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On the importance of typhoon size in storm surge forecasting

Md. Rezuanul Islam[1*] and Hiroshi Takagi[2]

1* - Correspondence to: Md. Rezuanul Islam. School of Environment and Society, Tokyo Institute of Technology (2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan); email address: fahiemislam@gmail.com

2 – School of Environment and Society, Tokyo Institute of Technology (2-12-1 Ookayama, Meguro ku, Tokyo 152-8550, Japan

Abstract

Over the past several decades, operational forecasts of typhoon tracks have improved steadily. However, storm surge forecast skills have experienced rather modest improvements as it has been assumed to be primarily a function of maximum typhoon wind speed. In this study, numerical sensitivity experiments have been conducted for the semi-enclosed Tokyo Bay to investigate the existence of any connection between typhoon size and peak storm surge height. The radius of the maximum wind (R_{max}) derived based on the 50-kt wind radius (R_{50}) is used to define the size of a typhoon. The results show that peak storm surge height tends to increase as the size of typhoon becomes larger, which may also be supported by historical observations. Storm size plays a significant role in surge generation, particularly for very large typhoons making landfall in the upper bay. Analyses show that for a given hypothetical typhoon, the water level in the inner bay is increased by 1 m, changing R_{max} from 13 km to 89 km. The findings of this study will be beneficial for the storm surge modeling community as it gives insight into the role of typhoon size, which is essential to forecast peak surge height precisely.

Keywords

Storm surge, Tropical cyclone size, Typhoon Lan, Coastal flooding, Tokyo Bay

1. Introduction

The global occurrence of destructive typhoons (TY) over the last several years has urged the development of a more reliable system for real-time prediction of typhoon-induced storm surges. Major typhoons, which caused more than 1000 fatalities, such as the 2005 Hurricane Katrina, the 2007 cyclone Sidr, the 2008 cyclone Nargis, and the 2013 typhoon Haiyan, all occurred in the past 15 years and many of these causalities were the direct result of the coastal surge [1]. However, this is the fifth decade in which the surface wind speed-based TY scale (i.e., Saffir-Simpson hurricane scale (SSHS)) has been used by meteorological scientists and emergency planners as a convenient tool for forecasting storm surge as well as wind intensity. Although there are many advantages to using wind speed-based scales through simple categorization of TY, the reliance on this scale as an indicator of potential storm surge has also led to significant misconceptions within the public and scientific communities. The primary disadvantage of the wind speed-based scale for TY surge warning is its inability to account for some of the important factors such as TY size, forward speed, and the track that directly influence storm surge generation [2].

Correlating maximum surge with TY meteorological conditions in the 1950s through the 1970s, previous studies suggested that the size of hurricane is weakly correlated with peak surge and SSHS may be a reasonable surge indicator [3, 4, 5, 6]. Consequently, most storm surge studies, for both forecasting and coastal protection design, have relied heavily on either central pressure deficit or the related maximum wind speed (i.e. SSHS) as the determining factors for surge response [7]. Prior to recognizing the limitations of the SSHS, Dolan and Davis proposed a new hurricane intensity scale in the early 1990s [8]. Nevertheless, no conclusion could be drawn in regard to the influence of hurricane size on surge for a given storm intensity. After the 2005 Hurricane Katrina caused catastrophic storm surge at the Gulf Coast of the United States, Irish et al. claimed that typhoon size plays a key role in storm surge generation, particularly over mildly sloping bathymetry [9]. Later, using long-term observation data for Gulf Coast, Needham and Keim revealed that hurricane size and storm surge are statistically correlated [10]. In this manner, few recent studies have advanced storm surge climatology particularly in the Gulf Coast of the United States. However, a thorough literature review on this topic reveals that no studies have been conducted on semi-enclosed bays particularly. Despite the importance of surface wind forcing, several recent studies have attempted to quantify the influence of hurricane track, forward speed, and landfall location to determine storm surge behavior [11, 12] in semi-enclosed bays. However, none of these studies have considered the relationship between hurricane size and storm surge.

