Maximum wind radius estimated by the 50 kt radius: improvement of storm surge forecasting over the western North Pacific

Hiroshi Takagi and Wenjie Wu
Tokyo Institute of Technology, Graduate School of Science and Engineering, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

Correspondence to: Hiroshi Takagi (takagi@ide.titech.ac.jp)

Received: 8 September 2015 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 27 October 2015
Revised: 18 February 2016 – Accepted: 24 February 2016 – Published: 11 March 2016

Abstract. Even though the maximum wind radius ($R_{\text{max}}$) is an important parameter in determining the intensity and size of tropical cyclones, it has been overlooked in previous storm surge studies. This study reviews the existing estimation methods for $R_{\text{max}}$ based on central pressure or maximum wind speed. These over- or underestimate $R_{\text{max}}$ because of substantial variations in the data, although an average radius can be estimated with moderate accuracy. As an alternative, we propose an $R_{\text{max}}$ estimation method based on the radius of the 50 kt wind ($R_{50}$). Data obtained by a meteorological station network in the Japanese archipelago during the passage of strong typhoons, together with the JMA typhoon best track data for 1990–2013, enabled us to derive the following simple equation, $R_{\text{max}} = 0.23 R_{50}$. Application to a recent strong typhoon, the 2015 Typhoon Goni, confirms that the equation provides a good estimation of $R_{\text{max}}$, particularly when the central pressure became considerably low. Although this new method substantially improves the estimation of $R_{\text{max}}$ compared to the existing models, estimation errors are unavoidable because of fundamental uncertainties regarding the typhoon’s structure or insufficient number of available typhoon data. In fact, a numerical simulation for the 2013 Typhoon Haiyan as well as 2015 Typhoon Goni demonstrates a substantial difference in the storm surge height for different $R_{\text{max}}$. Therefore, the variability of $R_{\text{max}}$ should be taken into account in storm surge simulations (e.g., $R_{\text{max}} = 0.15 R_{50}$–0.35 $R_{50}$), independently of the model used, to minimize the risk of over- or underestimating storm surges. The proposed method is expected to increase the predictability of major storm surges and to contribute to disaster risk management, particularly in the western North Pacific, including countries such as Japan, China, Taiwan, the Philippines, and Vietnam.

1 Introduction

The maximum wind radius ($R_{\text{max}}$) is one of the predominant parameters for the estimation of storm surges and is defined as the distance from the storm center to the region of maximum wind speed. The storm eye usually decreases in size as it deepens, with the minimum value occurring near the lowest pressure (Jordan, 1961), so that $R_{\text{max}}$ also decreases logarithmically with the central pressure depth (Fuji, 1998). Loder et al. (2009) examined various physical factors influencing peak surge elevation for an idealized marsh and demonstrated that a difference in $R_{\text{max}}$ of 3.7 times caused a difference of 40% in the simulated surge height. Jelesnianski (1972) for a basin of standard bathymetry that surge heights tend to increase as $R_{\text{max}}$ increases, while Jelesnianski and Taylor (1973) showed that a surge would become largest for a certain $R_{\text{max}}$ but decreased for an $R_{\text{max}}$ above or below the peak $R_{\text{max}}$. However, prior to Hurricane Katrina, little attention was given to the role of the hurricane size in surge generation (Irish et al., 2008).

Numerical simulations have often predicted the extent of inundation due to catastrophic storm surges. For example, in the storm surge model of the Japan Meteorological Agency (JMA), two kinds of meteorological forcing fields are used: a simple parametric model of the tropical cyclone (TC) structure and a prediction of the operational non-hydrostatic mesoscale model (JMA, 2009). Although TC forecasts with a mesoscale model have gradually improved, their mean po-
sition error remains around 100 km for 24 h forecasts (JMA, 2009). Furthermore, high spatial resolution is needed to solve the pressure gradients near the radius of maximum winds; thus, forecasted “low-resolution” storms tend to be weaker than they can be (Persing and Montgomery, 2005). The relationship between TCs and climate can be subtle, while differences in the spatial and temporal scales are large (Elsner and Jagger, 1998). In addition, it was found that the JMA Global Spectral and Typhoon models (GSMs) underestimate the intensity of TCs in their predictions of the central pressure and maximum wind speed (Hemming and Goerss, 2010). Therefore, the JMA still uses the parametric TC model to account for the errors in the TC track forecasts and their influence on storm surge prediction (JMA, 2009).

In a parametric model, TCs are defined by a few parameters (e.g., wind speed, central pressure, $R_{max}$). Such reconstructions are frequently used to force storm surge and wave models or models of wind damage applied to an urban area and are thus useful from operational forecasting and warning to climatological risk assessment and engineering design (Kepert, 2010; Takagi et al., 2011). However, it has been commonly recognized that the results drawn from individual storms may not necessarily be representative for the majority of storms (Shea and Gray, 1973).

