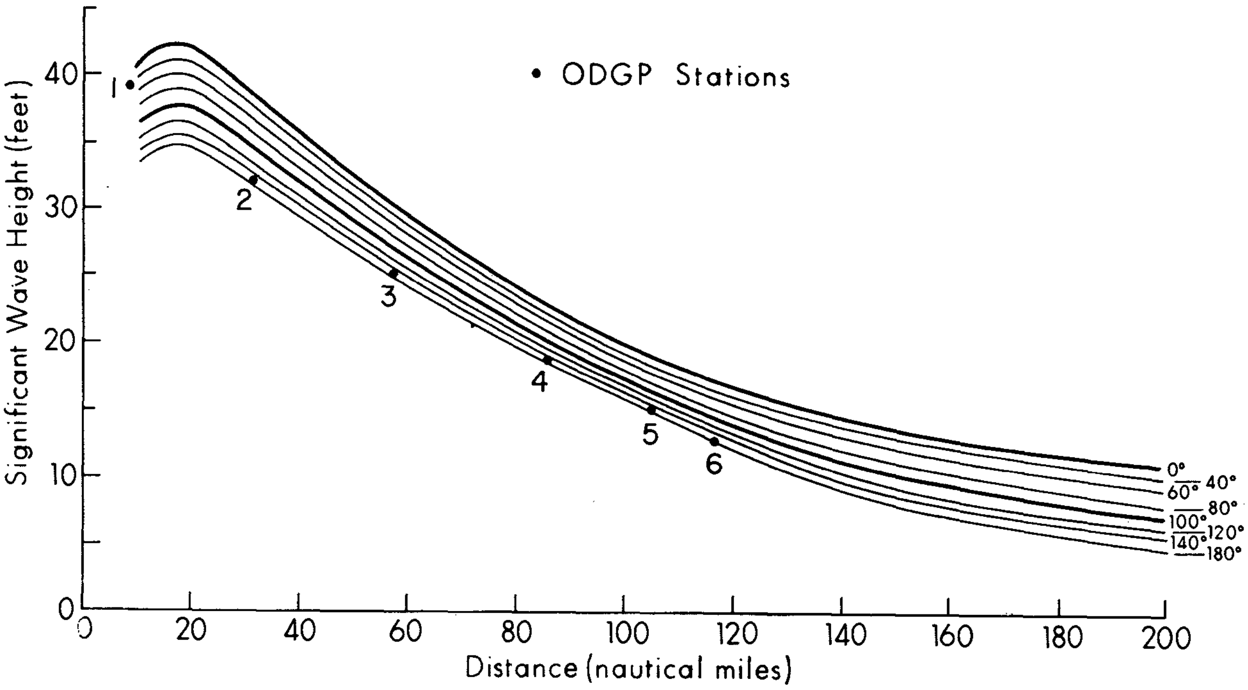


Fig. 11 Predicted Height of the Significant Wave Generated by Hurricane Camille (1969) at Various Distances from its Center. Angles are measured clockwise from true North to the particular station.