This study aimed to investigate the general influence of typhoon size in generating surge, considering Tokyo Bay as a study area. Tokyo Bay was chosen for two main reasons. As confirmed from Figure 1, the bay has intricate coastlines that can either defend the megacity composed of Tokyo, Kanagawa and Chiba Prefecture or render them particularly vulnerable because it may trap and amplify storm surges [13]. The other reason is that the frequency of typhoon landfall is not remarkably high compared to the western south part of Japan. Hence, the storm surge risk for Tokyo Bay has not been sufficiently understood. Considering the growing concern for unprecedented storm surge in the present-day, Tokyo Bay is a coastal system well suited for conducting the sensitivity of storm surge to typhoon size.

2. Methodology

The authors performed numerical simulations by employing the parametric typhoon model developed by Takagi et al. [14, 15, 16, 17], coupled with the fluid dynamics model Delft3D-FLOW [18]. The accuracy of the model has been validated for recent typhoons such as Haiyan in 2013, Goni in 2015, and Hato in 2017 all of which occurred in the North-West Pacific basin [14, 15, 16, 17]. The typhoon model calculates both the pressure and wind fields using parameters obtained from the Japan Meteorological Agency (JMA) best track dataset, which includes the central position of the typhoon, pressures, and 50-knot (26 m/s) wind radius (R_{50}) at every recording period. Delft3D-FLOW was then used to simulate the movement of a storm surge from the deep sea to shallow water.

In this study, two different domains (Figure 1) were used. First, the simulation was performed for a wide area (grid size: 250 m) encompassing parts of Tokyo, Kanagawa, and Chiba prefecture in order to assess potentially affected areas. Then, a more detailed simulation was performed for inner bay locations (grid size 25 m) where the mean bathymetry is shallower than 5 m. Using this grid configuration, numerical simulations were performed for four different bottom slopes, varying from

1:2050 to 1:117. The bathymetry data (50 m resolution) over the target area and astronomical tide data were collected from the Japan Coast Guard and the TPXO7.1 Global Tide Model [19], respectively. The numerical settings used in this study are shown in Table 1.