For hurricanes with central pressures of 909–993 hPa in 1893–1979, the mean $R_{max}$ was 47 km (Hsu and Yan, 1998). Fujii (1998) investigated typhoons with central pressures ≤ 980 hPa that hit the Japanese main islands and found an average $R_{max}$ of 84–98 km, depending on the track.

However, the $R_{max}$ should be selected depending on the characteristics of each typhoon. Therefore, several estimation models for $R_{max}$ have been proposed. Kossin et al. (2007) correlated the $R_{max}$ with the TC eye size (km), when a clear symmetric eye was identifiable, obtaining $R_{max} = 2.8068 + 0.8361 R_{eye}$, where $R_{eye}$ is the infrared-measured eye size (km). Although this method demonstrated good accuracy, it has not yet been employed for the western North Pacific (WNP).

Quiring et al. (2011) used the maximum wind velocity ($V_{max}$) to estimate $R_{max}$ for the entire Atlantic basin: $R_{max} = 49.67 - 0.24 V_{max}$, with $R_{max}$ and $V_{max}$ in nautical miles (nmi; 1 nmi = 1.85 km) and knots (kts; 1 kt = 0.52 ms$^{-1}$), respectively. The $V_{max}$ is a relatively easily available parameter typically included in a TC warning. However, it must be noted that the maximum wind velocities are differently defined, depending on the oceanic basin through which the TC transits. For instance, the JMA classifies the typhoon winds based on the 10 min maximum sustained wind speed, while the United States National Weather Service (NWS) defines sustained winds using 1 min averages. These differences in classification inevitably introduce differences in the relationship between $R_{max}$ and $V_{max}$. Therefore the Quiring et al. (2011) formula is not immediately applicable to TCs in other basins, though an empirical relationship between 1 and 10 min mean wind speeds could be applied for their conversion (Sampson et al., 1995).

The empirical formula developed by the National Institute for Land and Infrastructure Management (NILIM) (Kato, 2005) has been often used to estimate the $R_{max}$ for storm surge simulations, particularly among Japanese coastal engineers (e.g., Takagi et al., 2012; Nakajo et al., 2014), primarily because its estimation based on the TC’s central pressure ($P_c$), $R_{max} = 80 - 0.769 (950 - P_c) (P_c < 950)$, with $R_{max}$ and $P_c$ in km and hPa, respectively, is convenient. The Port and Airport Research Institute (PARI) and the Japan Weather Association (JWA) have also proposed exponential formulas of $R_{max}$ (km) using the central pressure (hPa): $R_{max} = 94.89 \exp(P_c - 967) / 61.5$ (Kawai et al., 2005) and $R_{max} = 52.15 \exp(P_c - 952.7) / 44.09$ (Kitano et al., 2002), respectively. An alternative $R_{max}$ estimation based on the latitude, $\bar{\psi}$, in addition to the pressure deficit, $\Delta P$, has been proposed by Vickery and Wadhera (2008) for TCs with a central pressure below 980 hPa traveling over the Atlantic and the Gulf of Mexico: $\ln(R_{max}) = 3.015 - 6.291 \times 10^{-5} \Delta p^2 + 0.0337 \bar{\psi}$, with $R_{max}$, $\Delta p$, and $\bar{\psi}$ in kilometers, hPa, and degrees, respectively.

The purpose of this paper is to examine the existing models for $R_{max}$ estimation and propose a new formula to minimize the estimation errors that result in an over- or underestimation of the storm surge height. The meteorological data for the development of a reliable model for typhoon and storm surge simulation were obtained on 10 stations, from Japan’s small southern islands. Our new methodology is expected to improve storm surge prediction particularly for the WNP, including Japan, China, Taiwan, the Philippines, and Vietnam.

## 2 Methodology

In this section, the data for the TC analysis, using only TCs crossing the Japanese archipelago, are elucidated. A brief description of the storm surge model is also presented.

### 2.1 Collection, selection, and processing of TC data

The major problems in obtaining TC maximum wind observations result from the sparseness of oceanic stations (Akinson et al., 1977). However, the good density of meteorological stations along the Japanese archipelago has great potential for collecting data during TC passages. Figure 1 indicates the 10 meteorological stations on Japan’s southern islands operated by the JMA. Using data from these stations, it was possible to analyze typhoons traveling within about 800 km between Naze and Yonaguni-jima (Fig. 1).

As a TC approaches the Japanese main islands, its track, shape, and intensity are altered due to topographical disturbance (Fujii, 2006). Therefore, the use of data from these remote islands avoids the substantial changes in TC structure induced by land topography.

