An Efficient Method for Simulating Typhoon Waves Based on a Modified Holland Vortex Model

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Abstract: A combination of the WAVEWATCH III (WW3) model and a modified Holland vortex model is developed and studied in the present work. The Holland 2010 model is modified with two improvements: the first is a new scaling parameter, b, that is formulated with information about the maximum wind speed (VMS) and the typhoon’s forward movement velocity (V); the second is the introduction of an asymmetric typhoon structure. In order to convert the wind speed, as reconstructed by the modified Holland model, from 1-min averaged wind inputs into 10-min averaged wind inputs to force the WW3 model, a gust factor (g) is fitted in accordance with practical test cases. Validation against wave buoy data proves that the combination of the two models through the gust factor is robust for the estimation of typhoon waves. The proposed method can simulate typhoon waves efficiently based on easily accessible data sources.

Keywords: Holland vortex model; WAVEWATCH III; scaling parameter; gust factor; typhoon waves

1. Introduction

Tropical cyclones, hurricanes, or typhoons (hereafter referred to simply as typhoons) are intensive ocean forces that can destroy coastal properties or offshore engineering structures, leading to significant economic losses [1]. Generally, the ocean waves induced by typhoons are characterized by extreme heights [2] and are critical inputs for the design of offshore or coastal structures. Historical typhoon waves are often used as fundamental samples to predict the possible wave loads that shore-based or floating structures will bear in the future [3–5].

In order to simulate typhoon waves, researchers have adopted numerical wave models [6,7], used empirical formulas [8], and given a parameterization of the nearshore wave front slope [9]. Machine-learning methods, such as artificial neural networks, have gradually been introduced to predict wave parameters [10–12]. To study typhoons, researchers have calculated the ultra-long return level of wind speed based on a deductive method [13], carried out systematic numerical experiments in an idealized continental shelf–beach–land system to identify the role of waves in storm surge and inundation under different storm characteristics [14], simulated 39 years of wave data with high temporal and spatial resolutions [15], and proposed a formula for blended tropical cyclone wind fields that combines two datasets and shows a good capacity to simulate a tropical cyclone’s wind field [16]. For all of the abovementioned methods, a realistic typhoon wind field should first be reconstructed as the input force. In other words, the accuracy of the typhoon wind field determines the quality of a model of typhoon waves [17].
There are three basic approaches to reconstructing typhoon wind fields. The first is to use atmospheric models, such as MM5 and WRF, to simulate typhoons [18–20]. The second is to adopt wind reanalysis products to reconstruct a typhoon’s wind field [6,21]. The third approach is to use parametric vortex models to reconstruct a typhoon’s wind field following typhoon track data. A typical parametric model is that created by Holland in 1980 [22], hereafter known as H80. Since its release, H80 has been extensively utilized in various types of applications with different modifications that agree well with researchers’ observations [23–26]. In particular, due to the typhoon track data that have been available since the 1940s and can be easily accessed via meteorological service websites, a parametric vortex model can be used to obtain wave samples that are more than 60 years old.

Holland (2008) developed a new parametric equation to formulate the scaling parameter $b$, which makes the H80 model more flexible. During its 30th anniversary in 2010, H80 was improved by a new analytic representation of the radial profile, which ensuring that the model has lower sensitivity to external parameters, such as the radius of maximum wind (RMW) and external winds (Holland et al., 2010 [27], hereafter known as H80H10).

Some researchers have coupled the Holland model with a third-generation wave model [28,29], such as WAVEWATCH III (WW3), to simulate typhoon waves. Practical applications show that the H10 model may be further improved, and, in this paper, we present two improvements: the introduction of an asymmetric typhoon structure and a robust Holland scaling parameter $b$. In the remainder of this paper, the modified H10 model will be abbreviated as MH10.

WW3 is a state-of-the-art third-generation wave model [10,30] widely used to forecast and hindcast ocean waves [31–33]. Considering its high efficiency and accuracy, we used the WW3 model to simulate typhoon waves in this study. Generally, the WW3 model is forced by the 10-min averaged 10-m surface wind $U_{10}^{10} \, \text{m/s}$, where the subscript refers to the surface height of 10 m and the superscript refers to the 10-min average. However, in the cyclone research community, it is usual to use the 1-min averaged wind $U_{10}^{1}$ [26]. In order to use the Holland wind to force the WW3 model, it is necessary to convert $U_{10}^{1}$ into $U_{10}^{10}$. Although some researchers have proposed a range of gust factors ($U_{10}^{10}/U_{10}^{1}$) to achieve this conversion [26], it is difficult to find a universal gust factor that applies to all typhoons [34,35]. With the aim of coupling the Holland wind and the WW3 model, we formulate a gust factor to convert $U_{10}^{1}$ into $U_{10}^{10}$ in accordance with test cases.

Furthermore, MH10 uses an empirical formula to define the RMW, since it is not always available in the track data distributed by different meteorological organizations. With the adoption of an RMW formula, the MH10 model is more flexible. In this study, we used a Chinese website http://www.wztj121.com/ (accessed on July 2017) (hereafter, WZTF) as a reference for the track data. Details about the RMW can be found in Section 3.4.

This article is structured as follows. Section 2 describes the wave dataset. Section 3 presents the standard H10 model and the modified H10 model. Section 4 validates the combination of the two models. Sections 5 and 6 present a discussion and our conclusions, respectively. Appendix A provides diagrams of the wave–time series, and Appendix B provides a table of results with all involved test cases.

