Nat. Hazards Earth Syst. Sci., 16, 705–717, 2016
www.nat-hazards-earth-syst-sci.net/16/705/2016/
doi:10.5194/nhess-16-705-2016

Natural Hazards and Earth System Sciences
Open Access
EGU

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

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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_{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_{max} based on central pressure or maximum wind speed. These over- or underestimate R_{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_{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, $R_{\mathrm{max}} = 0.23\ R_{50}$. Application to a recent strong typhoon, the 2015 Typhoon Goni, confirms that the equation provides a good estimation of R_{max}, particularly when the central pressure became considerably low. Although this new method substantially improves the estimation of R_{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_{max}. Therefore, the variability of R_{max} should be taken into account in storm surge simulations (e.g., $R_{\mathrm{max}} = 0.15\ R_{50}$–$0.35\ R_{50}$), 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_{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_{max} also decreases logarithmically with the central pressure depth (Fujii, 1998). Loder et al. (2009) examined various physical factors influencing peak surge elevation for an idealized marsh and demonstrated that a difference in R_{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_{max} increases, while Jelesnianski and Taylor (1973) showed that a surge would become largest for a certain R_{max} but decreased for an R_{max} above or below the peak R_{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-

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sition error remains around 100 km for 24 h forecasts (JMA, 2009). Furthermore, high spatial resolution is needed to resolve 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, 2013). 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 (Heming 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 $R_{\mathrm{max}} = 2.8068 + 0.8361\ R_{\mathrm{eye}}$, 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: $R_{\mathrm{max}} = 49.67 - 0.24\ V_{\mathrm{max}}$, with R_{max} and V_{max} in nautical miles (nmi; $1\,\mathrm{nm} = 1.85\,\mathrm{km}$) and knots (kts; $1\,\mathrm{kt} = 0.52\,\mathrm{ms}^{-1}$), 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}), $R_{\mathrm{max}} = 80 - 0.769\ (950 - P_{\mathrm{c}})$ ($P_{\mathrm{c}} < 950$), 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): $R_{\mathrm{max}} = 94.89\ \exp^{(P_{\mathrm{c}}-967)\,/\,61.5}$ (Kawai et al., 2005) and $R_{\mathrm{max}} = 52.15\ \exp^{(P_{\mathrm{c}}-952.7)\,/\,44.09}$ (Kitano al., 2002), respectively. An alternative R_{max} estimation based on the latitude, ψ, in addition to the pressure deficit, Δp, 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: $\ln(R_{\mathrm{max}}) = 3.015 - 6.291 \times 10^{-5}\ \Delta p^2 + 0.0337\ \psi$, with R_{max}, Δp, and ψ 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.

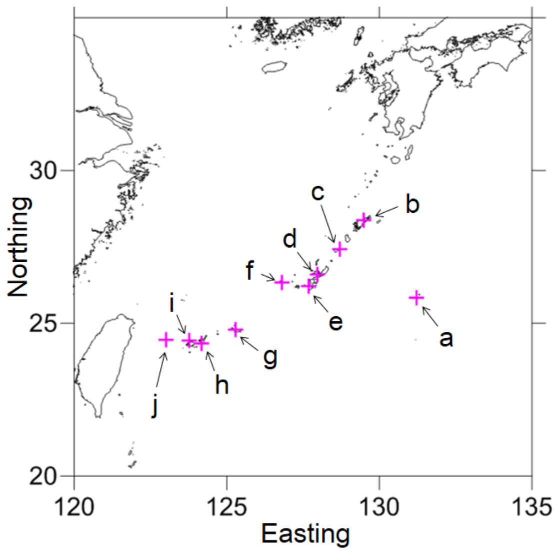
2 Methodology

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.



No	Station	E	N
a	Minamidaitou-jima 南大東島	131.23	25.83
b	Naze 名瀬	129.50	28.38
c	Okinoerabu 沖永良部	128.71	27.43
d	Nago 名護	127.97	26.59
e	Naha 那覇	127.69	26.21
f	Kume-jima 久米島	126.80	26.34
g	Miyako-jima 宮古島	125.28	24.79
h	Ishigaki-jima 石垣島	124.16	24.34
I	Iriomote-jima 西表島	123.77	24.43
j	Yonaguni-jima 与那国島	123.01	24.47

Figure 1. Ten meteorological stations along the Japanese archipelago operated by the Japan Meteorological Agency (JMA): Minamidaitou-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)**.