---

**Note:** The above text is a natural representation of the document, ensuring that the content is clear and accessible to readers. The text is formatted for readability and includes necessary citations and mathematical expressions as appropriate.
Figure 1. Ten meteorological stations along the Japanese archipelago operated by the Japan Meteorological Agency (JMA): Minamidaitojima (a), Naze (b), Okinoerabu (c), Nago (d), Naha (e), Kume-jima (f), Miyako-jima (g), Ishigaki-jima (h), Iriomote-jima (i), and Yonaguni-jima (j).

Figure 2. Tracks of the 17 selected tropical cyclones transiting over the ocean. The color differences represent the changes in central pressure. The crosses indicate the location of the 10 meteorological stations operated by the Japan Meteorological Agency (JMA): Minamidaito-jima (a), Naze (b), Okinoerabu (c), Nago (d), Naha (e), Kume-jima (f), Miyako-jima (g), Ishigaki-jima (h), Iriomote-jima (i), and Yonaguni-jima (j).

Data collection from the selected stations was restricted to when the station experienced low pressures ($P_c < 935 \text{ hPa}$) during the typhoon passage. The distance between the TC center and each meteorological station was calculated. Only TCs transiting within about 100 km from one or more stations were selected, while the vast majority of TCs that traveled far from the stations was neglected, as they seemed to be less influential.

Recent major TCs, which caused more than 2000 fatalities, such as the 2004 Hurricane Katrina, the 2007 Cyclone Sidr, the 2008 Cyclone Nargis, and the 2013 Typhoon Haiyan had very low central pressures (895–937 hPa) and caused severe storm surge disasters (Table 1). Of all hurricane damage, 80 % is caused by less than 20 % of the worst events (Jagger et al., 2007). The aim of the present study is to develop an $R_{\text{max}}$ estimation model, which is expected to increase the reliability of forecasting of strong storm surges. Therefore, only TCs with pressures below 935 hPa were included in constructing the model, excluding a majority of TCs that may not produce strong storm surges.

Because the JMA meteorological information contains hourly central pressures and wind speeds only after 1990 (before, data were limited to 3 or 6 h intervals), only data from 1990 to 2013 were used. A TC track analysis was carried out for the WNP, using the best track data from the JMA, which consisted of time, geographical position, sea level pressure at the storm center, maximum sustained wind speed, and auxiliary information for every 3 or 6 h. Only 17 out of the 621 TCs that occurred from 1990 to 2013 met the selection criteria and were used in this study. Their characteristics and tracks are presented in Table 2 and Fig. 2, respectively.
The atmospheric pressure inside a TC is generally expressed by an empirical formula. For our model, the Myers model was adopted to calculate the pressure at a distance $r$ from the TC center $P(r)$ (Myers, 1954):

$$ P(r) = P_0 + \Delta P \cdot \exp\left(-\frac{R_{\max}}{r}\right). $$

(1)

where $r$ denotes the distance from the center of the typhoon, $P_0$, the pressure at the typhoon center, $\Delta P$, the drop in pressure, and $R_{\max}$, the radius of the maximum wind.

For the estimation of $R_{\max}$, because the geographic locations (latitude and longitude) of the TC center from the best track were recorded every 3 or 6 h, the location coordinates were converted to the Universal Transverse Mercator (UTM) coordinate system and then temporally interpolated to hourly data. Then, the distance between the TC center and each station was calculated.

If the exact values for $r$, $P(r)$, $P_0$, and $\Delta P$ are known, $R_{\max}$ can also be calculated by inverting Eq. (1), namely,

$$ R_{\max} = r \ln \left(\frac{\Delta P}{P(r) - P_0}\right). $$

However, in this study the pressure at the station closest to the typhoon was estimated by Eq. (1) for different $R_{\max}$ at a 2.5 km interval and compared with the observed pressure at the station. Then, the radius that provided the best estimation was considered the optimum $R_{\max}$.

The reason for using a numerical rather than an analytical approach is twofold: (1) the present study aims at forecasting storm surges. Thus, we believe that the estimation of wind–pressure fields should be performed by the model that is also incorporated in the storm surge simulation. In addition, (2) because the central pressures in the JMA typhoon best track data were recorded at an interval of 5 hPa, a certain degree of error in the estimated $R_{\max}$ is inevitable even when the other parameters in Eq. (1) are correctly obtained. The possible error in $R_{\max}$ associated with this truncated central pressure can be calculated by the following equation:

$$ R_{\max}^t - R_{\max}^b = r \ln \left(\frac{\Delta P^t}{P(r) - P_0^t}\right) - r \ln \left(\frac{\Delta P^b}{P(r) - P_0^b}\right) $$

$$ \approx r \ln \frac{P(r) - P_0^b}{P(r) - P_0^t}. $$

(2)

where the superscripts $t$ and $b$ denote the true and the data from the best track, respectively. The possible error in $R_{\max}$ is calculated to be about 3.2–3.5 km, for instance when assuming $r = 40$ km, $P(r) = 960$ hPa, $P_0^t = 930$ hPa, and $P_0^t - P_0^b = \pm 2.5$ hPa. Thus, it should be noted that the $R_{\max}$ derived in the following section contains an inevitable error of up to a few kilometers.

