Forecasting Maximum Significant Wave Height Induced By Minimum Central Pressure of a Tropical Storm at Sea

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Abstract

Marine observations and predictions are integral components of many National Weather Services around the world. In order to issue warnings to mariners, to protect offshore oil and gas platforms, to estimate forces impacting coastal engineering structures due to beach erosion, and to improve storm-surge forecasting, information on maximum significant wave height is needed. The purpose of this paper is to provide marine forecasters with a simplified formula for forecasting a tropical storm's maximum significant wave height, H_s, from its minimum central pressure, P_0, projection. Some models use the wind speed, U_{10}, to predict H_s. However, because U_{10} is not representative when storms are near to land, we will use P_0 instead. Under hurricane/typhoon conditions, a third generation wave model (WAM) has been employed successfully to hindcast H_s in the Gulf of Mexico. Because tropical storms are generally fetch-limited, the non-dimensional fetch parameter for WAM overlaps the JONSWAP (Joint North Sea Wave Project) wave formulation. Therefore, the simplified JONSWAP wave model should be applicable. After some mathematical manipulation and the employment of the cyclostrophic equation, we have H_s (in meters) = 0.20 (1013 - P_0) where P_0 is in mb. This equation has been further verified by a 20 year data set obtained from the U.S. Army Corps of Engineers' Coastal Engineering Research Center (CERC). In this data set, 25 and 43 hurricanes from the Gulf of Mexico and the Atlantic, respectively, were studied. It was found that when H_s ranged from 4 to 20 m the root-mean-square error (RMSE) between our equation and the CERC data set was approximately 2 m. If one accepts this RMSE, the equation as proposed above should be useful under hurricane/typhoon conditions in the open sea. Estimation of significant wave height away from the storm center is also provided. Some of these results have been published in an official periodical by the U.S. NOAA.

1 Introduction

The purpose of this study is to develop a simplified formula for forecasting a tropical storm's maximum significant wave height from its minimum central pressure projection. It was motivated by a Glenn Hamilton article (1987), which showed that in R. B. Long's method for estimating significant wave heights large discrepancies resulted between measured heights and those predicted. One reason for this may be that when tropical storms are close to land, the wind speed is less representative than the central pressure.

The significant wave height, H_s, represents the average height of the highest one-third of the waves observed at a specific point at sea. H_s is a useful parameter because it is approximately equal to the wave height that a trained observer would visually estimate for a given sea state (see, e.g., Bishop, 1984). H_s also relates the aerodynamic roughness parameter at the air-sea interface for momentum flux computation (see, Hsu, 1988, p. 116).

2 Methods and Results

According to the WAMDI Group (1988), under hurricane conditions, a third generation wave model (WAM) has been used successfully to hindcast the significant wave heights in the Gulf of Mexico. Because tropical storms are generally fetch-limited, the non-dimensional fetch parameter for WAM overlaps the JONSWAP (Joint North Sea Wave Project) wave formulation (see Figs. 3 and 4 in the WAMDI Group, 1988). Therefore, the simplified JONSWAP wave model should also be useful that (see CERC, 1984, p. 3-44):

$$\frac{g H_s}{U_{10}^2} = 1.6 * 10^{-3} \left(\frac{g F}{U_{10}^2} \right)^{\frac{1}{2}} \quad \textbf{(1)}$$

$$\frac{g T_m}{U_{10}} = 2.857 * 10^{-1} \left(\frac{g F}{U_{10}^2} \right)^{\frac{1}{3}} \quad \textbf{(2)}$$

where g is the gravitational acceleration, H_s the significant wave height, F the fetch, U_{10} the wind speed at 10 m above the surface, and T_m the peak spectral period such that $T_p = 0.95T_m$, where T_p is the significant wave period related to H_s.