2. Data sources

2.1. Typhoon Track Data

The track data that are distributed through the website WZTF are characterized by different temporal intervals (6 h, 3 h, and 1 h) and gradually become finer from east longitudes to west longitudes in the Northwest Pacific Ocean. The finest time resolution of the typhoon track data from WZTF is 1 h. The track data from WZTF are structured by date, time, longitude, latitude, maximum wind speed (BS), maximum surface wind speed (m/s), central pressure (hPa), velocity of forward movement (km/h), moving dir., radius of BS-7 wind speed (km), and radius of BS-10 wind speed (km). However, the RMW is not explicitly provided.
2.2. Wave Data

An open source of buoy wave data, released by the Central Weather Bureau of Taiwan (CWBT), is adopted to validate the model. More detailed information about the buoys can be accessed through the website: [http://www.cwb.gov.tw/](http://www.cwb.gov.tw/) (access date: July 2017). Another set of buoy data is from three buoys moored in the northern South China Sea (SCS), as seen in Figure 1. All three buoys are moored in open ocean, where the water depth is approximately 30–50 m. The buoys are 50–85 km from the coastline. Wave heights and wave periods will be verified in accordance with the data from these buoys.

![Figure 1. Geographical location of wave buoys for model verification (QF301–QF303 are from some discontinuous scientific projects; others are from the Central Weather Bureau of Taiwan (CWBT))](image)

3. Standard and Modified H10 Models

3.1. Standard H10

Based on the radial surface pressure profile, approximated by a rectangular hyperbola as suggested by [36], H80 introduced an upgraded pressure profile formulated as in Equation (1), where \( p_s \) is the surface pressure at radius \( r \), \( p_{cs} \) is the central surface pressure, \( \Delta p_s = p_{ms} - p_{cs} \) is the pressure drop from an external \( p_{ms} \) to a central pressure (in hPa), \( r_{ms} \) is the radius of the maximum surface wind speed, and \( e \) is the base of nature logarithms [22]. Parameter \( b \) is a scaling parameter defining the proportion of pressure gradient near the RMW. In the last few decades, it has been proven that the introduction of parameter \( b \) is successful for the estimation of typhoon wind vortex profiles.

\[
p_s = p_{cs} + \Delta p_s e^{-\frac{r}{r_{ms}b}}
\]  

With Equation (1) as the basic form of the radial pressure variation, H10 proposed a new formula for wind profile as in Equation (2), where \( v_s \) is the surface typhoon wind at a 10-m height, \( v_{ms} \) is the surface maximum wind in m/s, \( b_s \) is the surface scaling parameter kept constant in a typhoon, and \( \rho_s \) is the air density. Notably, all of the variables in Equation (2) should be observations at a height of 10 m, where the variable \( x \) can be defined as in Equation (6).

\[
v_s = \left[ \frac{100b_s\Delta p_s(r_{ms}b_s)}{\rho_s e^{-\frac{r_{ms}b}{r}}} \right]^x
\]  
or
\[ v_x = v_{ms} \left[ \frac{r_{rms}}{r} b_x e^{[1-(r_{rms}/r)]x} \right] \]  

Once the maximum surface wind and central pressure are known, \( b_x \) can be estimated following H80 through Equation (3), where \( \rho_{ms} \) is the air density at a radius of surface maximum wind.

\[ b_x = \frac{v_{ms}^2 \rho_{ms} e^{\Delta p_s}}{100 \Delta p_s} \]  

Another method to derive the surface scaling parameter \( b_x \) is proposed by Holland as in Equation (4) [37], where \( v_x \) is the velocity of the forward movement of typhoons in m/s.

\[ b_x = -4.4 \times 10^{-5} \Delta p_s^2 + 0.01 \Delta p_s + 0.03 \frac{\partial p_{cs}}{\partial t} - 0.014 \varphi + 0.15 v_x^n + 1.0 \]

\[ n = 0.6 \left(1 - \frac{\Delta p_s}{215}\right) \]

\[ v_{ms} = \left( \frac{100b_x}{\rho_{ms}\Delta p_s}\right)^{0.5} \]  

The surface air density can be derived from Equation (5), where \( R = 286.9 \text{ J kg}^{-1}\text{K}^{-1} \), \( T_{vs} \) is the virtual surface temperature in K, \( q_s \) is the surface moisture in g kg\(^{-1} \), \( T_s \) is the surface temperature, and \( SST \) is the sea surface temperature.

\[ \rho_s = \frac{100p_s}{RT_{vs}} \]

\[ T_{vs} = (T_s + 273.15)(1 + 0.61q_s) \]

\[ q_s = RH_s \left( \frac{3.802}{100p_s} \right)^{\frac{17.67T_s}{253.3+T_s}} \]

\[ T_s = SST - 1 \]  

The exponent \( x \) in Equation (2) can be defined as in Equation (6), where \( x_a \) is an adjusted exponent that is fitted in accordance with the peripheral observations at a radius of \( r_o \).

\[ \left\{ \begin{array}{ll}
  x = 0.5 & r \leq r_{rms} \\
  x = 0.5 + \left(r - r_{rms}\right) \frac{x_{n-0.5}}{r_{n} - r_{rms}} & r > r_{rms}
\end{array} \right. \]  

Equations (1)–(6) define the H10 model. In H10, the scaling parameter \( b \) formulated in Equation (4) is more feasible and flexible than in H80, and the exponent \( x \) in Equation (2) varies with different radiiuses. Among these inputs of H10, the air density “is not critical and constant value of density can be used if preferred” [27]. Alternatively, if there is a good estimation for the maximum wind \( (v_{rms}) \), the air density will be disregarded, and Equation (2) can be used to get \( v_x \) directly.

3.2. Modifications of Standard H10

3.2.1. A More Informative Scaling Parameter

As a key parameter of the Holland model, scaling parameter \( b \) (in H80) or \( b_x \) (in H10) plays a major role in the accurate prediction of a radial wind profile. Two different types of empirical formulas for parameter \( b \) are provided in H80 and H08 [22,37]. There are also some statistical models fitted according to realistic typhoons to estimate parameter \( b \) [38,39].