Although the present study investigated only the station closest to the TC center, ignoring the other stations, including data from additional stations may improve the representation of the TC profile, particularly its tail. For the purpose of improving storm surge forecasting, however, the authors submit that the data closest to the TC center should be most emphasized rather than details of the tail profile, which is less influential for storm surge generations.

It is noted that the representation of $R_{\max}$ proposed in the present study has been confirmed only by the Myers model, which does not guarantee applicability to the other TC models. For example, Holland (1980) extended the Myers model into the form $P(r) = P_0 + \Delta P \cdot \exp(-R_{\max}/r)^B$, which includes a shape parameter $B$. The Holland model is another commonly used model for generating wind fields in storm surge simulations. The Myers model corresponds to the Holland model when $B$ is taken to be unity. The $B$ parameter plays an important role in modeling wind and pressure fields, because it has the effect of modulating both the maximum gradient wind speed and the shape of the outer wind profile. The value for $B$ has an upper limit of approximately 1.2–1.3 for large TCs in the Atlantic Basin and the Gulf of Mexico, having low central pressures (< 930 hPa) (Vickery and Wadhera, 2008). The estimation of $B$ essentially requires calibration to wind and pressure observations. However, the development of a relationship between $B$ and other physical parameters such as pressure data is difficult for TCs traveling over the WNP, where aircraft reconnaissance has been already terminated. Thus, for the sake of simplicity and practicality of application, we adopted the Myers model to simulate wind and pressure fields to be used in the storm surge model.

### 2.2 Storm surge model

The effectiveness of a new formula mainly aimed to improve the estimation of storm surges must be addressed through storm surge simulations. Takagi et al. (2015a, 2016) reproduced the storm surge from the 2013 Typhoon Haiyan for various parts of the Philippines, including Leyte, Samar, and Cebu. We extended this simulation by incorporating the new...
Table 2. Characteristics of the 17 typhoons selected for this study.

<table>
<thead>
<tr>
<th>No.</th>
<th>Typhoon</th>
<th>Progress of the central pressure (hPa)a</th>
<th>Maximum wind velocity (knot)b</th>
<th>50 kt radius ($R_{50}$) (km)b</th>
<th>Nearest stationc</th>
<th>Distance of TC center from nearest station (km)</th>
<th>Estimated $R_{\text{max}}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9019 (FLO)</td>
<td>925 → 920 → 915 → 910 → 905 → 900 → 895 → 890 → 895 → 900 → 905 → 910 → 915 → 920 → 925 → 930</td>
<td>102</td>
<td>232</td>
<td>b</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>9313 (YANCY)</td>
<td>930 → 925 → 930</td>
<td>95</td>
<td>204</td>
<td>f</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>9416 (FRED)</td>
<td>925 → 930</td>
<td>95</td>
<td>241</td>
<td>h</td>
<td>47</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>9609 (HERB)</td>
<td>930 → 925</td>
<td>95</td>
<td>333</td>
<td>i</td>
<td>22</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>9918 (BART)</td>
<td>930</td>
<td>90</td>
<td>204</td>
<td>f</td>
<td>39</td>
<td>35</td>
</tr>
<tr>
<td>6</td>
<td>0314 (MAEMI)</td>
<td>930 → 925 → 920 → 915 → 910 → 915 → 920 → 925 → 930</td>
<td>105</td>
<td>148</td>
<td>g</td>
<td>12</td>
<td>32.5</td>
</tr>
<tr>
<td>7</td>
<td>0418 (SONGDA)</td>
<td>925 → 930</td>
<td>95</td>
<td>222</td>
<td>d</td>
<td>14</td>
<td>80</td>
</tr>
<tr>
<td>8</td>
<td>0608 (SAOMAI)</td>
<td>930 → 925 → 930</td>
<td>103</td>
<td>120</td>
<td>g</td>
<td>63</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>0613 (SHANSHAN)</td>
<td>930 → 925 → 920 → 925 → 930</td>
<td>110</td>
<td>130</td>
<td>h</td>
<td>18</td>
<td>40</td>
</tr>
<tr>
<td>10</td>
<td>0704 (MAN-YI)</td>
<td>930</td>
<td>95</td>
<td>213</td>
<td>e</td>
<td>23</td>
<td>62.5</td>
</tr>
<tr>
<td>11</td>
<td>0712 (WIPHA)</td>
<td>930 → 925 → 930</td>
<td>100</td>
<td>167</td>
<td>i</td>
<td>7</td>
<td>35</td>
</tr>
<tr>
<td>12</td>
<td>0715 (KROSA)</td>
<td>925 → 930</td>
<td>105</td>
<td>259</td>
<td>j</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>13</td>
<td>0815 (JANGMI)</td>
<td>905 → 910 → 915 → 920 → 925 → 930</td>
<td>100</td>
<td>120</td>
<td>j</td>
<td>88</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>1011 (FANAPI)</td>
<td>930</td>
<td>95</td>
<td>167</td>
<td>j</td>
<td>52</td>
<td>35</td>
</tr>
<tr>
<td>15</td>
<td>1215 (BOLAVEN)</td>
<td>920 → 915 → 910 → 915 → 920 → 925 → 930</td>
<td>85</td>
<td>315</td>
<td>d</td>
<td>4</td>
<td>67.5</td>
</tr>
<tr>
<td>16</td>
<td>1216 (SANBA)</td>
<td>920 → 925 → 930</td>
<td>93</td>
<td>219</td>
<td>e</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>17</td>
<td>1217 (JELAWAT)</td>
<td>920 → 925 → 930</td>
<td>90</td>
<td>204</td>
<td>e</td>
<td>32</td>
<td>45</td>
</tr>
</tbody>
</table>