Furthermore, under hurricane conditions, the wave steepness can be written (see CERC, 1984, p. 3-85):

$$T_p = 12.1 \left(\frac{H_s}{g} \right)^{\frac{1}{2}}$$

or

$$\frac{H_s}{g T_p^2} = 0.0068 \qquad (3)$$

Since the fetch parameter is not measured, we divide Eq. (1) by the square of Eq. (2) and substitute the steepness factor from Eq. (3) with $T_p \approx T_m$. We then have

$$\left(\frac{gF}{U_{10}^2} \right) = 573.78 \qquad (4)$$

By substituting Eq. (4) into (1) then

$$H_s = 3.91 * 10^{-3} U_{10}^2 \qquad (5)$$

As a test of Eq. (5) we use the windspeed of 58 m/s measured on an offshore drilling rig in the Gulf of Mexico during Hurricane Camille in 1969 (see Fig. 16 in the WAMDI Group, 1988). If we approximate U_{10} = 58 m/s and substitute into Eq. (5), then H_s = 13.2 m, which is in good agreement with the measured value of 13.6 m as quoted in Table 5 in the WAMDI Group (1988).

A popular formula, which relates the maximum sustained surface wind (V_{max}) and the pressure gradient is (see Atkinson, 1971, p. 9-21)

$$V_{max}\ (m/s) = 7.22 \left(1013 - P_0\right)^{\frac{1}{2}} \qquad (6)$$

where P_0 is the sea level pressure (mb) at the storm center. The pressure value of 1013 mb represents conditions near the outer edges of the tropical storm. If we approximate $U_{10} = V_{max}$ and substitute Eq. (6) into (5), we have

$$H_s\ (meters) = 0.20 \left(1013 - P_0\right) \qquad (7)$$

Eq. (7) was first proposed by Hsu (1991) and published in an official periodical by U.S. NOAA.

3 Verifications

In order to verify Eq. (7), two extreme records of H_s as measured by buoy in 1985 were employed. The data are based on Hamilton (1987). For comparison purposes, H_s as computed from Ross-Long method (see Long, 1979) is also included. These results are shown in Table 1. It can be seen that using the central pressure method as proposed in Eq. (7) is better than the wind speed method as proposed by Long (1979). The main purpose of Eq. (7) is to forecast the maximum significant wave height induced by a tropical storm if its minimum central pressure projection is available, whereas Long's method may be used to estimate significant wave height if the wind speed at a given location from the storm is known.

Further verification of Eq. (7) is accomplished by employing 68 hurricane datasets containing P_0 and H_s. In this case H_s is the maximum H_s under the minimum P_0 conditions. The datasets were obtained from the Coastal Engineering Research Center (CERC) (1989). In this report, 25 and 43 hurricanes from the Gulf of Mexico and the Atlantic Ocean, respectively, were studied.

Fig. 1 shows the results of our comparison between Eq. (7) and the data set from CERC (1989). Since the value of the root-mean-square error (RMSE) (see, e.g., Panofsky and Brier, 1968, p. 201) is 2 m when H_s ranges from approximately 5 to 20 m, Eq. (7) may be considered to be verified. Furthermore, since the mean H_s of the CERC datasets is 10.1 m and that of Eq. (7) is 9.4 m, these two mean values are in agreement within 93% as shown by the large star for the grand mean in the chart. It should be noted that the H_s data provided in CERC are in whole meters.

On the basis of the above analyses it is concluded the Eq. (7) is verified for operational applications for quick estimates of H_s from P_0.

4 Ratio of H_{sr} / H_{smax}

If one accepts these verification results, Eq. (7) is then acceptable for operational use. The next question is "can we forecast the significant wave height away from the storm center?" Fig. 2 provides the answer for the dangerous semicircle in which H_{sr} is the significant wave height at the radial distance of r / R from the storm center (where R is the radius of maximum wind) and $H_{smax} = H_s$ as obtained from Eq. (7). On the basis of 59 hurricanes from 1893 through 1979 as listed in Simpson and Riehl (1981, pp. 389-391), the average R = 47 km. Thus, from Fig. 2, if one approximates R = 50 km, the value of significant wave height at a location 200 km away from R is about 60% of the H_{smax}.

5 Conclusions

One may draw several conclusions from this study:

(1) An operational formula is derived between the maximum significant wave height, H_s, and the minimum central

Table 1.
A Comparison Of Eq. (7) To Measurements and
the Ross-Long Method

Hurricanes in 1985	Buoy Station	Central Pressure	Measured H_s	Computed H_s from Eq. (7)	Computed H_s from Ross-Long
Gloria	41002	942 mb	14.3 m	14.2 m	8.4 m
Kate	42003	956 mb	10.7 m	11.4 m	9.2 m

pressure, P_0, for tropical storms, i.e. H_s (in meters) = 0.20 (1013 - P_0) where P_0 is in mb.

