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An “extended fetch” model for the spatial distribution of tropical cyclone wind–waves as observed by altimeter

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ABSTRACT

An extensive database of altimeter measurements of wind speed and significant wave height is analysed to investigate the spatial distribution of significant wave height within tropical cyclones. The database includes transects of 440 tropical cyclones. As such, the data covers the full range of expected values of the velocity of forward movement, maximum wind velocity and radius to maximum winds. The data confirms previous measurements that JONSWAP scaling can be used to represent such waves. In addition, the data supports the concept of an extended fetch in such systems. The maximum waves occur when the wind direction and direction of propagation of the storm are aligned. In such cases, the waves move forward with the storm and experience an extended fetch. A parametric model based on JONSWAP scaling and representing the extended fetch is developed and optimized using the data. Combined with previous in situ measurements, this model can reproduce the spatial distribution of significant wave height, as well as estimate the full directional spectrum.

1. Introduction

Tropical cyclones or hurricanes or typhoons are well formed, relatively small but intense low pressure systems. Unlike larger systems, their wind fields are similar and hence can be characterised in terms of relatively simple translating vortex models (e.g. Holland, 1980). The intense nature of such systems, however, means that they can generate winds up to 75 ms^{-1} (Holland, 1980). Surface gravity waves generated by such winds can be extreme. Liu et al. (2009) reported a significant wave height of 23.9 m and a crest to trough maximum wave height of 32.3 m for Typhoon Krosa in a water depth of 38 m.

Although the wind field in such systems can be characterised in terms of a relatively simple parametric model, the wave field tends to be more complex. The translational nature of the tropical cyclone vortex means that the wind field can move forward with the waves it has generated and in certain circumstances, the waves can remain in the high wind regions of the storm for extended periods. This process has been called an extended fetch or trapped fetch (King and Shemdin, 1978; Young, 1988; Young and Burchell, 1996; Bowyer and MacAfee, 2005). Using a combination of numerical modelling, in situ measurements and satellite data, efforts have also been made to developed parametric models to describe this extended fetch and hence model the wave field generated (Young, 1988; Young and Burchell, 1996; Bowyer and MacAfee, 2005). Such models are, however, limited by the available tropical cyclone data which needs to be extensive to cover all possible combinations of the key tropical cyclone parameters believed to be important—velocity of forward movement of the storm, maximum wind velocity (or central pressure) and the radius to maximum winds (or spatial scale).

The present analysis attempts to address this issue of limited data by using the combined altimeter data set of Zieger et al. (2009). This data set provides global coverage of wind speed and significant wave height observed by a total of 7 altimeters over a 23 year period. The data contains approximately 440 passes of an altimeter close to a recorded tropical cyclone. As such, the database provides a unique and very comprehensive exploration of the tropical cyclone wave field under a broad range of conditions. Based on these data, the translational fetch model of Young (1988) is modified to describe the distribution of significant wave height, H_s within tropical cyclones. These results are then extended to also represent the distribution of spectra within such systems.

The arrangement of the paper is as follows. Section 2 provides a review of the tropical cyclone wind and wave fields and previous attempts to measure and model waves under tropical cyclone conditions. Section 3 describes the altimeter database which forms the basis of the present study. Analysis of the data and how it relates to the concept of a translating or extended fetch within tropical cyclones is presented in Section 4. These results are

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extended to consider the full distribution of the spectrum in Section 5, followed by discussion and conclusions in Section 6.

2. Tropical cyclone wind and wave fields

Full boundary layer numerical models can be used to represent the wind field within tropical cyclones (e.g. Kepert, 2012). For the present application, however, we seek a simpler parametric approach, consistent with a desire to develop a parametric model for the wave field. As noted above, the wind field within a tropical cyclone can be represented by a translating vortex. A number of such models exist, the form proposed by Holland (1980), being widely used. This model represents the gradient wind field as:

$$U_g = \left[\frac{AB(p_n - p_0)\exp(-A/r^B)}{\rho_a r^B} + \frac{r^2 f_c^2}{4} \right]^{0.5} - \frac{r f_c}{2} \tag{1}$$

where U_g is the gradient wind (outside the atmospheric boundary layer) at radius r from the centre of the storm, f_c is the Coriolis parameter, ρ_a the air density, p_0 is the central pressure, and p_n the ambient atmospheric pressure far from the storm. The parameters A and B can be expressed in terms of the radius to maximum winds, R, as

$$R = A^{1/B} \tag{2}$$

The dimensionless parameter B defines the shape of the wind field with increasing distance from the centre of the tropical cyclone. From Fig. 8 of Holland (1980), B can be represented as $B = 1.5 + (980 - p_0)/120$, where p_0 has units of [hPa] or [mbar]. To convert from the gradient wind speed to the common reference height of 10 m, a boundary layer correction factor, K, must be assumed. In the present analysis this has been chosen as 0.8 (Graham and Numm, 1959).

In the analysis that follows, it has been assumed that the winds spiral in towards the centre of the storm with a constant inflow angle of 25° (Shea and Gray, 1973). Also, a first-order asymmetry has been applied by adding the hurricane velocity of forward movement, V_{fm}, to the symmetric flow and assuming the maximum winds occur at an angle of 70^0 to the direction of storm propagation (Holland, 1980). Asymmetry of hurricanes is variable and some researchers have suggested adding only a fraction of the forward speed of the storm.