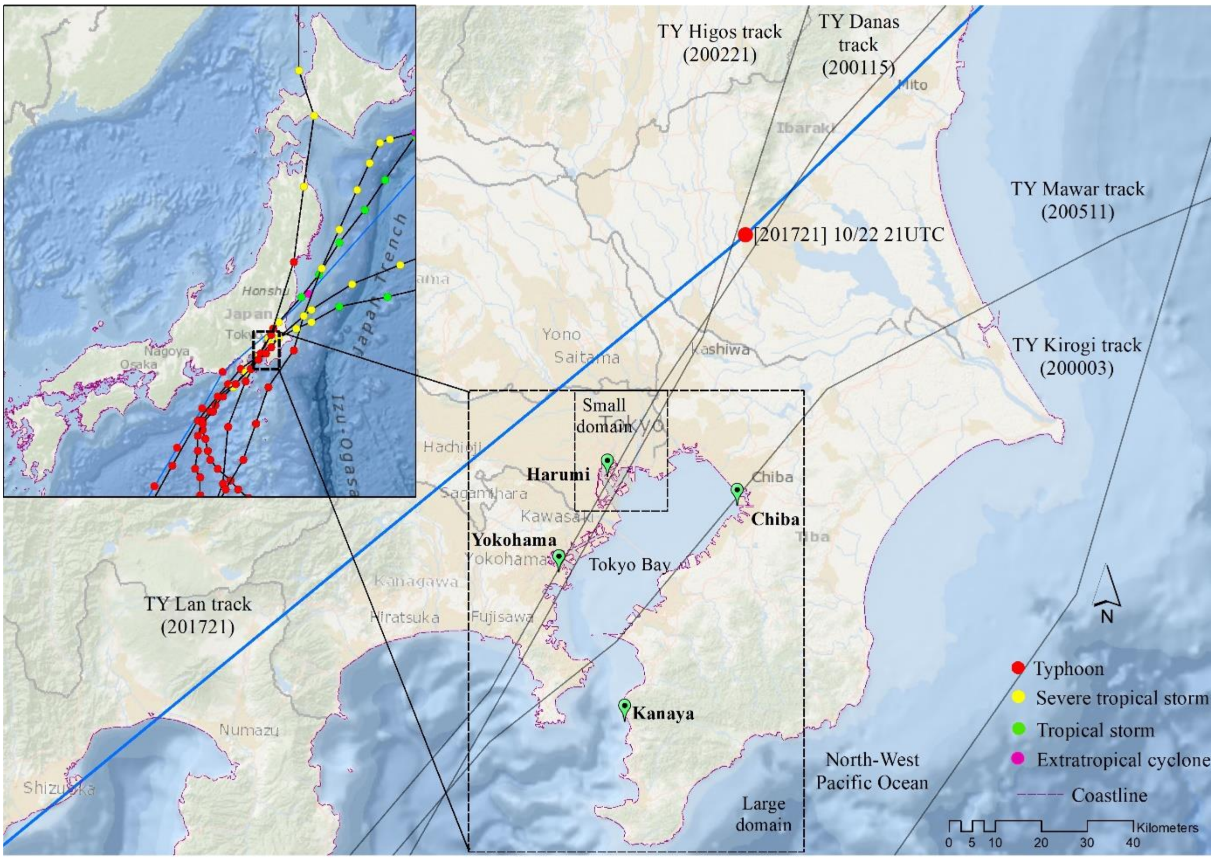

Figure 1: Track of Typhoon Lan in 2017 as it approaches Tokyo Bay [20]; Green marks indicate measurement stations used in this study

Table 1: Numerical model settings

Typhoon path	JMA typhoon best track https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html
Typhoon model	Pressure: empirical estimation by Myers formula; wind: gradient winds considering super-gradient wind effect
Fluid dynamics model	Delft3D flow ver. 6.02
Domain	Spherical coordinate system, large domain: 250 m; Small domain: 25 m
Bathymetry	50 m grid spacing (Source: Japan Coast Guard)

In order to assess the validity of the storm surge model, simulated results for the 2017 Typhoon Lan were compared with observations. A total of 4 tide observation stations was selected to determine the storm surge response of the bay. These stations are located at the upper bay (i.e., Harumi, Chiba), the middle bay (i.e., Yokohama), and the lower bay (i.e., Kanaya) (Figure 1).

A series of numerical sensitivity experiments was conducted considering the Typhoon Lan as a reference typhoon. On September 22, 2017, at 1800 UTC, Typhoon Lan made landfall (Figure 1) about 125 km southwest of Tokyo Bay with a minimum central pressure of 950 hPa and maximum sustained wind speed of 40 m/s. One of Lan's most unusual characteristics is that the overall size (R_{50} = 389 km at landfall) of the typhoon system was the largest in recorded history [21] and generated the highest storm tide in Yokohama and other coastal areas (e.g. Mera) of Tokyo Bay in recent decades. The average R_{50} for typhoons made landfall in Tokyo Bay is 187 km [20]. Therefore, considering Lan was a very large typhoon, additional four cases were analyzed to investigate the sensitivity of the storm surge by altering the original size.

Maximum wind radius (R_{max}) is a spatial parameter that directly represents typhoon size. However, R_{max} is not recorded in the JMA best track. Hence, R_{50} data were converted into a mean value of R_{max} using the simplified equation, $R_{max} = 0.23 \times R_{50}$ [14]. Five different radii of R_{max} (during landfall) ranging from 13 to 89 km were selected by referring to previous major typhoons in Tokyo Bay (Figure 1): R_{max}: Danas (2001) =13 km; Mawar (2005) = 26 km; Higos (2002) = 43 km; Kirogi (2000) = 55 km; Lan (2017) = 89 km). A plausible maximum rise of sea water level respective to each R_{max} was calculated, while other parameters such as typhoon track, forward speed and intensity remained same as the Typhoon Lan had. In this study, the impacts of waves on resultant water levels were neglected to simplify the analyses. The justification for this is twofold. First, this study is not aimed at improving the precise estimation of storm surge, but rather to segregate the effect of storm size on surge levels. Second, the contribution of the wave set up particularly at inner bays is negligible. Thus, the effect would not change the overall results of this study.

3. Results and discussion

3.1 Model validation

Figures 2 (a) to (c) represent the comparison of the simulated and measured storm tides at three tide stations (Harumi, Chiba, and Yokohama) [22], all of which are located within the computational domain (Figure 1). The model validation could not be carried out for Kanaya because observed storm tide data during Typhoon Lan is not available for this site. The coefficient of determination R^2 and the root mean square on the average of the three stations are 0.90 and 0.21 m, respectively. Overall, the time series of the simulated water levels agree well with the recorded tides. However, the predictions had slightly underestimated peak water levels at the Harumi and Yokohama stations.