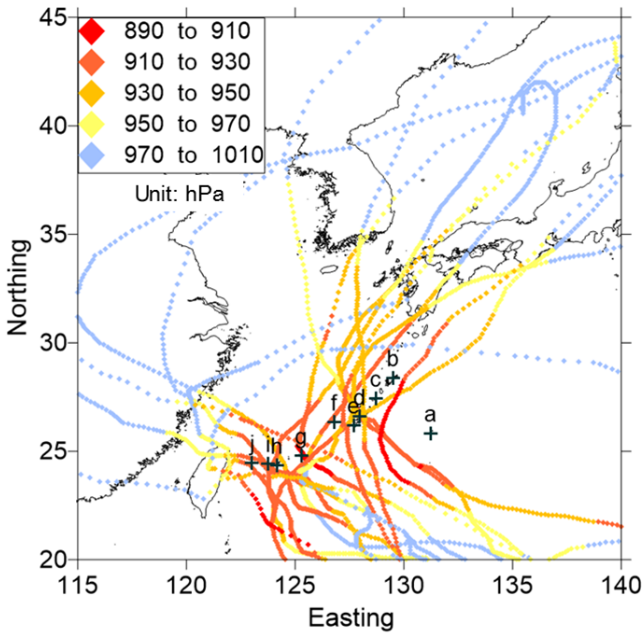


Figure 2. Tracks of the 17 selected tropical cyclones transiting over the ocean. The color differences represent the changes in central pressure. The crosses indicate the location of the 10 meteorological stations operated by the Japan Meteorological Agency (JMA): Minamidaito-jima **(a)**, Naze **(b)**, 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 ($P_c < 935$ 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_{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.

Table 1. Major tropical cyclones in the last 10 years causing extensive storm surges.

Name	Date	Central pressure	Wind speed	Fatalities
Katrina	29 Aug 2005	923 hPa	110 kt	2000
Sidr	15 Dec 2007	926 hPa	140 kt	3600
Nargis	4 May 2008	937 hPa	115 kt	138 000
Haiyan	8 Nov 2013	895 hPa	170 kt	6000

Note: central pressure and wind speed shown in the table are from when the TC made landfall.
Data source: National Hurricane Center (NHC) http://www.nhc.noaa.gov/data/ and Joint Typhoon Warning Center (JTWC, 2012) http://www.usno.navy.mil/JTWC/.

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):

$$P(r) = P_0 + \Delta P \cdot \exp\left(-\frac{R_{\max}}{r}\right), \tag{1}$$

where r denotes the distance from the center of the typhoon, P_0, the pressure at the typhoon center, ΔP, 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 ΔP 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:

$$R^{\mathrm{t}}_{\max} - R^{\mathrm{b}}_{\max} = r\ \ln\left(\frac{\Delta P^{\mathrm{t}}}{P(r) - P^{\mathrm{t}}_0}\right) - r\ \ln\left(\frac{\Delta P^{\mathrm{b}}}{P(r) - P^{\mathrm{b}}_0}\right)$$
$$\approx r \ln \frac{P(r) - P^{\mathrm{b}}_0}{P(r) - P^{\mathrm{t}}_0}, \tag{2}$$

where the superscripts t and b denote the true value 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, $P^{\mathrm{b}}_0 = 930$ hPa, and $P^{\mathrm{t}}_0 - P^{\mathrm{b}}_0 = \pm 2.5$ 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.

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

[a] Numbers in bold indicate the pressure of the typhoon when it passed the station.
[b] Maximum wind velocities (V_{max}) and the 50 kt radii (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_{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

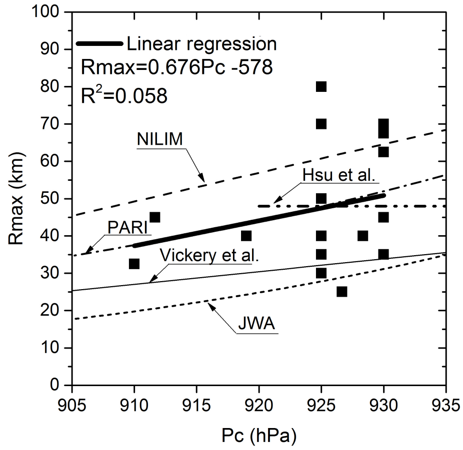


Figure 3. Wind radii and central pressures of 17 tropical cyclones and estimations from the National Institute for Land and Infrastructure Management (NILIM), Port and Airport Research Institute (PARI), Japan Weather Association (JWA), Hsu and Yan (1998) models, and Vickery and Wadhera (2008).

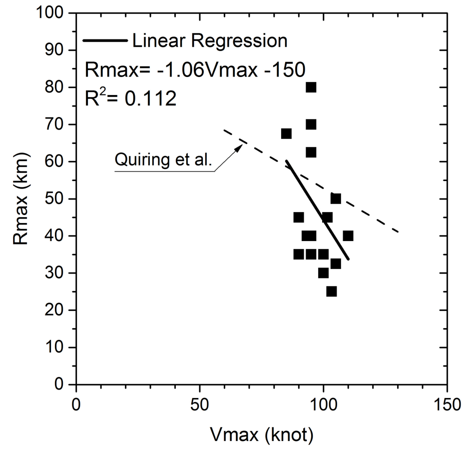


Figure 4. Estimated wind radii (R_{max}) versus maximum wind speeds (V_{max}) for the 17 studied tropical cyclones. The estimation by Quiring et al. (2011) is also presented after a mean wind speed conversion according to Sampson et al. (1995) (i.e., 10 min mean speed = 0.88 × 1 min mean speed).