In the H80 model, the gradient wind speed is defined as in Equation (7), where \( v_g \) is the gradient wind speed at the location with distance \( r \) from the typhoon center, \( f_c \) is the Coriolis parameter, \( \rho_a \) is the air density, \( p_c \) is the central pressure, and \( p_a \) is the ambient air pressure.
There is a relationship between the parameters $A$, $b$, and RMW formulated as in Equation (8) [22]. The maximum wind speed of the typhoon occurs at $r = r_{ms}$, where the Coriolis force can be negligible. Then, the surface maximum wind speed can be estimated through Equation (9) [8].

$$ r_{ms} = A^\frac{1}{4} $$

$$ v_{ms} = b \frac{(p_n - p_c)}{\rho_a e} \frac{1}{2} + \frac{v_t}{2} $$

Equation (9)

Equation (10)

The parameter $p_n$ can be approximately estimated with a constant, such as 1005 hPa [27]. Consequently, Equation (10) can be easily utilized to calculate parameter $b$. Compared with other RMW-dependent methods [38], Equation (10) tends to be more independent, feasible, and simple.

### 3.2.2. Asymmetric Typhoon Structure

Plotting the realistic evolution of a typhoon is a very complicated process [41–43]. The actual structure of the typhoon is asymmetric, with the maximum wind possibly located in the rear-right quadrant or in the front-right quadrant [44,45]. An asymmetric structure is helpful for accurate estimations of coastal risks, such as the surge [46]. In order to convert the axis-symmetric H10 into an asymmetric model, an asymmetric term caused by typhoon forward movement can be superimposed [46–48,25]. Equation (11) is one type of an asymmetric term, where $V_{add}$ is the component of the asymmetric wind speed, $v_n$ is the forward movement velocity of the typhoon, $\beta$ is the angle from the typhoon moving direction [47] $^1$, and $C$ and $n$ are positive constants. In the present work, $C$ and $n$ are determined to be 0.4 and 1, respectively, according to some tentative tuning. The final asymmetric wind is formulated in Equation (12) [25], where $v_w$ is the asymmetry surface wind and $v_n$ is the Holland surface wind calculated in Equation (2). The forward movement velocity, $v_n$, is explicitly provided in the WZTF track data. Even if $v_n$ is not available in the typhoon track data, it can be approximately estimated by referring to the geographical coordinates of typhoon centers at different times.

$$ V_{add} = C \cdot v_n^n \cdot \sin \beta $$

$^1$ The original definition by Georgiou (1986) is the trigonometric angle where $0^\circ =$ East and $90^\circ =$ North, assuming a northward typhoon motion. In order to be consistent with the following formulas in the present work, this is converted into the angle from the typhoon’s moving direction.
\[ v_{as} = v_s + V_{add} = v_s + 0.4v_s \sin \beta \] (12)

3.3. A New Gust Factor

As mentioned above, the wind in Equation (2) is 1-min averaged \( U_{10} \) [8], which is not suitable for the numerical wave models [49]. The wind field from Equation (2) should be converted into 10-min averaged \( U_{10} \) for further forcing WW3.

We accomplish this conversion with the following sequence of steps. First, we find out the maximum wind speed and its occurrence time from a track data file. Second, we utilize this maximum wind speed to normalize 48-h wind speeds before the maximum wind hour and get the standard deviation of the normalized wind speed. Thirdly, the gust factors can be estimated based on the standard deviations of normalized wind speed following Equation (13), where \( g_f \) is the gust factor and \( s_{id} \) is the standard deviation of the normalized wind speed in the 48 h before the wind peak. A gust factor curve is fitted as in Figure 2. According to Figure 2, the gust factor decreases while the standard deviation increases, meaning that a sharply fluctuating typhoon should be reduced in a larger proportion. A detailed discussion of Equation (13) is presented in Section 5.1.

\[ g_f = \frac{U_{10}^{10}}{U_{10}^{1}} = 0.827 - 0.036 \times \ln (s_{id}) \] (13)

![Figure 2](image)

**Figure 2.** Fitted curve of the gust factor and the manually adjusted gust factors.

3.4. Approximation of RMW

Although the H10 model shows little sensitivity to the RMW, and even errors of up to 50% in this radius result in relatively small errors in the overall wind profile [27], RMW is a mandatory input parameter. For universalization of the Holland model, it is helpful to find an effective method to approximate RMW.

There have been some statistical RMW models fitted regionally [39] for local predictions, but there is not a model available for the SCS. In this paper, a classical method of empirical formula [50] is adopted to approximate RMW following Equation (14), where \( \varphi \) is the latitude of the typhoon center.

\[ r_{rms} = 28.52h[0.0873 \times (\varphi - 28) + 12.22e^{\frac{(Pc_1-1013.2)}{33.86}} + 0.2v_t + 37.2] \] (14)

It is difficult for Equation (14) to provide accurate estimations for every typhoon. In order to verify the accuracy of Equation (14), IBTrACS data [51] are adopted to extract realistic RMW values for typhoons in the Northwest Pacific. A virtual benchmark is utilized to check the sensitivity of H10
to RMW, where \( r = 180 \text{ km} \) and \( v_{ms} = 40 \text{ m/s} \) in Equation (2). Several typhoons in the Northwest Pacific indexed from 022015 (Typhoon NO. and YYYY) to 132015 (Typhoon NO. and YYYY) are investigated.

RMWs from Equation (14) are distributed in a narrow range from 40 to 60 km. Contrarily, the RMWs extracted from IBTrACS are widely distributed from 9 to 90 km, as seen in Figure 3. Although there are some distinct differences in the two datasets of the RMWs, the wind speed, reconstructed based on the RMWs, show small differences, as in Table 1.