a Numbers in bold indicate the pressure of the typhoon when it passed the station.
b Maximum wind velocities ($V_{\text{max}}$) and the 50 kt radius ($R_{50}$) shown are from when the typhoon passed near a station.
c Naze (b), Nago (d), Naha (e), Kume-jima (f), Miyako-jima (g), Ishigaki-jima (h), Iriomote-jima (i), and Yonaguni-jima (j).

$R_{\text{max}}$ estimation to see whether the simulation reasonably estimated the observed surge heights.

We applied a parametric typhoon model based on the Myers model (Takagi et al., 2012; Takagi et al., 2015a) coupled with the fluid dynamics model Delft3D Flow to estimate the extent of two strong storm surges: one in the Philippines during the 2013 Typhoon Haiyan and the other in the southern islands of Japan during the 2015 Typhoon Goni. This
parametric typhoon model calculates both pressure and wind fields using the parameters from the typhoon track data set of the JMA (i.e., central positions and pressures). The Delft3D Flow model was applied to the simulation of a storm surge traveling from the deep sea to shallow waters and eventually running over coastal areas. Although this model is applicable to a 3-D domain, the present study uses a 2-D horizontal grid, making the code equivalent to a non-linear long wave model, which is most commonly used for storm surge simulations.

3 Results and discussion

In this section, the estimations of $R_{\text{max}}$ based on the existing models are reviewed, and subsequently a new method is proposed to overcome significant estimation errors. Furthermore, a storm surge model is used to investigate the sensitivity of the storm surge height to changes in $R_{\text{max}}$.

3.1 $R_{\text{max}}$ estimation based on the central pressure

Figure 3 shows a scatter plot for $P_c$ and the estimated $R_{\text{max}}$ along with the regression curves from the NILIM, PARI, and JWA models and a linear regression line for the present 17 TCs investigated ($R_{\text{max}} = 0.676 P_c - 578$, with $R_{\text{max}}$ and $P_c$ in km and hPa, respectively). The PARI model, in particular, describes the average $R_{\text{max}}$ well. The NILIM and JWA models slightly over- or underestimated the radii, although the lines were present within the entire plots. The $R_{\text{max}}$ derived for 11 strong cyclones with central pressures of 920–944 hPa is also indicated (Hsu and Yan, 1998) and is similar to the present regression line at around 925 hPa. The model from Vickery and Wadhera (2008), assuming a latitude of $27^\circ$ N as the central value for the meteorological station distribution (Fig. 1), slightly underestimated the plots.

However, individual radius values show significant scatter around the regression lines. In fact, the coefficient of determination $R^2$, which indicates how well a statistical model fits the data, is 0.058, confirming a weak correlation.

3.2 $R_{\text{max}}$ estimation based on the maximum wind speed

The $V_{\text{max}}$ is negatively correlated with the $R_{\text{max}}$ (Shea and Gray, 1973), suggesting that years with more intense TCs tend to have smaller than average $R_{\text{max}}$ (Quiring et al., 2011). Figure 4, derived from the 17 studied typhoons, confirms this trend. However, the correlation between $V_{\text{max}}$ and $R_{\text{max}}$ is weak, as confirmed by an $R^2$ of 0.112. In addition, the fact that $R_{\text{max}}$ is highly sensitive to slight changes in $V_{\text{max}}$ makes it more difficult to determine the optimum $R_{\text{max}}$. Shea and Gray (1973) confirmed that a significant variation in the relationship between these two parameters exists, particularly for lower tropospheric data, obtained through aircraft reconnaissance by the National Hurricane Research Laboratory. Therefore, the validity of the estimation of $R_{\text{max}}$ based on $V_{\text{max}}$ is questionable at least for the WNP.