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_{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_{max}.

3.1 R_{max} estimation based on the central pressure

Figure 3 shows a scatter plot for P_{c} and the estimated R_{max} along with the regression curves from the NILIM, PARI, and JWA models and a linear regression line for the present 17 TCs investigated ($R_{\mathrm{max}} = 0.676\ P_{\mathrm{c}} - 578$, with R_{max} and P_{c} in km and hPa, respectively). The PARI model, in particular, describes the average R_{max} well. The NILIM and JWA models slightly over- or underestimated the radii, although the lines were present within the entire plots. The R_{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° 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_{max} estimation based on the maximum wind speed

The V_{max} is negatively correlated with the R_{max} (Shea and Gray, 1973), suggesting that years with more intense TCs tend to have smaller than average R_{max} (Quiring et al., 2011). Figure 4, derived from the 17 studied typhoons, confirms this trend. However, the correlation between V_{max} and R_{max} is weak, as confirmed by an R^2 of 0.112. In addition, the fact that R_{max} is highly sensitive to slight changes in V_{max} makes it more difficult to determine the optimum R_{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_{max} based on V_{max} is questionable at least for the WNP.

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

The relative inadequacy of P_{c} and V_{max} as predictors of R_{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

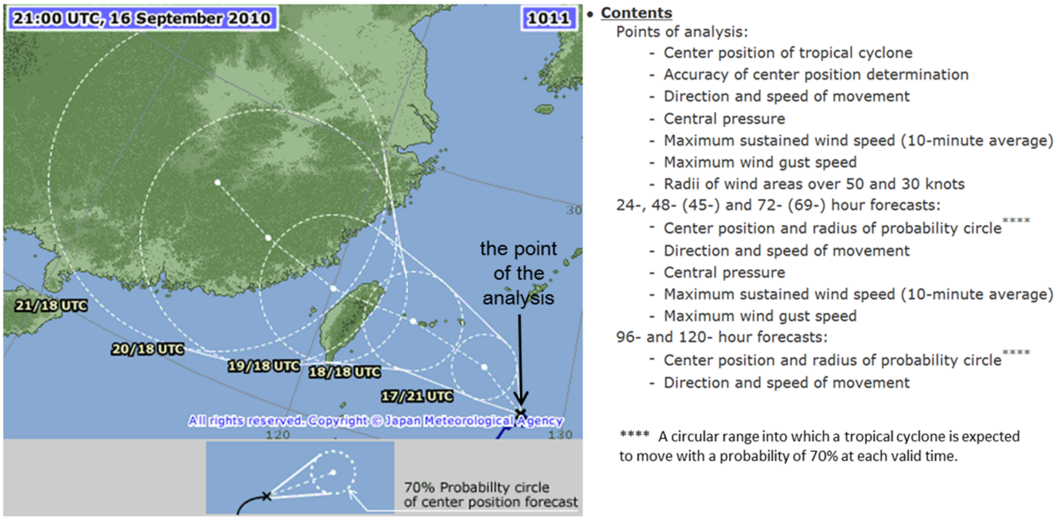


Figure 5. Tropical cyclone information from the Regional Specialized Meteorological Center (RSMC) Tokyo/Japan Meteorological Agency (JMA) (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm).

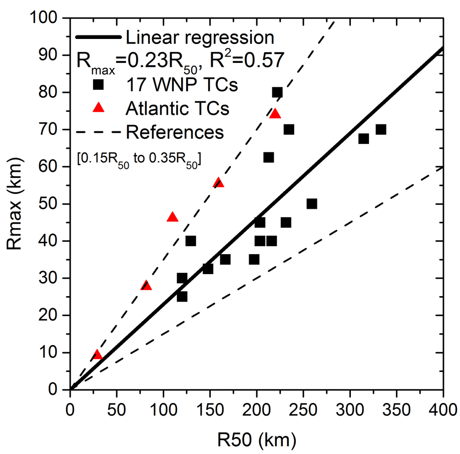


Figure 6. Relationship between the radii of the 50 kt winds around a typhoon (R_{50}) and the maximum wind radius (R_{max}). The two broken lines indicate the range in which 95 % of the plots fall (i.e., 95 % prediction interval). The Atlantic TC plot is derived from Kimball et al. (2004).