![Figure 3. Comparison of the radius of maximum winds (RMW) by Equation (14) against RMW from IBTrACS (left) and comparison of wind speed deduced from the two RMWs (right).](image)

| Variable | Description | Unit (IS) | Definition |
|----------|-------------|-----------|------------|
| \( P_{cs} \) | Typhoon central pressure | hPa | Available in distributed track data |

3.5. Descriptions of Model Input

The final MH10 model consists of Equations (2), (6), (10), (12), and (13). If the RMWs of typhoons are not available, Equation (14) can be adopted to approximate RMWs. Input variables to run MH10 are listed in Table 2. The model MH10 can be easily utilized based on the tracking data distributed through WZTF.

Besides the easily accessible typhoon track data resources, both the MH10 model and the WW3 model can perform reliable simulations of typhoon waves with high efficiency on a desktop workstation ensuring that a researcher can gain insight into typhoon waves. For example, a simulation from 1949 to 2017 with more than 200 typhoons takes about 40 h at a workstation computer with two Intel E5-2650 processors.

![Table 2. Variables to run modified H10 (MH10).](image)
4. Test of Model Performance

4.1. Basic Setup of WW3

WW3 (V4.18) code is compiled to establish a regional hindcasting wave model covering latitudes of 5°–45°N and longitudes of 100°–145°E, with a grid resolution of 10° × 10°. A numeric obstacle technique has been embedded to simulate the effect of numerous islands [30]. The classical source term package of Tolman and Chalikov (T&C package) [52] is adopted to simulate wave physics, including wave generation and wave dissipation with quaternate timesteps set up as 180 s, 900 s, 180 s, and 45 s. The compiling option FLX3 is switched on, since the option is purposely designed for hurricane winds to alleviate the problem of an unrealistically high drag coefficient leading to unrealistically high wave growth rates. Though some researchers have found that the classical T&C package (or the ST2 switch) frequently underestimates typhoon waves [28,29], this paper will demonstrate that the T&C package performs well in the SCS.

4.2. Setup of Input Wind

The wind fields reconstructed by MH10 and H10 are both gridded as 15° × 15° with a temporal interval of 1 h. Practical simulations have proven that the wind field with one-quarter degree is precise enough to force the WW3 model with grids of 10° × 10°. The reconstructed wind field covers the same area as in the WW3 model, covering latitudes of 5°–45°N and longitudes of 100°–145°E. The reconstructed wind field will be reduced by the gust factor before it works to force the WW3 model.

4.3. Explanations of Test Cases

In order to verify the combination of the MH10 model and WW3, 12 typhoons tracking in the Northwest Pacific are investigated in this study. All of these typhoons have been reconstructed through three models: the standard H10 model, indexed as B2-A1-A1; the varying scale parameter b, without asymmetric typhoon structure, indexed as B3-A1-A1; and the modified parameter b, with asymmetric typhoon structure, i.e., the MH10 model, indexed as B3-A1-A2. All three models will be reduced by a gust factor that is calculated separately for different typhoons following Equation (13). Due to the limited length of this paper, seven representative typhoons, seen in Figure 4, will be selected and discussed, with explanatory illustrations to gain insight into the simulation capability of the combination. All simulation results of the 12 typhoons are listed in Table A1.
4.4. Model Verification

The wave time series comparisons between the buoy data and the modeling results, as seen in Figures A1–10, show that the wave series created by MH10 is characterized by swifter feedback to wind input than by the standard H10. All of the wave series figures in Appendix A show that the introduction of an asymmetric structure enhances the model’s ability to capture extreme wave parameters. Generally, MH10 created a more realistic wave time series than standard H10.

An error analysis of the results in Table A1 is conducted for the absolute value error and the percentage error, which are summarized in Table 3. According to Table 3, the RMSEs (root mean square errors) of $H_s$ (Hs is significant wave height) induced by standard H10 and MH10 wind are 1.14 m and 0.86 m, respectively. The MAEs (mean absolute errors) of $H_s$ induced by standard H10 and MH10 wind are 1.36 m and 0.78 m, respectively, and the SDs (standard deviations) of equivalent variables are 1.05 m and 0.67 m. For those percentage errors, the mean error of $H_s$ forced by standard H10 is 20%, and the equivalent error of MH10 is 10%. Additionally, the maximum error is decreased from 75% (standard H10) to 31% (MH10), and the standard deviation of errors is reduced from 19% (standard H10) to 9% (MH10), showing that MH10 has a more stable simulating ability than H10. All of the error results demonstrate that MH10 generally performs better than standard H10. From Table 3, it can be concluded that the new scaling parameter $b_s$ and the asymmetric structure both lead to improved performance.

In general, the three parametric typhoon wind models show equal performances to the force wave model in capturing peak wave periods. Table 3 shows that the three kinds of models tested have a similar ability in the simulation of wave periods whose mean errors are 13% (Standard H10) and 11% (MH10). Both the error analysis and the wave series comparisons reveal that the wave period is more difficult to simulate accurately than the wave height. Especially after the peak time, the wave period will decrease sharply, which is mainly attributed to the absence of an external background wind field. Considering that the restricted wind model is often adopted to estimate extreme sea states and the model results can give a good estimation of the typhoon waves, the disagreement after the peak time is not a significant concern.