3.3 New $R_{\text{max}}$ estimation based on the 50 kt wind radius

The relative inadequacy of $P_c$ and $V_{\text{max}}$ as predictors of $R_{\text{max}}$ motivated the authors to investigate another methodology to minimize the estimation error. The Regional Specialized Meteorological Center (RSMC) Tokyo led by the JMA is responsible for issuing TC track and intensity forecasts for the WNP. The JMA produces forecasts of the center position and associated 70% probability, direction, and speed for 120 h
(Knaff, 2010), among other information (Fig. 5). We considered that the radius of 50 kt winds around the typhoon ($R_{50}$), which is contained in the TC forecast information of the JMA, could alternatively be used for the estimation of $R_{\text{max}}$, since both $R_{\text{max}}$ and $R_{50}$ are spatial parameters that directly represent TC sizes. The $R_{50}$ is defined as the maximum radial extent (in nautical miles) of winds reaching 50 kt.

The $R_{\text{max}}$ proportionally increases with the increase in $R_{50}$ (Fig. 6), according to the following average linear relationship:

$$R_{\text{max}} = 0.23 R_{50}.$$

(3)

To compensate for asymmetries in the $R_{50}$, an average value for the difference between the longest and shortest radii could be used. The $R^2$ is 0.57, demonstrating a relatively good correlation. Scatter tends to decrease with decreasing $R_{50}$, implying that the reliability of the $R_{\text{max}}$ estimation improves for stronger TCs, since they generally intensify with decreasing $R_{\text{max}}$. Although this relationship was developed based on the Myers model, the Holland model would also be applicable when the $B$ parameter is set to unity.

Although this new method was expected to improve the estimation of $R_{\text{max}}$, an estimation error is unavoidable because of the fundamental uncertainty regarding the TC structure. Therefore, to minimize the risk of over- or underestimation of storm surges, the surge simulations should be repeated for different estimation lines covering a certain percentage of the data (e.g., a 95 % prediction interval) such as

$$R_{\text{max}} = 0.15 R_{50} - 0.35 R_{50}.$$

Figure 6 also indicates the estimated $R_{\text{max}}$ for the Atlantic from Kimball et al. (2004), after converting the wind speed from a 1 to a 10 min mean and an interpolation to match the $R_{50}$.

### 3.4 Storm surge simulation based on the new $R_{\text{max}}$ model

Two major typhoons, Goni and Haiyan, both of which were not included in the data used for the development of the present $R_{\text{max}}$ model, are investigated to confirm the accuracy of storm surge simulations with the new method.

#### 3.4.1 2015 Typhoon Goni

Figure 7 presents an application of the proposed method to a recent strong typhoon, Typhoon Goni, which traveled over
the southern oceanic basin of Japan in August 2015. This severe typhoon brought about very strong winds, reaching up to 71.0 m s\(^{-1}\) in Ishigaki-jima, which were the strongest winds ever recorded on this island (JMA, 2015). The storm surge induced by strong winds and low pressures was successfully recorded by the tidal gauge in the port of Ishigaki-jima, which is being operated by JMA. The maximum storm surge height (observed water levels – astronomical tides), which was recorded to have reached 57 cm during the passage of the typhoon over the island, was compared with storm surges simulated by the model with three different values of \(R_{\text{max}}\). The observed storm surge lies between those estimated for \(R_{\text{max}}\) using 0.15 \(R_{50}\) and 0.35 \(R_{50}\), which demonstrates the validity of the model.

The present analysis indicates that the larger the typhoon radius, the greater the storm surge height is at a tide station. Figure 8 also demonstrates how changes in \(R_{\text{max}}\) would change the spatial distributions of water-level departures. The size of \(R_{\text{max}}\) appears to be important for precise estimation. Impacts of the storm surge may be limited within a certain area in the case of a smaller radius, whereas the affected area would vastly extend if the size of the typhoon became large. However, it should be noted that a smaller typhoon could have a very strong impact on a specific location, because the pressure gradient tends to be steep, which results in stronger winds near the TC center. These observations suggest that \(R_{\text{max}}\) is indeed an important parameter for determining the intensity and size of TCs and, thus, should not be overlooked.