(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_{max}, since both R_{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_{max} proportionally increases with the increase in R_{50} (Fig. 6), according to the following average linear relationship:

$$R_{max} = 0.23 R_{50}. \tag{3}$$

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_{max} estimation improves for stronger TCs, since they generally intensify with decreasing R_{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_{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 $R_{max} = 0.15\ R_{50} - 0.35\ R_{50}$.

Figure 6 also indicates the estimated R_{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_{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_{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

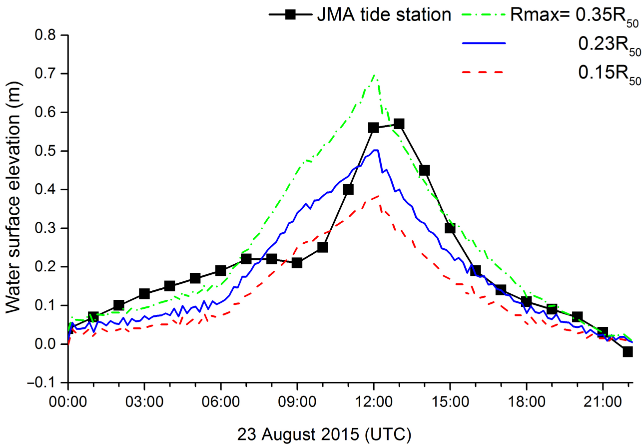


Figure 7. Comparison of observed and simulated storm surges during the passage of Typhoon Goni in 2015. The water level was observed at the tide station of Ishigaki-jima, which is located at 24°20′ N and 124°10′ E.

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_{max}. The observed storm surge lies between those estimated for R_{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_{max} would change the spatial distributions of water-level departures. The size of R_{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_{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

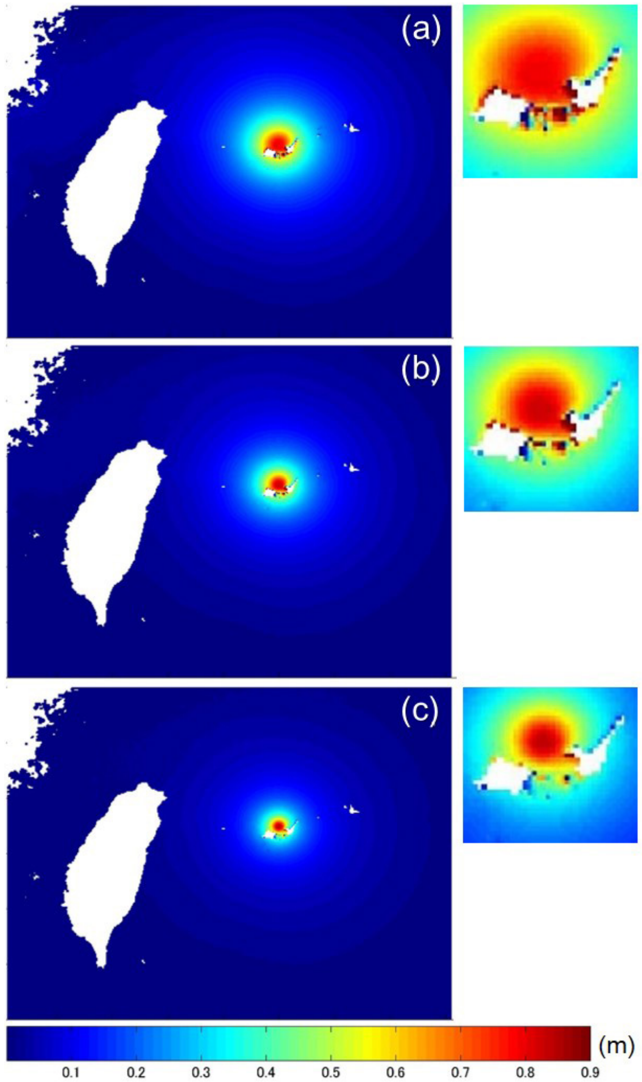


Figure 8. Distribution of storm surge heights at the time of Typhoon Goni passed over Ishigaki-jima, estimated with R_{max} derived from **(a)** 0.35 R_{50}, **(b)** 0.23 R_{50}, and **(c)** 0.15 R_{50}.

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).

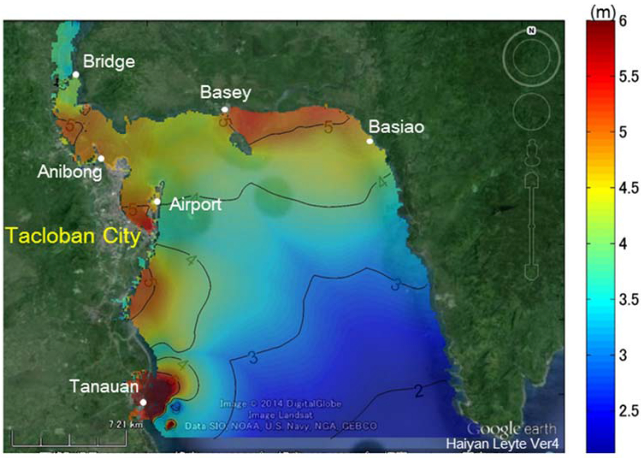


Figure 9. Maximum storm surge heights in San Pedro Bay due to the passage of Typhoon Haiyan (after Takagi et al., 2015a).