In most of the test cases, both the wave height and wave period at the peak time can be simulated well. However, the WW3 model, forced by a reconstructed wind field, will perhaps generate more swells than in a natural ocean setting, and the swells may propagate unrealistically far away. The major reason for this may be that the reconstructed wind field fails to represent the ambient wind field. The ambient wind field may influence the swell dissipation and induce local sea winds, which can reduce the wave periods. This is what happened at Taitung Open Ocean during typhoon 012016 (Nepartak) and at Pratas during typhoon 142016 (Meranti), as seen in Figures A6 and Figure A10; there is an obvious difference between the buoy-measured wave periods and the WW3 wave periods. (Hs is significant wave height; Tr is average period)

Table 3. Error analysis of the three models.
5. Discussion

5.1. Gust Factor

Literature reviews indicate that there has been no definitive conclusion regarding the gust factors for tropical cyclones and extratropical winds. It is revealed that the gust factor is sensitive to surface roughness, and the gust reduction in typhoon winds can be higher than in extratropical winds [35]. In the WW3 model, the wave growth rate is determined by both an effective roughness $z_w$ and the friction velocity $u^*$ [53,30]. However, WW3 is prone to overestimating the drag coefficient for hurricane winds, leading to unrealistically high wave growth [30], since the WW3 model is supported by wave data measured in low-to-moderate wind conditions [53,29]. According to in situ measurements, the drag coefficient decreases as the wind speed increases [54]. Fetch is another important influence for the sea surface roughness [55], and the fetch can be approximately estimated by the pre-peak time. In short, there are many unknown conditions that weaken the WW3 model’s performance at simulating intense typhoon waves.

Physically, the gust factor defined in this paper is purposely utilized to convert different timescale wind speeds. However, the practical applications proved that the gust factor can act as an external adjustor to alleviate some uncertainties caused by various unknown factors, such as the surface roughness, drag coefficient, fluctuation of wind speed, and other unresolved physical parameters.

In general, Equation (13) works well for typhoons with smooth tracks and for those buoys that are moderately far away from the typhoon centers. While a typhoon track shows sharp changes when the buoys are in the typhoon centers, Equation (13) is incapable of making a good estimation of gust factors. For example, the center of Typhoon Vicente (082012) turned sharply away from its preceding track path (see Figure 4), and QF302 is almost overlapping with the center. The gust factor extrapolated by Equation (13) is 0.88, and the best manually adjusted factor is 0.96, as seen in Figure 5.

Figure 5 presents several other cases where the two gust factors are different. Statistics of their difference show that the wave height biases between buoy peak and modeling peak vary between 0.5 and 1.4 m, with the gust factor difference varying between 0.03 and 0.08. For a sharply turbulent typhoon wave series, this magnitude of peak wave difference may be negligible considering that the error ratio of all cases is about 10%, as in Table 3. (TC is the abbreviation of tropical cyclones)
5.2. Scaling Parameter

During Typhoon Meranti (142016), four buoys’ data were available simultaneously. This case provided a good chance to investigate the models’ ability to reconstruct a wind field across a large geographical range.

Following Equation (13), the gust factor of Meranti is defined as $g_f = 0.918$. Both MH10 and the standard H10 have successfully captured the extreme waves at the Eluanbi buoy with a maximum $H_s$ of approximately 18 m (Figure A7). However, H10 poorly simulates the other three buoys (Figures A8–10), whereas the MH10 model works well.

In accordance with Figure 6, in which wind field contours are mapped, and the wind reconstructed by standard H10 is obviously different from that of MH10. The wave fields induced by winds from three kinds of models are depicted in Figures 7–9. All the figures indicate that the maximum wave height occurs at the front-right quadrant of the typhoon motion, and the waves at the right side are usually severer than at the left side. Obviously, the standard H10 overestimates the wind speed, leading to too-large a wave height in the ambient oceans.
Figure 6. Wind fields (unit as m/s) restructured by MH10 (asymmetric structure as solid line, B3-A1-A2); standard H10 (axis-symmetric structure as a dashed line, B2-A1-A1); and the varying scaling parameter $b_s$ without asymmetric structure (depicted with the dashed–dotted line, B3-A1-A1) at Eluanbi Station peak wave time during Typhoon Meranti (142016).

Figure 7. A wave field (unit: cm) induced by the wind field from the standard H10 (B2-A1-A1) at Eluanbi Station peak wave time during Typhoon Meranti (142016), where the bigger black dot is the location of the typhoon’s center.
5.3. Asymmetric Structure of Typhoon

In Table 3, the mean error percentage of B3-A1-A1 when the asymmetric typhoon structure is excluded is 16%, and the error of B3-A1-A2 when the asymmetric structure is included is 10%. The model verification has shown that the introduction of the empirical asymmetric structure is helpful to enable the model to capture wave extremes. Similar conclusions can be visually drawn from the figures in Appendix A.

Another example is typhoon 172011 (Nesat). During this typhoon, three buoys QF301–QF303 worked well; their track is depicted in Figure 10, where the wind structure at the peak wave time is plotted. With this asymmetric wind field, higher wind speed is formulated in the right half of the typhoon track than in the left half, leading to an appropriate simulation of all three buoys in Figure 11 (QF301 and QF303) and Figure A3 (QF302). Though it is hypothetically triggered by the typhoon
motion only, the asymmetric structure is indeed helpful to improve the accuracy of reconstructing the wind field.

![Image of wind fields](image)

**Figure 10.** Wind fields (unit: m/s) restructured by MH10 (asymmetric structure as solid line, B3-A1-A2) and the model with a varying parameter b but without an asymmetric structure (B3-A1-A1) at QF301 Station peak wave time during Typhoon Nesat (172011).

![Image of buoy Hs](image)

**Figure 11.** Simulation of wave height at buoys QF301 (left) and QF303 (right) during typhoon Nesat (172011): the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

5.4. Limitations of the Model Combination

5.4.1. Variability of Gust Factor

As a statistical model for gust factor, Equation (13) can be further optimized based on more studies of the typhoon wave simulations. If the samples utilized for fitting Equation (13) can be increased, the empirical formula may be given with more confidence.