### 3.4.2 2013 Typhoon Haiyan

Typhoon Haiyan caused the worst storm surge disaster in the recorded history of the Philippines, striking Leyte Island in November 2013 and causing inundations of up to 6–7 m in Tacloban City, where most casualties occurred (Nakamura et al., 2015; Mikami et al., 2016; Esteban et al., 2015, 2016). High inundation heights were observed even outside the Leyte Gulf along the eastern coast of Eastern Samar, which faces the Pacific Ocean in the deep Philippine Trench. Haiyan generated the strongest winds among over 400 past storms, being 16% stronger than the second strongest recorded typhoon. Haiyan’s forward speed was nearly twice the average speed of these weather systems, potentially making it the fastest recorded typhoon (Takagi et al., 2015b). A numerical simulation indicated inundation above 3 m along the entire bay and up to 6 m in the inner bay (Fig. 9; Takagi et al., 2015a). The maximum hindcast significant wave heights caused by the extremely strong winds reached 19 m off Eastern Samar (Bricker et al., 2014; Roeber et al., 2015).
To assess which areas of the Philippines were affected by Typhoon Haiyan, a simulation was initially carried out for a wide area encompassing most of the Philippines. Then, a more detailed simulation was performed for San Pedro Bay in the Leyte Gulf, an area where the massive storm surge engulfed and claimed thousands of lives. The numerical simulation for these two domains had already been implemented in a previous study by the authors (Takagi et al., 2015a).

Figure 10 presents the estimated maximum storm surge heights for six locations around San Pedro Bay. The simulation was implemented for two different radii covering the 95 % prediction interval, namely $R_{\text{max}} = 0.15 \ R_{50}$ and 0.35 $R_{50}$, to examine the sensitivity of the results to $R_{\text{max}}$. Except for Basey and Basiao, the observed heights were mostly within the two estimated values, implying that an estimation using different radii is effective to mitigate the estimation errors. In other words, storm surge simulations must take into account the $R_{\text{max}}$ uncertainty, rather than using a singular value, to avoid significant errors.

Although previous research (e.g., Jelesnianski, 1972, Loder et al., 2009) suggested that peak surge elevation would increase for a large $R_{\text{max}}$, this is not always true as the surge increased even for smaller $R_{\text{max}}$ in some locations (Fig. 10). It is interesting to note that the simulation based on the small radius ($= 0.15 \ R_{50}$) exhibits a far larger surge height than the ones based on the large radius ($= 0.35 \ R_{50}$), particularly for Tanauan. In contrast, the surge increased with typhoon radius for Airport, Anibong, and Bridge. Since Tanauan was located nearby the TC’s center (Fig. 11), the storm surge height was more susceptible to $R_{\text{max}}$ changes there than at distant locations.

### 3.5 Applicability and limitations of the new model

The $R_{\text{max}}$ shows significant scatter when derived from $P_c$ or $V_{\text{max}}$ (Figs. 3 and 4). This resulted in the development of a new approach with smaller estimation errors, where $R_{\text{max}}$ was estimated based on $R_{50}$ by Eq. (3). The relatively high $R^2$ demonstrates that the new method effectively reduced the estimation error of $R_{\text{max}}$.

As the $R_{50}$ is easily obtained from the TC warning information, the method can be applied to any TC transiting over an ocean basin, for which $R_{50}$ values are available from a reliable meteorological agency. The RSMC Tokyo, a regional specialized meteorological center under the World
Meteorological Organization (WMO), covers a vast area of the WNP including Japan, China, Taiwan, the Philippines, and Vietnam and issues TC information, which includes $R_{50}$ (Fig. 5) and warnings to the neighboring agencies when a typhoon arises. To mitigate typhoon-related disasters, the authorities must instantaneously predict the storm surge using a simple parametric typhoon model, incorporating the $R_{50}$ or other parameters estimated by a precise model from a neighboring meteorological agency. Our method should particularly facilitate a prompt early warning by local authorities who cannot operate complex non-hydrostatic mesoscale models but have sufficiently precise local data (e.g., topography, bathymetry, infrastructure conditions, and household information) to greatly improve the prediction of the local amplification of the storm surge.

However, some estimation errors (Fig. 6) were unavoidable because of fundamental uncertainties in the TC structure and insufficient number of available TCs to derive the relationship from Eq. (3). For example, a challenge for the $R_{\text{max}}$ estimation is associated with the occurrence of “flat” tangential wind profiles, i.e., when the wind decays very slowly with increasing radius (Kossin et al., 2007). These errors result in over- or underestimations of the TCs and their subsequent storm surges, whose heights substantially varied with $R_{\text{max}}$ changes (Fig. 10). Figure 6 also shows a noticeable discrepancy in the $R_{\text{max}}$ estimated by the present method for the WNP and the Atlantic, indicating that our method may over- or underestimate the $R_{\text{max}}$ in other basins. This gap may be associated with differences in TC sizes between different basins. In fact, Kimball et al. (2004) suggested that TC eyes are relatively smaller in the WNP than in the Atlantic, potentially resulting in a smaller $R_{\text{max}}$ in the former.