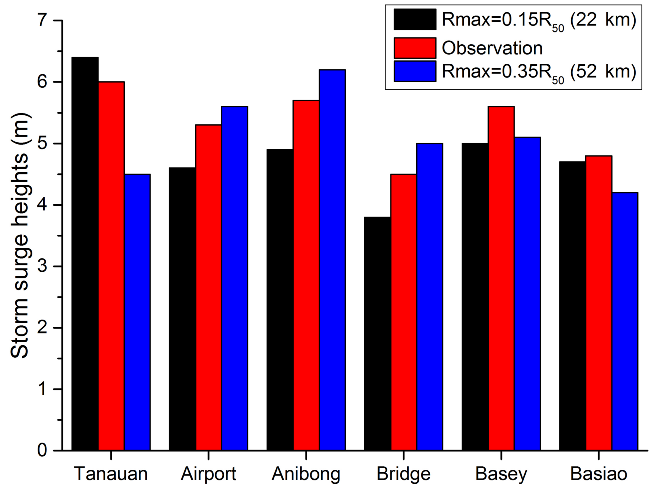


Figure 10. Simulated storm surge heights (black and blue) derived from different maximum wind radii (R_{max}) and observed storm surge heights (red).

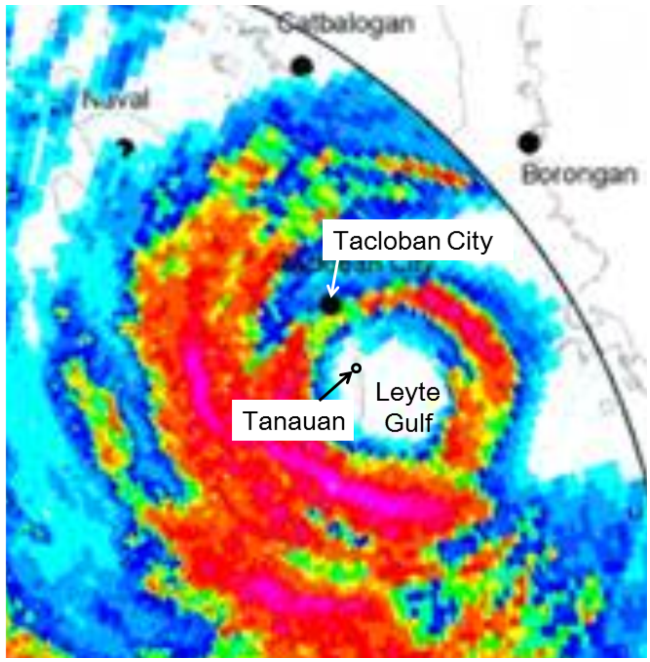


Figure 11. Rainfall intensity detected by the Doppler radar system on Cebu Island when Typhoon Haiyan passed the Leyte Gulf.

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 $R_{max} = 0.15\ R_{50}$ and 0.35 R_{50}, to examine the sensitivity of the results to R_{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_{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_{max}, this is not always true as the surge increased even for smaller R_{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_{max} changes there than at distant locations.

3.5 Applicability and limitations of the new model

The R_{max} shows significant scatter when derived from P_c or V_{max} (Figs. 3 and 4). This resulted in the development of a new approach with smaller estimation errors, where R_{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_{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_{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_{max} changes (Fig. 10). Figure 6 also shows a noticeable discrepancy in the R_{max} estimated by the present method for the WNP and the Atlantic, indicating that our method may over- or underestimate the R_{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_{max} in the former.

Some TC parameters such as center positions, P_{c}, V_{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_{max} values as proposed by Koba et al. (1991). Possible errors in R_{50} are of vital interest when the relationship $R_{\mathrm{max}} = 0.23R_{50}$ 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).