5.4.2. Effective Radius

Though the new formulated scaling parameter $b$ enhances its reconstructing ability both in time series and geographical covering, MH10 fails to correctly restructure the wind field in oceans far away from the typhoon centers. The standard H10 has a similarly limited performance. For instance,
with buoy QF301 during the Nock-ten (082011), buoy QF303 during the Usagi (192013), and buoy Pratas during the Sarika (212016) (see Figure 24), the model results show large bias compared to the buoy data. In fact, it is difficult for a typhoon to induce destructive ocean waves further from its track path than about 400 km.

In general, the parametric MH10 vortex wind model is more efficient in oceans within 3.5–4.0° of the typhoon’s center.

6. Conclusions

A combination of a modified Holland vortex model (MH10) and the WW3 wave model is suggested in this paper and expected to lead to more accurate predictions of typhoon waves. Validation against buoy data and altimeter data proved that the combination of the two models works well.

With these improvements, the MH10 typhoon vortex model shows a robust ability to reconstruct a typhoon wind field. Practical testing cases indicate that the new formula of scaling parameter $b$ tends to reproduce a more realistic wind field in both temporal and spatial contexts. Furthermore, the asymmetric typhoon structure proves to be helpful to capture extreme wave parameters.

The gust factor fitted in this paper bridges the gap between the Holland vortex model and the WW3 model. With the gust factor, the WW3 model performs much more realistically in the typhoon wave simulation, avoiding unrealistic wave growth. The introduction of an effective empirical formula to estimate RMW universalizes the utilization of MH10.

However, the combination of the models should be limited to estimating the sea state in those oceans located within a radius of 3.5–4.0 geographical degrees from the typhoon centers. For oceans too far away from the typhoon center, vortex wind models, including both H10 and MH10, are not able to accurately estimate wind speeds.

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Appendix A.
Figure A1. Comparison of typhoon waves induced by Typhoon Chanthu (03-2010) at buoy QF303: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

Figure A2. Comparison of typhoon waves induced by Typhoon Nock-ten (08-2011) at buoy QF302: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.
Figure A3. Comparison of typhoon waves induced by Typhoon Nesat (17-2011) at buoy QF302: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

Figure A4. Comparison of typhoon waves induced by Typhoon Vicente (08-2012) at buoy QF301: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.
Figure A5. Comparison of typhoon waves induced by Typhoon Soudelor (13-2015) at buoy Guishandao: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

Figure A6. Comparison of typhoon waves induced by Typhoon Nepartak (01-2016) at buoy Taitung Open Ocean: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.
**Figure A7.** Comparison of typhoon waves induced by Typhoon Meranti (14-2016) at buoy Eluanbi: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

**Figure A8.** Comparison of typhoon waves induced by Typhoon Meranti (14-2016) at buoy Taitung Open Ocean: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.
Figure A9. Comparison of typhoon waves induced by Typhoon Meranti (14-2016) at buoy Taitung: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

Figure A10. Comparison of typhoon waves induced by Typhoon Meranti (14-2016) at buoy Pratas: the standard H10 is indexed as B2-A1-A1, the model with varying parameter b without an asymmetric typhoon structure is indexed as B3-A1-A1, and MH10 is indexed as B3-A1-A2.

Appendix B.

Table A1. Paired peak-value of buoy extremes and simulated extremes in every case.

| Index of Typhoon | Case No. | ID of Buoy | Measured Extremes | Simulated Extremes |
|------------------|----------|------------|-------------------|--------------------|
|                  |          |            | Hs (m) | Tr (s) | B2-A1-A1 | B3-A1-A1 | B3-A1-A2 |
| 032010 Chanthu   | 1        | QF303      | 6.50   | 9.00   | 5.93     | 8.54     | 6.67     | 8.86     | 6.42     | 8.79     |
| 2                | 2        | QF301      | 2.90   | 7.70   | 1.98     | 6.26     | 1.99     | 6.31     | 2.97     | 7.30     |
| 082011 Nock-ten  | 3        | QF302      | 4.00   | 8.20   | 3.45     | 7.67     | 3.38     | 7.84     | 3.98     | 8.34     |
| 4                |          | QF303      | 5.60   | 10.10  | 4.24     | 8.02     | 4.37     | 8.05     | 4.94     | 8.35     |
| 5                |          | QF301      | 5.60   | 11.40  | 5.25     | 9.46     | 4.71     | 9.56     | 5.56     | 9.83     |
| 172011 Nesat     | 6        | QF302      | 8.00   | 10.70  | 7.57     | 10.67    | 7.14     | 10.42    | 7.85     | 10.84    |
| 7                |          | QF303      | 8.70   | 10.70  | 8.61     | 10.97    | 8.22     | 10.84    | 9.01     | 11.10    |
| 082012 Vicente   | 8        | QF301      | 7.50   | 9.40   | 5.66     | 8.82     | 6.17     | 8.97     | 6.72     | 9.16     |
| Year | Storm | Location | QF302 | QF301 | QF303 | Pratas | Guishan dao |
|------|-------|----------|-------|-------|-------|--------|-------------|
| 2013 | Usagi | Taitung | 9     | 10    | 11    | 12     | 13          |
| 2015 | Soudelor | Taitung | 14    |       |       |        |             |
| 2016 | Nepartak | Open Oce. | 15    |       |       |        |             |
| 2016 | Meranti | Pratas | 16    |       |       |        |             |
| 2016 | Megi | Guishan dao | 17    |       |       |        |             |
| 2016 | Aere | Pratas | 18    |       |       |        |             |
| 2016 | Sarika | Pratas | 19    |       |       |        |             |
| 2016 | Haiama | Pratas | 20    |       |       |        |             |

