COMPUTATIONALLY EFFICIENT TROPICAL CYCLONE PARAMETRIC WIND-WAVE MODEL

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INTRODUCTION

Waves generated by tropical cyclones (TCs) can cause damage to offshore structures and coastal settlements and play an important role in the design criteria for engineering projects, risk assessments and insurance purposes. Developing a rapid and simple way to estimate the wave heights associated with TCs has both a social and an economical advantage.

The present study aims to develop a parametric TC wave prediction model, based on data generated by numerous simulations with a validated version of the WAVEWATCH III (WW3) spectral wave model (WW3DG, 2019).

WIND VORTEX MODEL FOR TROPICAL CYCLONES

As an initial step, the TC wind vortex model of Holland et al. (2010) was extended to include asymmetry and variable wind inflow angle. The observational results of Tamizi et al. (2020) were used for this purpose. They showed that the asymmetry and wind inflow angle are functions of the velocity of the forward movement (V_{fm}) and central pressure (p_0). In addition, the inflow angle is a function of the distance from the storm center. Parametric relations were developed for both asymmetry and inflow angle and the resulting wind field model was successfully validated against H*Wind post storm analysis data (Powell et al., 1998) from selected historical hurricanes in the Northern Hemisphere.

The parameterized inflow angle equation has the cosine form: $\theta = a * \cos(\alpha + \varphi + \theta_{fm}) + b$ (1); where, θ is the inflow angle, a is the amplitude of the cosine curve $a = 5 + V_{fm}$ (2); α is the azimuthal angle, φ is the phase shift of the maximum inflow angle with a constant value of 75 degrees, θ_{fm} is the direction of propagation of the tropical cyclone, b is the offset $b = 0.3 * \frac{R}{R_{max}} + 19$ (3) and R_{max} is the radius of maximum winds.

The parameterized vortex model showed significant skill in reproducing TC wind fields using wind parameters from the IBTrACS dataset (Knapp et al., 2010) and in the majority of cases, the difference in the maximum wind speed between the parameterized wind vortex model and the H*Wind was less than 10%.

TROPICAL CYCLONE WAVE FIELD GENERATION

The parametric wind fields were used to force the WW3 model for a range of historical North Atlantic hurricanes and the wave parameters were validated against NDBC buoys. Again, the parameters used to define the wind fields were taken from IBTrACS dataset. The WW3 model compared well with the buoy data for integral wave properties and directional spectra.

Once validated, a moving grid implementation of WW3 (Alves et al., 2004) was used to run a broad range of combinations of idealized TCs, covering the parameter space defined by: central pressure (p_0), velocity of forward movement (V_{fm}), radius to gales (R_{34}) and radius to maximum winds (R_{max}). This generated an extensive model database that was used to develop the wave height parametric model.

The results show that the maximum values of significative wave height (H_s) within the storm increase as both the maximum wind velocity (V_{max}) and velocity of forward movement (V_{fm}) increase. At values of V_{fm} approximately equal to 12.5 m/s, a maximum is reached. At larger values of V_{fm} the storm appears to move too fast and H_s begins to decrease (Figure 1). The peak frequency (f_{p}) related to the maximum values of H_s were used to calculate the resulting group velocity (C_g) and the results show that C_g increases as a function of V_{fm} and V_{max} until a peak is reached in a similar pattern to H_s (Figure 2). These results broadly agree with concept of an extended fetch proposed by Young (1988), where waves generated in intense wind regions propagates ahead of the storm, however for storms moving faster than waves group velocity, the waves are left behind the storm.

The present results, alongside Alves et al. (2004), expand the work of Young (1988), investigating in detail this concept with a model using a contemporary representation of the nonlinear source terms. The inclusion of the nonlinear terms in the model means that, compared to the results of Young (1988), there is a stronger transfer of energy to longer waves and, hence wave growth can be sustained for faster moving TC than previously believed.