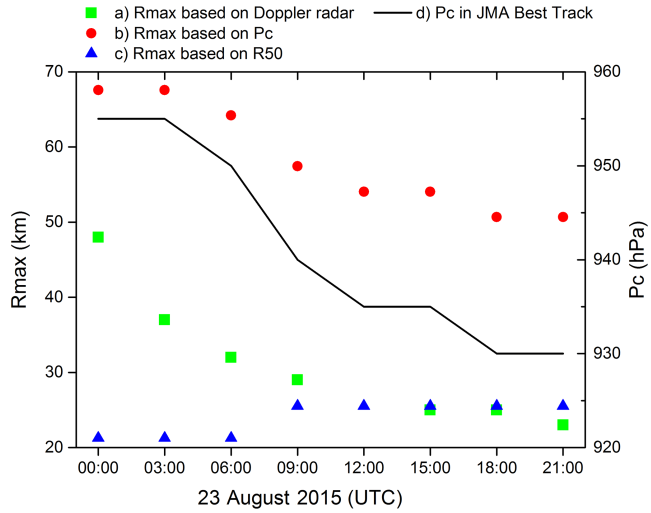


Figure 12. Estimated maximum wind radius and central pressures of the 2015 Typhoon Goni during its transit near Ishigaki-jima, **(a)** R_{max} detected by a Doppler radar operated by JMA, **(b)** R_{max} estimated from the relationship $R_{\mathrm{max}} = 0.676\ P_{\mathrm{c}} - 578$, **(c)** R_{max} from $R_{\mathrm{max}} = 0.23\ R_{50}$, and **(d)** Pc in the JMA best track data.

It should also be noted that various R_{max} have been assumed in studies of Typhoon Haiyan. Takagi et al. (2015a) simulated the storm surge (Fig. 9) by subjectively estimating R_{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_{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_{max} (Shea and Gray, 1973). Mori et al. (2014) estimated the R_{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_{max}, even using the best data available and current technology.

With regard to Typhoon Goni, the progress of R_{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_{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_{max} value for a typhoon with a central pressure that is substantially low, while the method may not provide a good estimation in the case of a less violent typhoon. It is also recognized that the estimation from P_c appears to overestimate R_{max} throughout the time period shown in Fig. 12.

The consideration of these uncertainties in storm surge simulation is also relevant with regard to the uncertainty in the TC information issued by the agencies. An examination of our 17 selected TCs indicates that temporal changes in R_{max} averaged 0.75 % h^{-1} and reached up to 8.3 % h^{-1}. For the RSMC Tokyo, the wind radii estimates are part of the 3 h advisories and warnings issued by the JMA. Therefore, R_{max} may change by up to 24.9 % by the time new information is available. These temporal changes in R_{max} are another source of error that must be considered.

Therefore, the variability of R_{max} should be taken into account in storm surge simulations, regardless of the model used, to minimize estimation errors that may compromise an early evacuation of the affected population.

4 Conclusions

Using observations from a number of Japanese islands and best track data, 17 typhoons with central pressures below 935 hPa that passed near meteorological stations were selected to examine existing methods and a new method is presented to calculate R_{max}. Values for R_{max} produced by the existing methods, based on central pressure or maximum wind speed, show substantial scattering around the regression lines. Alternatively, we propose an R_{max} estimation based on the radius of the 50 kt wind (R_{50}): $R_{max} = 0.23\ R_{50}$. Although this equation is expected to substantially improve the estimation of R_{max}, estimation errors are unavoidable and result in an over- or underestimation of storm surges. In fact, simulations of the storm surges from the 2013 Typhoon Haiyan and the 2015 Typhoon Goni demonstrated that the estimated storm surge heights substantially vary with changes in R_{max}, highlighting a fundamental difficulty in estimating storm surge heights based on only one predetermined radius. Therefore, to minimize the risk of storm surge over- or underestimation, the variability of R_{max} should be taken into account in the simulations, such as $R_{max} = 0.15\ R_{50}$–$0.35\ R_{50}$. The proposed R_{max} estimation method is expected to increase the reliability of storm surge predictions and contribute to disaster risk management of tropical cyclones and storm surges.

Acknowledgements. 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/rsmc-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

Akinson, G. D. and Holliday C. R.: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the Western North Pacific, Mon. Weather Rev., 105, 421–427, 1977.

Bricker, J. D., Takagi, H., Mas, E., Kure, S., Adriano, B., Yi, C., and Roeber, V.: Spatial Variation of Damage due to Storm Surge and Waves during Typhoon Haiyan in the Philippines, J. Jpn. Soc. Civil Eng., 70, 231–235, 2014.

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.

Dvorak, V. F.: Tropical cyclone intensity analysis using satellite data, NOAA Tech. Rep. 11, 45 pp., 1984.

Elsner, J. B. and Jagger, T. H.: Hurricane Climatology: a modern statistical guide using R, Oxford University Press, New York, 373 pp., 2013.

Esteban, M., Takagi, H., and Shibayama, T.: Handbook of Coastal Disaster Mitigation for Engineers and Planners, 1st Edition, Elsevier, ISBN: 9780128010600, 2015.

Esteban, M., Valenzuela, V. P., Matsumaru, R., Mikami, T., Shibayama, T., Takagi, H., Nguyen, D. T., and de Leon, M.: Storm surge awareness in the Philippines prior to typhoon Haiyan: a comparative analysis with tsunami awareness in recent times, Coast. Eng. J., 2016.