From (1) and (2), the full tropical cyclone wind field can be determined by specification of $V_{fm,}$ p_0 and R. Alternatively, from (1) with $r = R$, p_0 can be related to the maximum wind velocity in the storm, by $V_{\max} = K[B(p_n - p_0)/\rho_a e]^{1/2}$.

Numerous studies have investigated the wave field generated by the tropical cyclone vortex. The most sophisticated of these approaches use full spectral wave models (Patterson, 1972; Bea, 1974; Uji, 1975; Cardone et al., 1977, Young, 1988; Moon et al., 2003; Chen et al., 2007). Such models are often forced using the wind field specified by (1) and (2), or variations of these equations. Such models can predict the full directional wave spectrum, account for temporal changes in the tropical cyclone parameters, as well as changes in the speed of propagation of the storm and irregular path behaviour.

Observational data under tropical cyclone conditions have been obtained from in situ instruments (both directional and omni-directional) and remote sensing approaches. The first comprehensive attempts to collect data under tropical cyclone conditions were through the Ocean Data Gathering Program (Shemdin, 1977; Ward, 1974; Hamilton and Ward, 1976). The NOAA Data Buoys deployed in the Gulf of Mexico have been frequently used as a data source (e.g. Withee and Johnson, 1975; Ochi, 2003). In situ data collected in other geographical regions includes that of Young (1997, 2003) and Liu et al. (2009).

Although such omni-directional data provides a valuable understanding of the tropical cyclone wave field, directional data provides much greater insight. The corresponding database of in situ directional data is more limited. In situ data for individual storms have been presented by a number of authors (e.g., Cardone and Pierson, 1975; Forristall et al., 1978, 1980; Black, 1979). More comprehensive studies using data from multiple storms have been presented by Young (2006) and Hu and Chen (2011).

Remote sensing data can be either onmi-directional or directional depending on the instrument utilized and can be either aircraft or satellite based. Omni-directional data obtained from satellite-based radar altimeters have been obtained by Young (1988) and Young and Burchell (1996). Remote sensing data providing directional information have been presented by Elachi et al. (1977), King and Shemdin (1978), Holt and Gonzalez (1986), Wright et al. (2001) and Moon et al. (2003).

Noting the relatively simple parametric form for the wind field and the various data sets of tropical cyclone wave data, a number of parametric models have been proposed to represent the wave field. The simplest of these assume that the wave field will reflect the spatial distribution of the tropical cyclone vortex which generates it (e.g. Bretschneider, 1959; Ross, 1979). King and Shemdin (1978) examined synthetic aperture radar (SAR) images of Gulf of Mexico hurricanes and noted that waves ahead of these hurricanes were made up of a mix of swell radiating out from the intense wind regions near the centre of the storm and locally generated wind–sea. These same features have been observed using in situ buoy data by Young (2006). Using such data, Shemdin (1977) and King and Shemdin (1978) noted that the wave field was not simply determined by the local wind velocity. Rather, remotely generated swell played an important part in defining the full wave field. As much of this swell was generated in the intense wind regions near the centre of the tropical cyclone, they proposed that $V_{\max}$, V_{fm} and R were also critical in determining the local wave conditions. They proposed the concept of an "extended fetch" for tropical cyclones.

For a northern hemisphere tropical cyclone, waves generated in the intense wind regions to the right of the storm centre will propagate in a direction approximately parallel to the direction of propagation of the storm. Conversely, on the left side of the storm, waves will propagate in the approximately opposite direction to the storm propagation. Therefore, the waves to the right of the storm will experience high winds for an extended period, as the storm is moving in the same direction as the wave propagation. This phenomenon was termed "extended fetch" by Shemdin (1977). The maximum wave height would occur when the group velocity of the waves (C_g) was approximately equal to the speed of translation of the storm (V_{fm}). In such a case, the waves would remain "trapped" in the intense wind region and receive maximum energy input from the wind. Based on model results, Young (1988) noted that since C_g increased with $V_{\max}$, then the relative values of V_{fm} and $V_{\max}$ were critical in determining the maximum significant wave height, $H_s^{\max}$ in the storm. For a given V_{fm}, if $V_{\max}$ is small then the waves generated will have a low C_g and will be "out run" by the storm. Conversely, for a high value of $V_{\max}$, the waves generated will "out run" the storm. In either of these extreme cases, the waves will only remain in the intense wind region for a limited time. The optimal value of $V_{\max}$ will occur at some point between these limits when the period that the waves remain in the intense wind region is a maximum.

Based on this concept of extended fetch, models to describe the wave field have been proposed by Young (1988), Young and Burchell (1996) and Bowyer and MacAfee, (2005). Using numerical model data, Young (1988) defined an equivalent fetch, F, for tropical cyclone conditions

$$\frac{F}{R'} = aV_{\max}^2 + bV_{\max}V_{fm} + cV_{fm}^2 + dV_{\max} + eV_{fm} + f \tag{3}$$