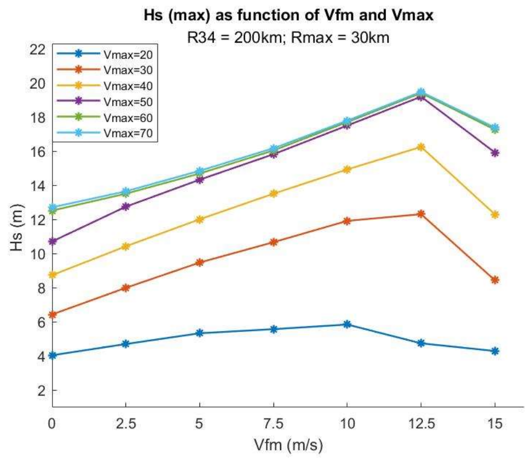

Figure 1 - Maximum H_s in a TC as function of V_{max} and V_{fm}. Case when R_{34} is 200km and R_{max} is 30km.

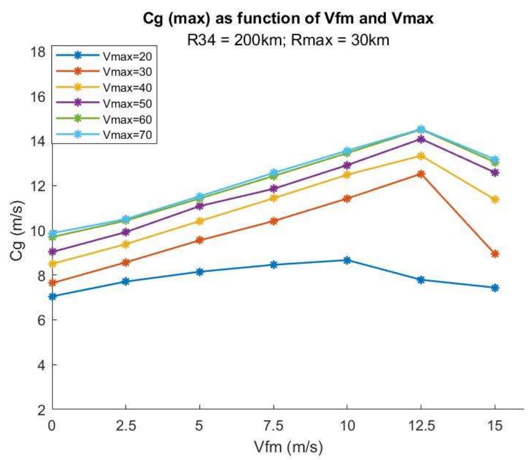

Figure 2 - Maximum C_g in a TC as function of V_{max} and V_{fm}. Case when R_{34} is 200km and R_{max} is 30km.

PARAMETRIC WAVE HEIGHT MODEL

An equivalent fetch (F) for each synthetic TC wave field was calculated using the JONSWAP fetch limited growth relationship. These results show how the extended fetch within a TC is defined by both V_{fm} and V_{max}, as well as the scale parameters R_{max} and R_{34}.

The new parameterized fetch model has the form:

$$\frac{F}{\lambda * \gamma} = (aV_{max}^3 + bV_{max}^2 + cV_{fm}^2 + dV_{max}^2 V_{fm} + eV_{max}V_{fm}^2 + fV_{max}V_{fm} + gV_{max} + hV_{fm} + i) * exp(C\, V_{fm}) \qquad (4)$$

where λ and γ are scale correction factors for R_{max} and R_{34}, respectively, C is a constant with a fixed value of 0.1 and a to i are coefficients, also with fixed values.

The resulting model parameterized in this manner, retains the important physical concept of the extended fetch (Young & Vinoth, 2013), in association with preliminary results reported in Alves et al. (2004), it significantly updates previous understanding by using a state of the art spectral wave model (WW3) forced with an updated wind field to generate the synthetic data used to develop the model.
It is possible to calculate the maximum H_s value for each calculated fetch using the same JONSWAP relationship. This maximum H_s value can be applied to a normalized $H_s/H_{s(max)}$ spatial distribution for the selected synthetic TC wave field scaled in terms of R_{max} to determine the bidimensional H_s distribution within the storm.
This approach was validated for a range of Northern Hemisphere hurricanes using data from NDBC buoys and altimeter satellite data. An example of this evaluation is shown in the next session for Hurricane Ivan.

MODEL RESULTS FOR HURRICANE IVAN

Hurricane Ivan crossed the North Atlantic and Gulf of Mexico in September 2004 and reached the Saffir-Simpson hurricane intensity scale (SSHS) category 5 strength. The storm track from 1200 UTC 14 September to 2100 UTC 15 September is shown in Figure 3. Ivan's H_s was sampled by radar altimeters on board two satellites, Envisat and ERS-2, when the storm was in the Gulf of Mexico. The ERS-2 track through the storm occurred between 0404 and 0406 UTC 15 September (Figure 3) and its wave height data is presented in this paper (Figure 4).

The H_s spatial distribution calculated by the parametric model using the IBTrACS parameters when the altimeter passed by this storm is presented on Figure 3. At this time the parameters used were V_{max}= 62m/s, V_{fm}= 5m/s and R_{34}= 345km. There is no information for R_{max} on IBTrACS dataset for this storm and an assumed value of 30km was adopted.