Fujii, T.: Statistical analysis of the characteristics of severe typhoon hitting the Japanese main islands, Mon. Weather Rev., 126, 1901–1907, 1998.

Fujii, T.: On a pressure distribution of typhoons having made landfall on the Japanese main islands in 2004, J. Nat. Disaster Sc., 25, 317–328, 2006.

Jagger, T. H., Elsner, J. B., and Saunders, M. A.: Forecasting U.S. insured hurricane losses, in: Climate Extremes and Society, edited by: Murnane R. J., Madigan D., Diaz H. F., Cambridge University Press, Cambridge, UK, chapt. 10, 2007.

JMA (Japan Meteorological Agency): Outline of the Storm Surge Prediction Model at the Japan Meteorological Agency, Technical Review No. 11, available at: http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/techrev/abs11.htm#11-3 (last access: 15 February 2015), 2009.

JMA (Japan Meteorological Agency): Typhoon intensity estimation, Meteorological Research Institute, available at: http://www.mri-jma.go.jp/Dep/ty/ty2/tyest/tyest2.html (last access: 24 December 2015), 2014.

JMA (Japan Meteorological Agency): JMA Press Release on 29 September 2015, available at: http://www.mri-jma.go.jp/Topics/H27/270929/Press20150929.pdf (last access: 24 December 2015), 2015.

Jelesnianski, C. P.: SPLASH (special program to list amplitudes of surges from hurricanes) I. Landfall storms. NOAA technical memorandum NWS TDL-46. National Weather Service Systems Development Office, Silver Spring, Maryland, 56 pp., 1972.

Jelesnianski, C. P. and Taylor, A. D.: A preliminary view of storm surges before and after storm modifications, NOAA Technical Memorandum ERL WMPO-3, 33 pp., 1973.

Joint Typhoon Warning Center: Northern Indian Ocean Best Track Data, avalable at: http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/ (last access: 8 February 2015), 2012.

Jordan, C. L.: Marked changes in the characteristics of the eye of intense typhoons between the deepening and filling stages, J. Meteorol., 18, 779–789, 1961.

Heming, J. and Goerss, J.: Track and structure forecasts of tropical cyclones, in: Global Perspectives on Tropical Cyclones, edited by: Johnny, C. L. C. and Jeffrey, D. K., World Scientific, 287–323, 2010.

Holland, G.: An analytic model of the wind and pressure profiles in hurricanes, Mon. Weather Rev., 108, 1212–1218, 1980.

Hsu, S. A. and Yan, Z.: A Note on the Radius of Maximum Wind for Hurricanes, J. Coast. Res., 14, 667–668, doi:10.2307/4298820, 1998.

Irish, J. L., Resio, D. T., and Ratcliff, J. J.: The Influence of Storm Size on Hurricane Surge. J. Phys. Oceanogr., 38, 2003–2013, doi:10.1175/2008JPO3727.1, 2008.

Irish, J. L., Resio, D. T., and Ratcliff, J. J.: The influence of storm size on hurricane surge, J. Phys. Oceanogr., 38, 2003–2013, doi:10.1175/2008JPO3727.1, 2008.

Kato, F.: Study on risk assessment of storm surge flood, Technical note of National Institute for Land and Infrastructure Management of Japan, No. 275, 2005.

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.

Kepert, J. D.: Tropical Cyclone Structure and Dynamics, in: Global Perspectives on Tropical Cyclones, edited by: Johnny, C. L. C. and Jeffrey, D. K., World Scientific, 3–54, 2010.

Kim, K. O.: Typhoon storm surge simulation for Typhoon Haiyan, Journal of International Development and Cooperation, Hiroshima University, 21, 17–25, 2015.

Kimball, S. K. and Mulekar, M.: A 15-Year Climatology of North Atlantic Tropical Cyclones. Part I: Size Parameters, J. Climate, 17, 3555–3575, 2004.

Kitano, M., Arimitsu, T., and Takayama, T.: Generation of Swell and Its simplified Prediction Method for Coastal Disaster Prevention, P. Coast. Eng., 49, 1431–1435, 2002.

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

Koba, H., Hagiwara, T., Osano, S., and Akashi, S.: Relationships between CI Number and Minimum Sea Level Pressure/Maximum Wind Speed of Tropical Cyclones, Geophys. Mag., 44, 15–25, 1991.

Kossin, J. P., Knaff, J. A., Berger, H. I., Herndon,D. C., Cram, T. A., Velden, C. S., Murnane, R. J., and Hawkins, J. D.: Estimating hurricane wind structure in the absence of aircraft reconnaissance, Weather Forecast., 22, 89–101, doi:10.1175/WAF985.1, 2007.