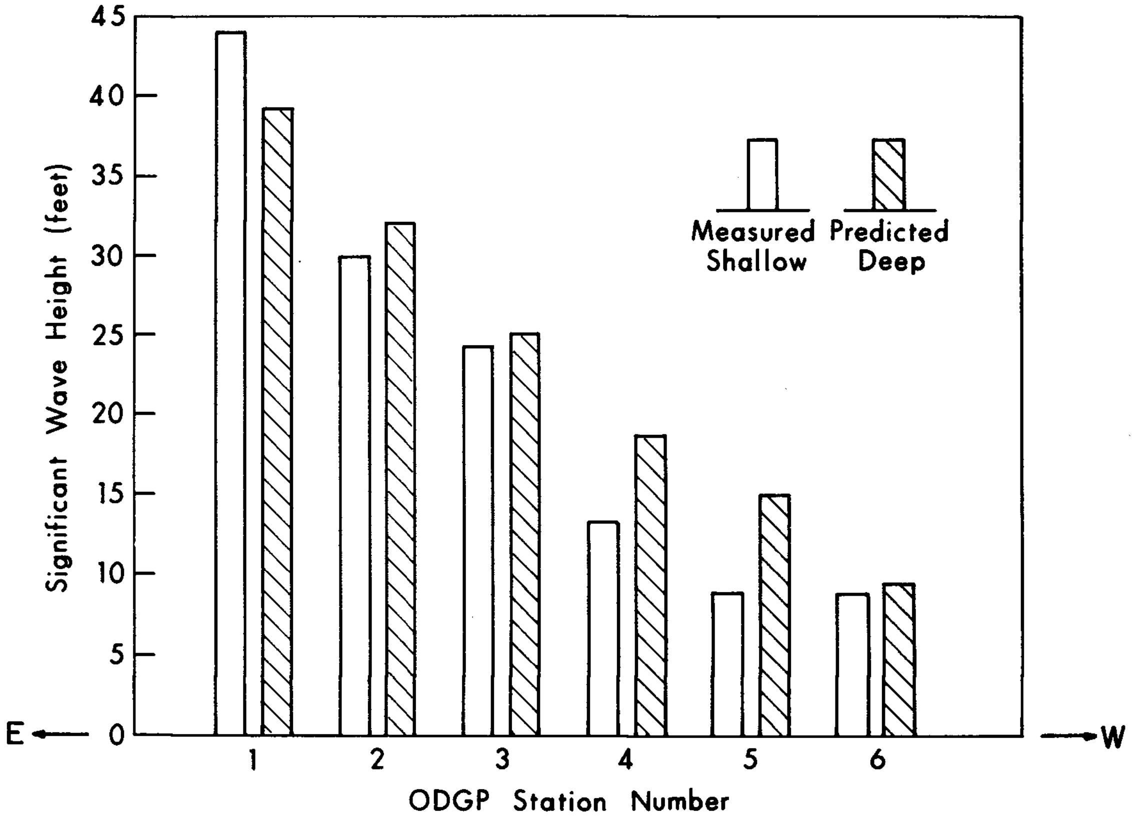


Fig. 12 Predicted and Measured Height of the Significant Wave Generated in the Gulf of Mexico at Six Different Measuring Stations of Shell's Ocean Data Gathering Program by Hurricane Camille , 1969. Values estimated from Fig. 11.