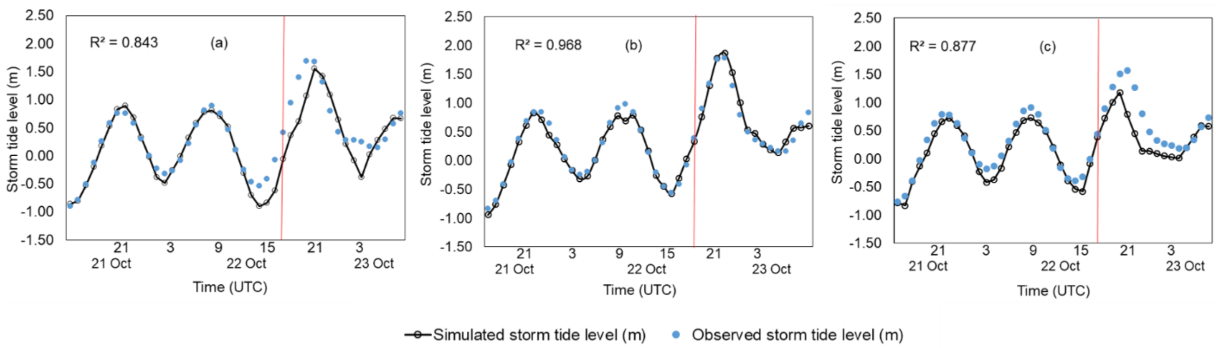

Figure 2: Comparison of observed and simulated storm tides at Harumi (a), Chiba (b) and Yokohama (c). The red colored line indicates the time of landfall.

3.2 Sensitivity analysis

Figure 3 (a) illustrates the obtained relationship between storm size (R_{max}) and surge response in Tokyo Bay. Here, the influence of typhoon intensity was separated by dividing peak surge by the central pressure deficit Δp from mean sea level pressure (i.e. 1013 hPa). The rough estimation of Δp is proportional to the square of the maximum wind speed, corresponding to the Saffir-Simpson scale [23]. This figure reveals that storm surge height tends to increase towards the inner Tokyo Bay as the typhoon size (R_{max}) increases. In addition, with the increment of storm size, the linear trend becomes steeper as the shelf slope becomes smaller, indicating the significance of typhoon size over flat seabed areas. Figure 3 (b) demonstrates that the historically observed data support the numerical findings

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presented in Figure 3 (a). Data for Chiba, Yokohama, and Kanaya are not presented in Figure 3 (b) because the database of past storm surge for mean sea level at these sites is not available. Furthermore, the role of typhoon size near open coast areas (i.e., Kanaya) could not be explained properly because the wave-induced set up was neglected in the numerical model. The size of a storm affects both the fetch and duration of the generating waves. Therefore, wave heights tend to increase with increasing storm size, which would lead to higher wave set up and coastal surges along open coasts [9]. Nevertheless, the findings presented in this study are consistent with the results of a storm surge study by Irish et al. [9], in which they also demonstrated that increases in storm size increase storm surge and that this relationship becomes more significant as shelf slope becomes milder.