(2) On the basis of 43 hurricanes in the Atlantic Ocean and 25 in the Gulf of Mexico (from 1956 through 1975) plus two strong ones in 1985, this proposed formula is found to be consistent with the observation and to be better than the forecasting method based on wind speed rather than central pressure as used here.

(3) A regression curve is also provided so that the significant wave height at a location away from the radius of maximum wind, R, in the dangerous semicircle can be estimated. An example is given for R = 50 km, which is the approximate value for the average R (= 47 km) as obtained from 59 hurricanes between 1893 and 1979.

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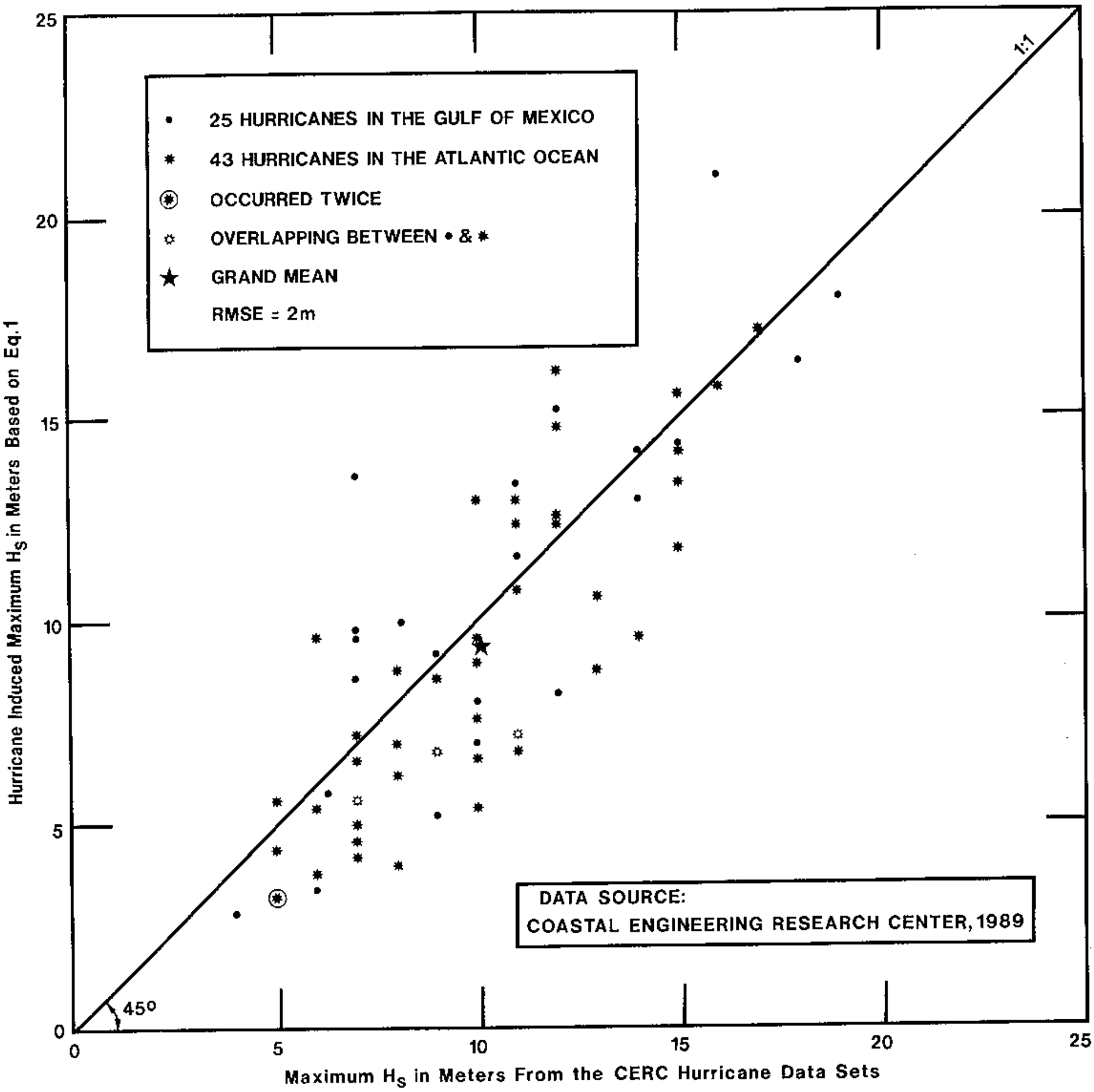

Fig. 1 A comparison between Eq.(7) and the hurricane datasets from C E R C(1989).