Loder, N. M., Cialone, M. A., Irish, J. L., and Wamsley, T. V.: Idealized marsh simulations: Sensitivity of storm surge elevation to seabed elevation, Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-I-78. Vicksburg, MS, U.S. Army Engineer Research and Development Center, 2009.

Mikami, T., Shibayama, T., Takagi, H., Matsumaru, R., Esteban, M. Nguyen, D. T., de Leon, M., Valenzuela, V. P., Oyama, T., Nakamura, R., Kumagai, K., and Li, S.: Storm Surge Heights and Damage Caused by the 2013 Typhoon Haiyan along the Leyte Gulf Coast, Coast. Eng. J., doi:10.1142/S0578563416400052, 2016.

Muramatsu, T.: The Study on the Changes of the Three-dimensional Structure and the Movement Speed of the Typhoon through its Life Time, Tech. Rep., Meteorol. Res. Inst. Japan, no. 14. 117 pp., 1985.

Myers, V. A.: Characteristics of United States hurricanes pertinent to levee design for lake Okeechobee, Florida, Hydrometeorological Report, US Weather Bureau, No. 32, 106 pp., 1954.

Muramatsu, T.: The Study on the Changes of the Three-dimensional Structure and the Movement Speed of the Typhoon through its Life Time, Tech. Rep., Meteorol. Res. Inst. Japan, Number 14, 117 pp., 1985.

Nakajo, S., Mori, N., Kim, S. Y., Yasauda, T., Yamada, F., and Mase, H.: Basic study on estimation method of return period and variation range of severe storm surge event, Proceedings of 34th Conference on Coastal Engineering, 11 pp., 2014.

Nakamura, R., Oyama, T., Shibayama, T., Esteban, M., and Takagi, H.: Evaluation of storm surge caused by Typhoon Yolanda (2013) and using weather-storm surge-wave-tide model. 8th International Conference on Asian and Pacific Coasts (APAC2015), Madras, India, doi:10.1016/j.proeng.2015.08.306, 2015.

Persing, J. and Montgomery, M. T.: Is Environmental CAPE Important in the Determination of Maximum Possible Hurricane Intensity?, J. Atmos. Sci., 62, 542–550, 2005.

Quiring, S., Schumacher, A., Labosier, C., and Zhu, L.: Variations in mean annual tropical cyclone size in the Atlantic, J. Geophys. Res., 116, D09114, doi:10.1029/2010JD015011, 2011.

Roeber, V. and Bricker, J. D.: Destructive tsunami-like wave generated by surf beat over a coral reef during Typhoon Haiyan, Nature Commun., 6, 7854, doi:10.1038/ncomms8854, 2015.

RSMC Tokyo: Activities of RSMC Tokyo and its Contribution to SWFDP in Southeast Asia, DPFS/RAII/SeA-SWFDP-RSMT/Doc. 5.2.2, World Meteorological Organization, 13 pp., 2015.

Sampson, C. R., Jeffries, L. R., Chu, J. H., and Neumann, C. J.: Tropical Cyclone Forecasters Reference Guide 6. Tropical Cyclone Intensity, Naval Research Laboratory, NRL/PU/7541-95-0012, 1995.

Shea, D. J. and Gray, W. M.: The hurricane's inner core region. I. Symmetric and asymmetric structure, J. Atmos Sci., 30, 1544–1564, 1973.

Takagi, H., Kashihara, H., Esteban, M., and Shibayama, T.: Assessment of future stability of breakwaters under climate change, Coast. Eng. J., World Scientific Ltd., 53, 21–39, doi:10.1142/S0578563411002264, 2011.

Takagi, H., Nguyen, D. T., Esteban, M., Tam, T. T., Knaepen, H. L., and Mikami, T.: Vulnerability of coastal areas in Southern Vietnam against tropical cyclones and storm surges , The 4th International Conference on Estuaries and Coasts (ICEC2012), 8 pp., 2012.

Takagi, H., Esteban, M., Shibayama, T., Mikami, T., Matsumaru, R., Nguyen, D. T., Oyama, T., and Nakamura, R.: Track Analysis, Simulation and Field Survey of the 2013 Typhoon Haiyan Storm Surge, J. Flood Risk Manage., in press, doi:10.1111/jfr3.12136, 2015a.

Takagi, H. and Esteban, M.: Statistics of Tropical Cyclone Landfalls in The Philippines, Unusual Characteristics of 2013 Typhoon Haiyan, Nat. Hazards, 80, 211–222, doi:10.1007/s11069-015-1965-6, 2015b.

Takagi, H., Li, S., de Leon, M., Esteban, M., Mikami, T., Matsumaru, R., Shibayama, T., and Nakamura, R.: Storm surge and evacuation in urban areas during the peak of a storm, Coast. Eng., 108, 1–9, doi:10.1016/j.coastaleng.2015.11.002, 2016.

Vickery, P. and Wadhera, 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. Climatol., 47, 2497–2517, 2008.