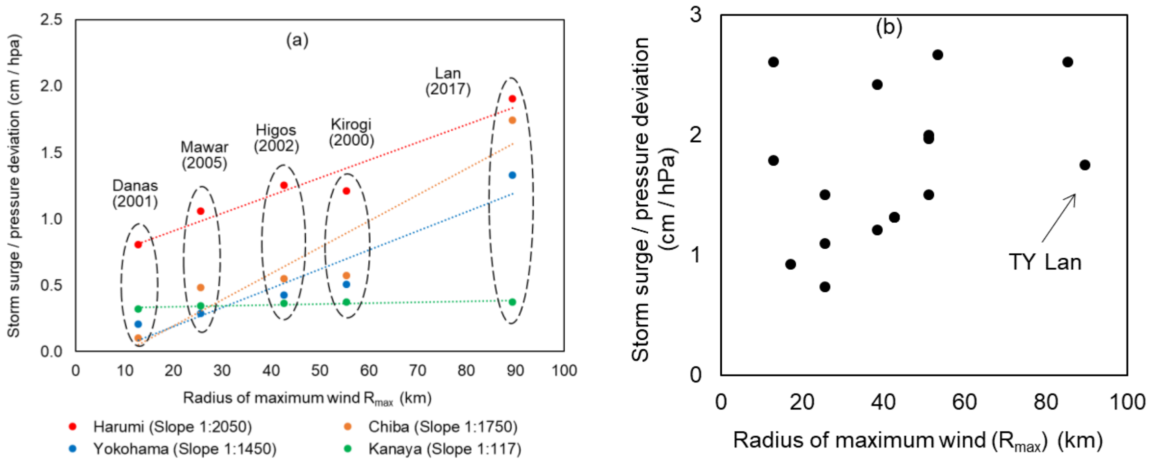

Figure 3: (a) Simulated peak storm surge normalized by central pressure deficit vs typhoon size (R_{max}) at landfall; (b) Observed peak storm surge normalized by central pressure deficit vs typhoon size (R_{max}) at typhoon landfall for Harumi observation station during 1979–2018.

The results of this study suggest that if typhoon parameters including intensity, track and forward speed remain constant, sea water level in a semi-enclosed bay varies with typhoon size. As an example, the simulated wind speed and water surface elevation from mean sea level (before and after 6 h of landfall) associated with each typhoon size for Harumi station (innermost part of the bay) are presented in Figure 4. This statistic explains the previous figure as well, particularly for a very large typhoon (i.e., R_{max} = 89 km) compared to an average sized (R_{max} ~ 43 km in Tokyo Bay), corresponding to an increase in wind speed of up to 70%. Therefore, even though it makes landfall, the resultant large swath of strong wind affects a larger area of the sea, bringing more water into motion and elevates approximately 0.7 m of water level over that by a typhoon with R_{max} = 43 km causes. Furthermore, Figure 4 reveals that a larger storm (i.e. R_{max} = 89 km) along with strong wind (≥ 20 m/s) affects a certain location for a longer period—it takes longer time for the whole storm to pass over a certain point because of the size and the time (hour) stretches over more than triple that of an average sized typhoon (R_{max} ~ 43 km). Thus, the time series distribution of strong winds and water levels would also change with the change of typhoon size. This numerical finding is partially explained that why Typhoon Lan raised water level approximately 2 m in upper Tokyo Bay, even though it made landfall