References

1. Ambinakudige, S.; Khanal, S. Assessment of impacts of Hurricane Katrina on net primary productivity in Mississippi. *Earth Interact* 2010, **14**, 1–12.
2. Forristall, G.Z. Comparing hindcasts with wave measurements from Hurricanes Lili, Ivan, Katrina and Rita. In Proceedings of the 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazards Symposium, North Shore, Oahu, HI, USA, 11–16 November 2007.
3. Anthony, M.V.; George, Z.F.; Bryan, R.P.; Habib, J.D. Estimation of extreme wave and wind design parameters for offshore wind turbines in the Gulf of Maine using a POT method. *Ocean Eng.*, 2015, **104**, 649–658.
4. Goda, Y. On the methodology of selecting design wave height. In Proceedings of the Coastal Engineering Conference, Torremolinos, Spain, 20–25 June 1988.
5. Wei, W.; Fu, S.; Moan, T.; Song, C.; Ren, T. A time-domain method for hydroelasticity of very large floating structures in inhomogeneous sea conditions. *Mar. Struct.* 2018, **57**, 180–192.
6. Wang, D.P.; Oey, L.Y. Hindcast of waves and currents in hurricane Katrina. *BAMS* 2008, **89**, 487–496.
7. Padilla-Hernández, R.; Perrie, W.; Toulaney, B.; Smith, P.C. Modeling of two Northwest Atlantic storms with third-generation wave models. *Weather Forecast.* 2007, **22**, 1229–1242.
8. Young, I.R. A review of the sea state generated by hurricanes. *Mar. Struct.* 2003, **16**, 201–218.
9. Zhang, C.; Zhang, Q.; Zheng, J.; Demirbilek, Z. Parameterization of nearshore wave front slope. *Coast. Eng.* 2017, **127**, 80–87.
10. Browne, M.; Castelle, B.; Strauss, D.; Tomlinson, R.; Blumenstein, M.; Lane, C. Near-shore swell estimation from a global-wave model: Spectral process, linear, and artificial neural network models. *Coast. Eng.* 2007, **54**, 445–460.
11. Durán-Rosal, A.M.; Hervás-Martínez, C.; Tallón-Ballesteros, A.J.; Martínez-Estudillo, A.C.; Salcedo-Sanz, S. Massive missing data reconstruction in ocean buoys with evolutionary product unit neural networks. *Ocean Eng.* 2016, **117**, 292–301.
12. Herman, A.; Kaiser, R.; Niemeyer, H.D. Wind-wave variability in a shallow tidal sea—Spectral modelling combined with neural network methods. *Coast. Eng.* 2009, **56**, 759–772.
13. Yan, Z.; Liang, B.; Wu, G.; Wang, S.; Li, P. Ultra-long return level estimation of extreme wind speed based on the deductive method. *Ocean Eng.* 2020, **197**, 106900.
14. Wu, G.; Shi, F.; Kirby, J.T.; Liang, B.; Shi, J. Modeling wave effects on storm surge and coastal inundation. *Coast. Eng.* 2008, **140**, 371–382.
15. Liang, B.; Gao, H.; Shao, Z. Characteristics of global waves based on the third-generation wave model SWAN. *Mar. Struct.* 2019, **64**, 35–53.
16. Shao, Z.; Liang, B.; Li, H.; Wu, G.; Wu, Z. Blended wind fields for wave modeling of tropical cyclones in the South China Sea and East China Sea. *Applied Ocean Res.* 2018, **71**, 20–33.
17. Rogers, W.E.; Kaihatu, J.M.; Hsu, L.; Jensen, R.E.; Dykes, J.D.; Holland, K.T. Forecasting and hindcasting waves with the SWAN model in the Southern California Bight. *Coast. Eng.* 2007, 54, 1–15.
18. Chen, S.S.; Curcic, M. Ocean surface waves in Hurricane Ike (2008) and Superstorm Sandy (2012): Coupled model predictions and observations. *Ocean Model.* 2016, 103, 161–176.
19. Kuester, M.A.; Alexander, M.J.; Ray, E.A. A model study of gravity waves over Hurricane Humberto (2001). *J. Atmos. Sci.* 2008, 65, 3231–3246.
20. Li, Q.; Duan, Y.; Yu, H.; Fu, G. A high-resolution simulation of Typhoon Rananim (2004) with MM5. Part I: Model verification, inner-core shear, and asymmetric convection. *Mon. Weather Rev.* 2008, 136, 2488–2506.
21. Rusu, L.; Pilar, P.; Guedes Soares, C. Hindcast of the wave conditions along the west Iberian coast. *Coast. Eng.* 2008, 55, 906–919.
22. Holland, G.J. An analytical model of the wind and pressure profiles in hurricanes. *Mon. Weather Rev.* 1980, 108, 1212–1218.
23. Hubbert, G.D.; Holland, G.J.; Leslie, L.M.; Manton, M.J. A real-time system for forecasting tropical cyclone storm surges. *Weather Forecast.* 1991, 6, 86–97.
24. Willoughby, H.E.; Rahn, M.E. Parametric representation of the primary hurricane vortex. Part I: Observations and evaluation of the Holland (1980) Model. *Mon. Weather Rev.* 2004, 132, 3033–3048.
25. Xie, L.; Bao, S.; Pietrafesa, L.J.; Foley, K.; Fuentes, M. A real-time hurricane surface wind forecasting model: Formulation and verification. *Mon. Weather Rev.* 2006, 134, 1355–1370.
26. Young, I.R. A review of parametric descriptions of tropical cyclone wind-wave generation. *Atmosphere* 2017, 194, 1–20.
27. Holland, G.J.; Belanger, J.I.; Fritz, A. A revised model for radial profiles of hurricane winds. *Mon. Weather Rev.* 2010, 138, 4393–4401.