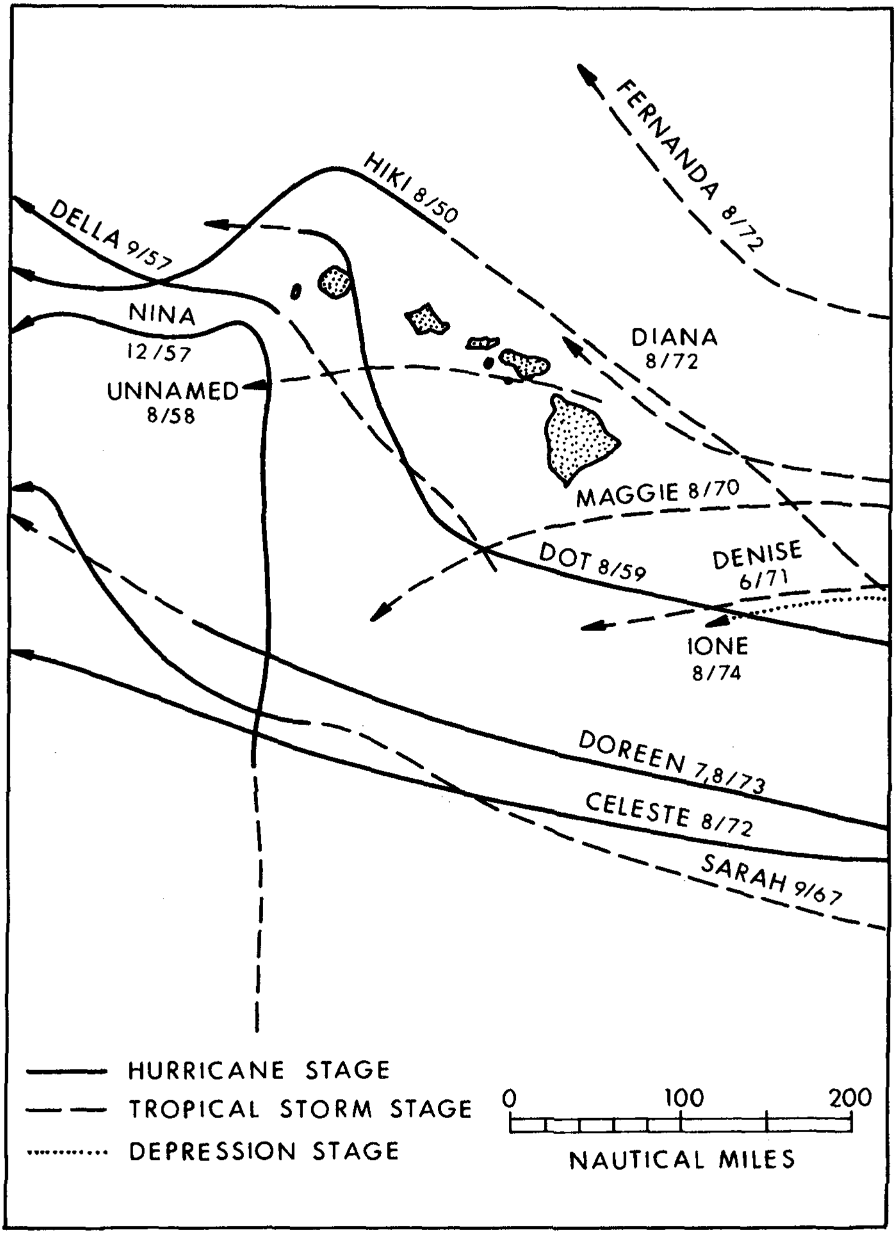


Fig. 14 Tracks of Hurricanes and Tropical Storms in the Vicinity of the Hawaiian Islands for the period 1950-1974 [from National Weather Service of NOAA]

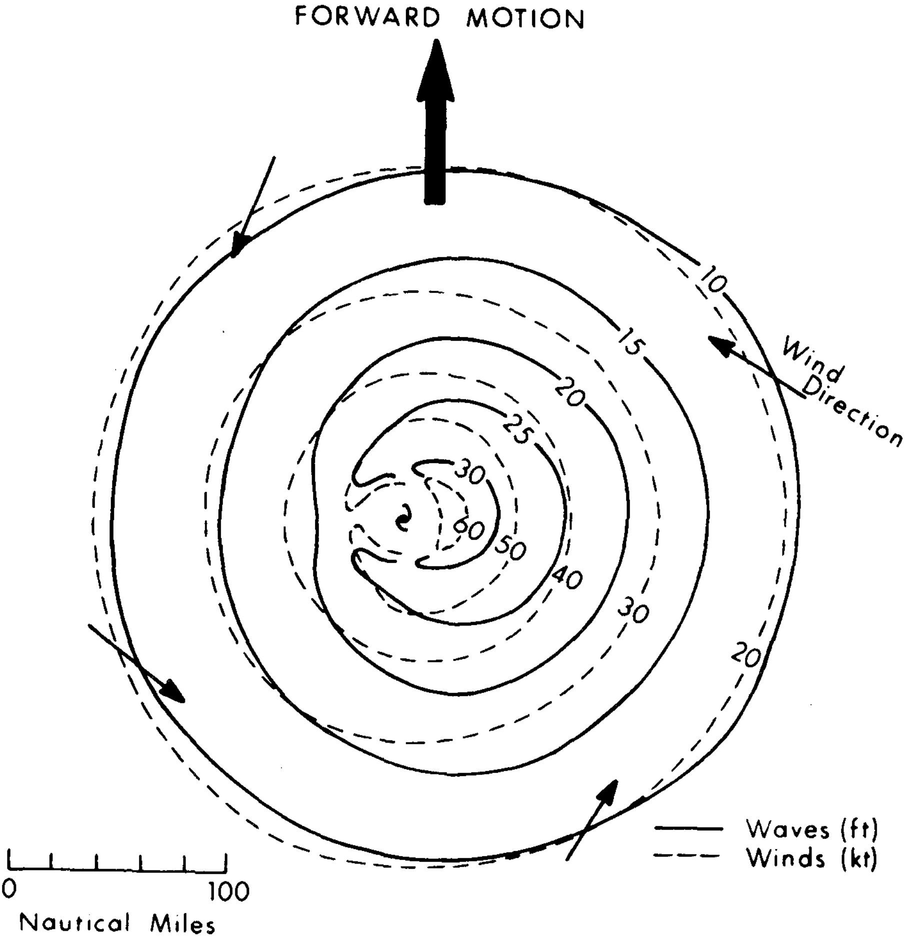


Fig. 15 Hurricane Wind and Wave Field Model for use with Fig. 14 hence it should be to same scale as Fig. 14. Place on Fig. 14 to obtain wind-wave field in area selected.