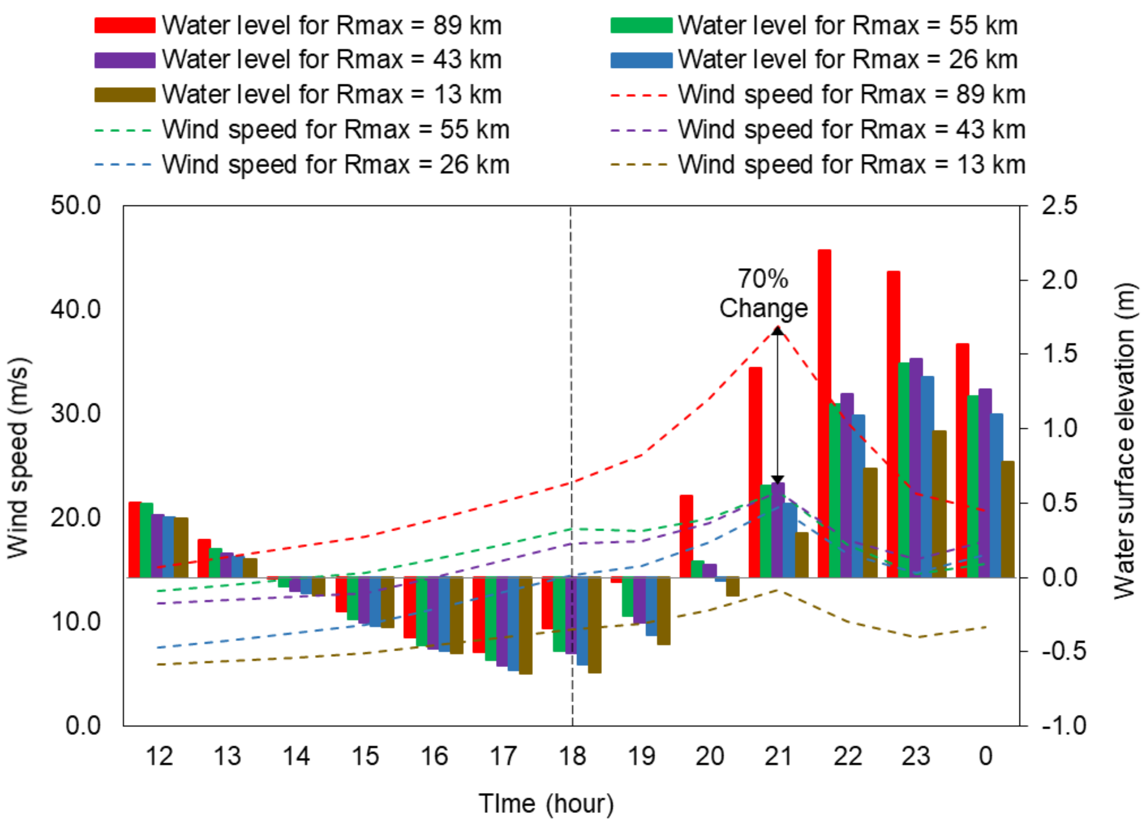

Figure 4: Time series (before and after 6 h of typhoon landfall) simulated wind speed and water surface elevation varying with typhoon size at Harumi observation station. The dash black colored line indicates the time of the landfall.

far away from the Bay. It is also evident from Figure 4 that water level more than 1 m stands considerably larger in duration when the typhoon is very large (i.e. R_{max} = 89 km). The results show that the impact of the storm surge, particularly in the upper bay, appears to be limited when a comparatively smaller typhoon (i.e. $R_{max} \leq 26$ km) passes over Tokyo Bay (Figure 4). However, it should be noted that a smaller but powerful typhoon could have a very strong impact on a particular location as the pressure gradient tends to be steep, resulting in stronger winds near the typhoon eye [24]. Additionally, regardless of the size and intensity of the typhoon, other factor such as forward speed may also drive surge variability [25] which was not discussed as it is beyond the scope of this study.