Some TC parameters such as center positions, $P_c$, $V_{\text{max}}$, and $R_{50}$ are determined with full use of available observational data such as radar, surface synoptic observations (SYNOP), ship, buoy, and advanced scatterometer (ASCAT) (RSMC Tokyo, 2015), in addition to Dvorak techniques (Dvorak, 1982, 1984). Moreover, the JMA uniquely uses a table, often referred to as the Koba table, for conversion of the Dvorak CI number to $P_c$ or $V_{\text{max}}$ values as proposed by Koba et al. (1991). Possible errors in $R_{50}$ are of vital interest when the relationship $R_{\text{max}} = 0.23R_{50}$ is applied to a real-time forecast. The $R_{50}$ is estimated according to the statistical relationship between $P_c$ and $R_{50}$ in the absence of necessary observations (RSMC Tokyo, 2015).

Therefore, the estimation of $R_{50}$ appears to be highly correlated with the reliability of $P_c$. Although JMA has adopted the Koba table to improve the estimation of TC intensities in the WNP, there exists a certain degree of estimation error in the conversion process of the Dvorak method. Nevertheless, a series of Dvorak methods using satellite images have been commonly used over the last couple of decades and are considered to be the most reliable estimation of TC intensities in the WNP, where aircraft reconnaissance had been terminated in 1987 (JMA, 2014).

![Figure 12](image.png)

It should also be noted that various $R_{\text{max}}$ have been assumed in studies of Typhoon Haiyan. Takagi et al. (2015a) simulated the storm surge (Fig. 9) by subjectively estimating $R_{\text{max}}$ to have been 15–25 km, based on the author’s empirical judgment that the heaviest rainfall in intense tropical cyclones occurs near the radius of maximum wind (Muramatsu, 1985) (Fig. 11). However, using Eq. (3), the $R_{\text{max}}$ when the typhoon struck Leyte Island was estimated to have been 34 km, with an $R_{50}$ of 80 nmi (= 148 km). Although the reason for this discrepancy is not clear, it can be partly explained by the fact that the inner radar eye radius (IRR) occurs at radii of 5–6 nmi inside the $R_{\text{max}}$ (Shea and Gray, 1973). Mori et al. (2014) estimated the $R_{\text{max}}$ that best described the storm to have been 50–60 km using a numerical weather prediction and a storm surge model, while Kim (2015) assumed it as 30.2 km for the Leyte Gulf landfall for Holland’s wind model (Holland, 1980). These substantial differences in radius imply fundamental difficulties in a precise estimation of $R_{\text{max}}$, even using the best data available and current technology.

With regard to Typhoon Goni, the progress of $R_{\text{max}}$ during the typhoon passage estimated with the Doppler radar installed at Ishigaki-jima (JMA, 2015) can be compared with those estimated by the proposed method. When Goni approached Ishigaki-jima, the TC central pressure had dropped to 935 hPa, as shown in Fig. 12. The estimated $R_{\text{max}}$ value agrees well with those detected by the radar when the typhoon transited near the island, while the accuracy of the estimation appears to become lower when the typhoon was far away from the island.

This example implies that the new estimation is expected to provide a reliable $R_{\text{max}}$ value for a typhoon with a cen-
The present research was funded by the JSPS KAKENHI grant number 26702009 and the Environment Research and Technology Development Fund (S-14) of the Ministry of the Environment, Japan. The JMA typhoon best track data are available at http://www.jma.go.jp/jma/jma-eng/jma-center/rsme-hp-pub-eg/besttrack.html, while the JMA meteorological station network data for the Japanese archipelago can be found at http://www.data.jma.go.jp/obd/stats/etrn/index.php.

Edited by: S. Tinti
Reviewed by: two anonymous referees

References


Dvorak, V. F.: Tropical cyclone intensity analysis and forecasting from satellite visible or enhanced infrared imagery, NOAA NESS, Applications Laboratory Training Notes, 42 pp., 1982.


Kawai, H., Honda, K., Tomita, T., and Kakinuma, T.: Characteristic of Typhoons in 2004 and Forecasting and Hindcasting of Their Storm Surges, Technical Note of the Port and Airport Research Institute, No. 1103, 34 pp., 2005.


Knaff, J. A.: Tropical cyclone surface wind structure and wind pressure relationships, Seventh International Workshop on Tropical Cyclones, WMO, France, 35 pp., 2010.


H. Takagi and W. Wu: Maximum wind radius estimated by the 50 kt radius