28. Liu, Q.; Babbin, A.; Fan, Y.; Zieger, S.; Guan, C.; Moon, I. Numerical simulations of ocean surface waves under hurricane conditions: Assessment of existing model performance. *Ocean Model.* 2017, 118, 73–93.
29. Zieger, S.; Babbin, A.V.; Erick Rogers, W.; Young, I.R. Observation-based source terms in the third-generation wave model WAVEWATCH. *Ocean Model.* 2015, 96, 2–25.
30. Tolman, H.L. User Manual and System Documentation of WAVEWATCH III version 4.18; Environmental Modeling Center Marine Modeling and Analysis Branch (NOAA): Silver Spring, MD 20910, USA, 2014.
31. Bernier, N.B.; Alves, J.G.M.; Tolman, H.; Chawla, A.; Peel, S.; Pouliot, B.; Roch, M. Operational wave prediction system at environment Canada: Going global to improve regional forecast skill. *Weather Forecast.* 2016, 31, 353–370.
32. Chen, S.S.; Zhao, W.; Donelan, M.A.; Price, J.F.; Walsh, E.J. The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere–wave–ocean models for hurricane research and prediction. *B. Am. Meteorol. Soc.* 2007, 88, 311–317.
33. Seemanth, M.; Bhowmick, S.A.; Kumar, R.; Sharma, R. Sensitivity analysis of dissipation parameterizations in a third-generation spectral wave model, WAVEWATCH III for Indian Ocean. *Ocean Eng.* 2016, 124, 252–273.
34. Powell, M.D.; Vickery, P.J.; Reinhold, T.A. Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature* 2003, 422, 279–283.
35. Yu, B.; Chowdhury, A.G. Gust factors and turbulence intensities for the tropical cyclone environment. *J. Appl. Meteorol. Clim.* 2009, 48, 534–552.
36. Schloemer, R.W. Analysis and synthesis of hurricane wind patterns over Lake Okeechobee, Florida Hydrometeorological Report 31; US Weather Bureau, Department of Commerce, and Army Corps of Engineers: Washington, DC, USA, 1954.
37. Holland, G. A revised hurricane pressure–wind model. *Mon. Weather Rev.* 2008, 136, 3432–3445.
38. Vickery, P.J.; Forrest, J.M.; Mark, D.P.; Dhiraj, W. Hurricane hazard modeling: The past, present, and future. *J. Wind Eng. Ind. Aerol.* 2009, 97, 392–405.
39. Vickery, P.J.; Wadhya, D. Statistical models of Holland pressure profile parameter and radius to maximum winds of hurricanes from flight-level pressure and H*Wind data. *J. Appl. Meteorol. Clim.* 2008, 47, 2497–2517.
40. Vickery, P.J.; Skerlj, P.F.; Steckley, A.C.; Twisdale, L.A. Hurricane wind field model for use in hurricane simulations. *J. Struct. Eng.* 2000, 126, 1203–1221.
41. Gonzalez, A.O.; Slocum, C.J.; Taft, R.K.; Schubert, W.H. Dynamics of the ITCZ boundary layer. *J. Atmos. Sci.* 2016, 73, 1577–1592.
42. Lee, C.; Chen, S.S. Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere - wave - ocean models and observations. J. Atmos. Sci. 2012, 69, 3576–3594.
43. Miyamoto, Y.; Satoh, M.; Tomita, H.; Oouchi, K.; Yamada, Y.; Kodama, C.; Kinter, J. Gradient wind balance in tropical cyclones in high-resolution global experiments. Mon. Weather Rev. 2014, 142, 1908–1926.
44. Bell, K.; Ray, P.S. North Atlantic Hurricanes 1977-99: Surface Hurricane-Force Wind Radii. Mon. Weather Rev. 2004, 132, 1167–1189.
45. Yoshizumi, S. On the asymmetry in the lower layer of wind distribution in typhoon. J. Meteorol. Soc. Jpn 1968, 46, 153–159.
46. Lin, N.; Chavas, D. On hurricane parametric wind and applications in storm surge modeling. J. Geophys. Res. 2012, 117, 1–19.
47. Georgiou, P.N. Design Wind Speeds in Tropical Cyclone-prone Regions. Ph.D. Thesis, University of Western Ontario, London, ON, Canada, 1986.
48. Liu, H.; Xie, L.; Pietrafesa, L.J.; Bao, S. Sensitivity of wind waves to hurricane wind characteristics. Ocean Model. 2007, 18, 37–52.
49. Stoffelen, A. Error modeling and calibration: Towards the true surface wind speed. J. Geophys. Res. 1998, 103, 7755–7766.
50. Yang, Y.; Zhu, Z.; Zhou, K. Numerical simulation of typhoon waves in Northwest Pacific Ocean. Mar. Sci. 2010, 34, 62–67.
51. Knapp, K.R.; Kruk, M.C.; Levinson, D.H.; Diamond, H.J.; Neumann, C.J. The International Best Track Archive for Climate Stewardship (IBTrACS). Bull. Amer. Meteor. Soc. 2010, 91, 363–376.
52. Tolman, H.L.; Chalikov, D. Source terms in a third generation wind wave model. J. Phys. Oceanogr. 1996, 26, 2497–2518.
53. Fan, Y.; Rogers, W.E. Drag coefficient comparisons between observed and model simulated directional wave spectra under hurricane conditions. Ocean Model. 2016, 102, 1–13.
54. Hackerott, J.A.; Pezzi, L.P.; Paskyabi, M.B.; Oliveira, A.P.; Reuder, J.; Souza, R.B.; Camargo, R. The role of roughness and stability on the momentum flux in the Marine Atmospheric Surface Layer: A study on the Southwestern Atlantic Ocean. J. Geophys. Res. Atmos. 2018, 123, 3914–3932.

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