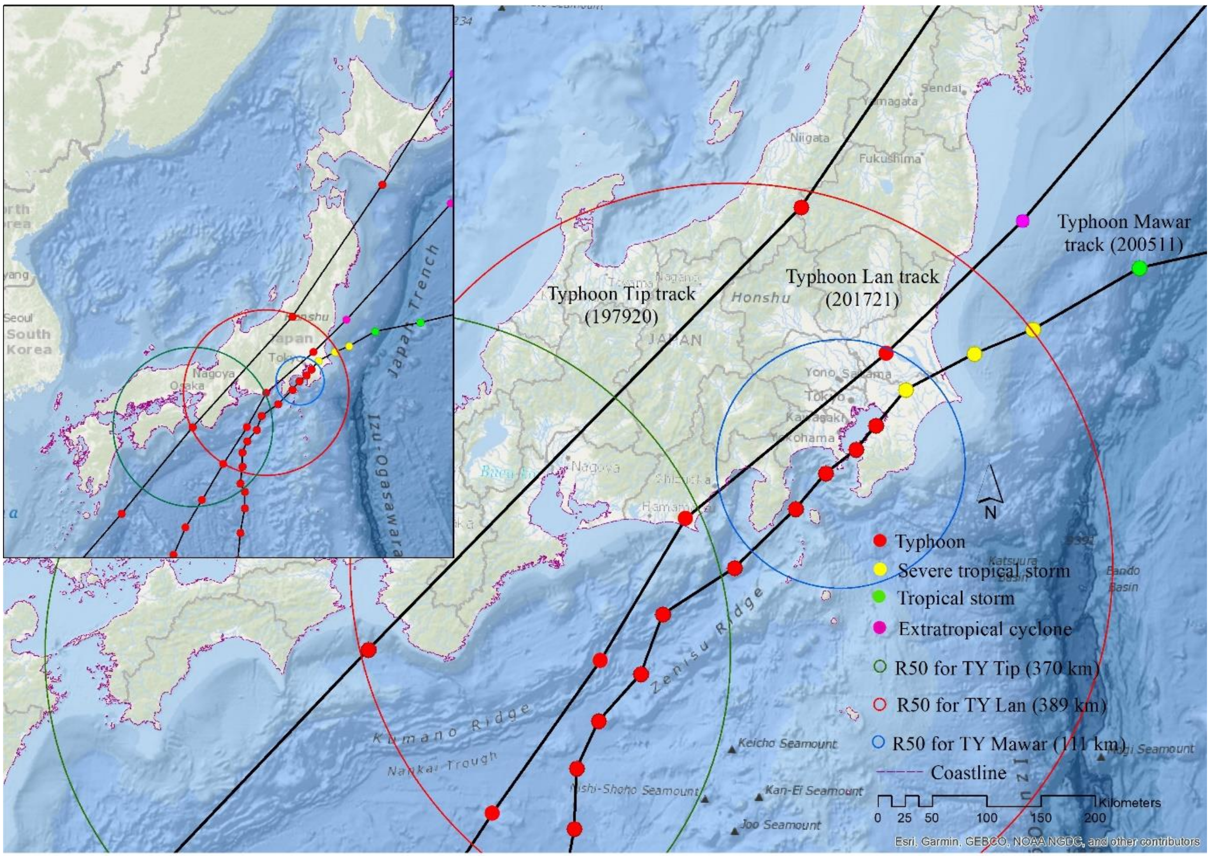

Figure 5: Track and 50-kt (26 m/s) wind radius (R_{50}) of Typhoon Tip in 1979, Typhoon Mawar in 2005 and Typhoon Lan in 2017 [20] as it approaches Japan

Illustrating the importance of typhoon size, the numerical simulations in this study revealed that physical phenomena governing surge generation in a semi-enclosed bay depends not only on wind intensity but also on typhoon size, which could exacerbate storm surge, particularly in the upper bay. The variations in many recorded storm surges could be explained by the differences in storm size. For instance, TY Lan (2017) having a R_{max} 3.5 times larger than TY Mawar (2005) (R_{50} = 111 km; R_{max} = 26 km) (Figure 5) produced a storm surge 4 times (1.2 m) that generated by Typhoon Mawar (0.3 m) at upper Tokyo Bay [20, 22]. Although the maximum sustained wind speed (35 m/s) and track for both typhoons are comparable, TY Mawar made landfall directly over Tokyo Bay (Miura peninsula) [20]. A similar type of incident was observed when 1.25 m of storm surge engulfed the upper Tokyo Bay during TY Tip (1979) (Figure 5) that made landfall approximately 430 km southwest of the bay [20, 22]. It also had a very large wind field with a R_{max} of 85 km (R_{50} = 370 km;) [20]. Such statistics imply that the passage of a typhoon far away from a semi-enclosed bay does not necessarily imply the occurrence of correspondingly small storm surges. Nevertheless, upper bay areas are more vulnerable to intense storm surges when typhoons make landfall with large swaths of strong wind [26]. This is contrary to the conventional perception that the storm surge disaster risk of any given coastal place lessens as the distance from the track increases.

4. Conclusion

This study performed numerical sensitivity analysis on the relationship between typhoon size and maximum storm surge heights by taking Typhoon Lan as a reference case. Despite the lack of systematic study of the potential impact of typhoon size in semi-enclosed bays, the analyses demonstrate that peak storm surge height tends to intensify as the size of typhoons (R_{max}) increases. Storm size plays a key role in generating surge at upper bay, particularly for very large typhoons making landfall in upper bay areas, which is also evidenced from historical records. Thus, the findings suggest the incorporation of the role of storm size into the wind speed-based TY scale (i.e., SSHS), which has historically provided the basis of estimating storm surge height.

The findings presented in this paper would be most advantageous in two main areas. First, meteorologists and oceanographers could re-evaluate the importance of typhoon size for predicting peak surge heights precisely. Secondly, depending on the storm size, disaster management practitioners could determine the proper geographical extent in order to warn citizens of potential coastal surges. Considering that typhoon intensity is not the only factor affecting the generation of storm surges, the findings of this study will significantly contribute to improved typhoon categorization and planning measures to mitigate disasters related to storm surges.

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