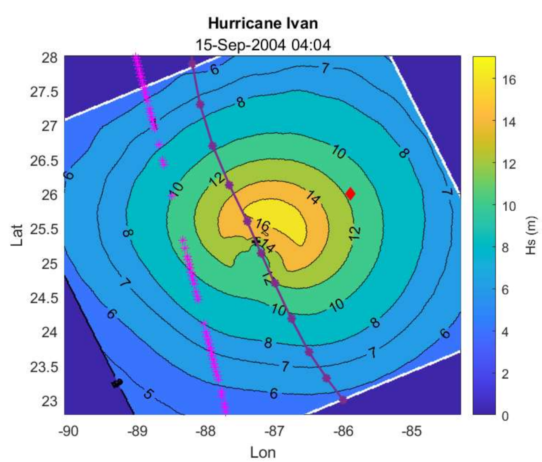

Figure 3 - Significant wave height H_s(m) distribution determined using the synthetic TC wave field for selected storm parameters for Hurricane Ivan. In magenta the altimeter ERS-2 track, the dotted line is the storm track, and the red diamond is the location of the NDBC buoy 42003.

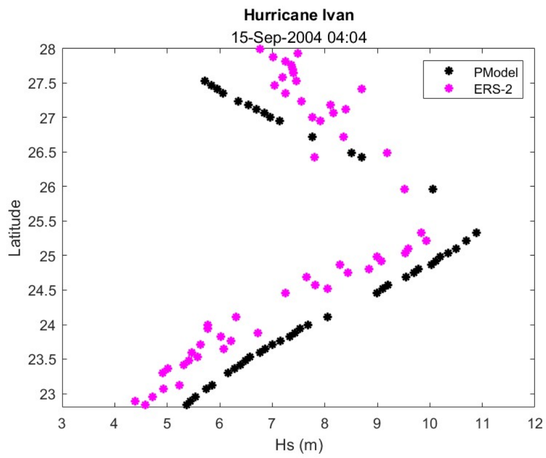

Figure 4 - Comparison between measured H_s data from the altimeter (magenta) and simulated H_s from the parametric model (black) along satellite track.

Figure 4 shows that the parametric model can capture the H_s measured by the altimeter with an underestimation around two meters ahead of the storm center (25.3 degrees in latitude) and with an overprediction around one meter behind the TC center.

NDBC buoy 42003 was located on the right side of the storm track (Figure 3) and recorded the H_s time series through the passage of the storm. This observed H_s data were used to compare with H_s calculated by the parametric model using IBTrACS wind field data (Figure 5). The nearest point of approach between the storm and the buoy occurred between 0300 and 0600 UTC 15 September. The comparison shows that the parametric model predicted the H_s reasonable, however, it overestimates the waves by approximately two meters when the storm was passing nearest to the buoy.

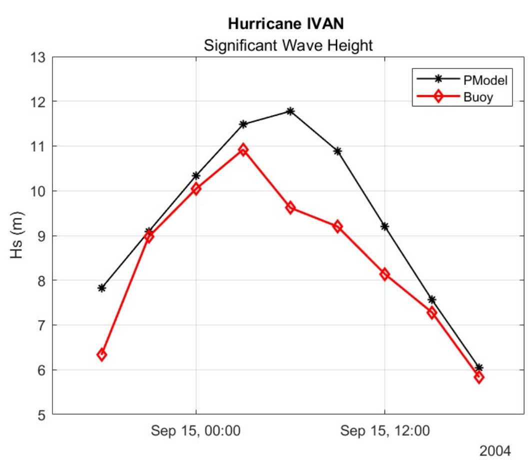

Figure 5 – Comparison between the measured H_s data from NDBC buoy 42003 and H_s simulated by the parametric model for Hurricane Ivan.

The observed errors can be explained in a range of ways. As the parametric model was designed for waves propagating in deep water and in a constant storm direction, it cannot predict attenuation of H_s caused by the storm changing direction or the sheltering effect of islands or any other barrier. An example would be protection resulting from the confined Gulf of Mexico. Also, the wind model does not represent strong mesoscale ocean features that could modify the wave field.
Finally, the parametric model uses the IBTrACS parameters to obtain the wave field and any error associated with these storm parameters will impact the results predicted by the model.

CONCLUSIONS

The resulting model is highly computationally efficient making it ideal for engineering applications which require simulation of numerous TC cases. Despite some limitations, it is a useful tool for the prediction of wave heights in TCs or the synthetics or historical events.

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