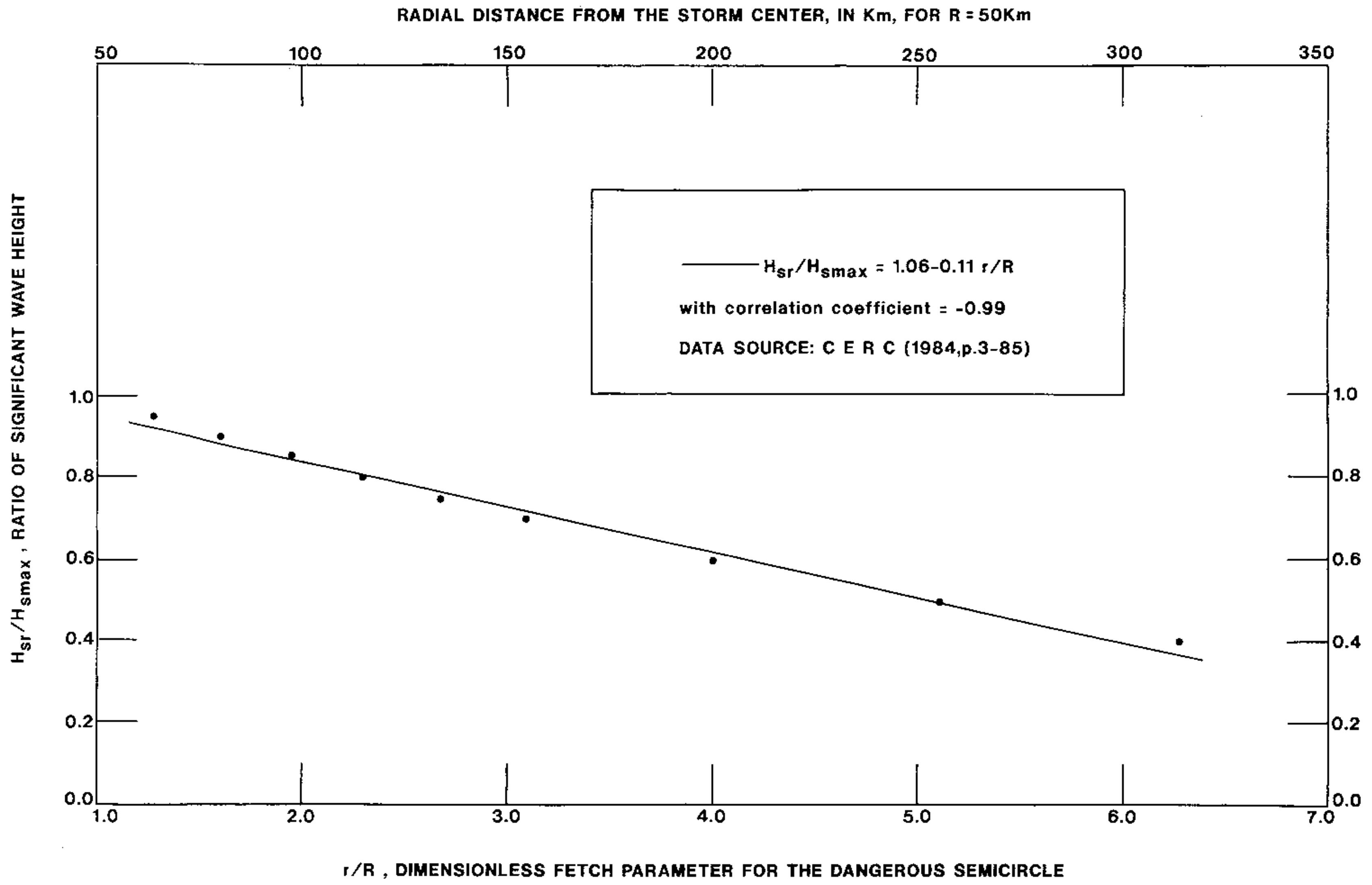

Fig. 2 A relationship between H_{sr}/H_{smax} and r/R (see text for explanation)