

## SENSITIVITY OF TROPICAL CYCLONE TRACK TO ASSESSMENT OF SEVERE STORM SURGE EVENT AT TOKYO BAY

Sota Nakajo<sup>1</sup>, Hideyuki Fujiki<sup>2</sup>, Sooyoul Kim<sup>3</sup> and Nobuhito Mori<sup>4</sup>

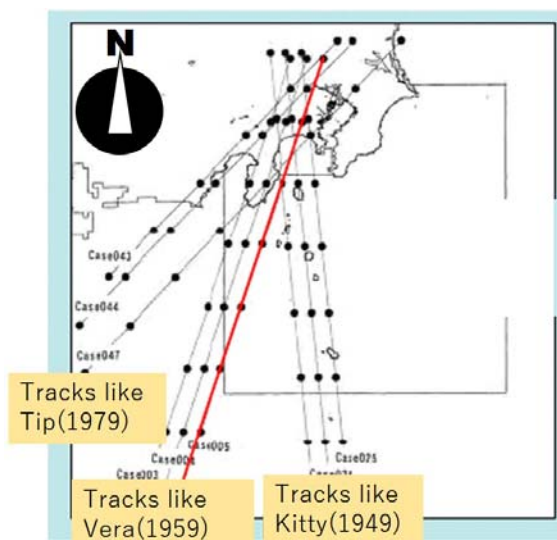
In total 82 tropical cyclones data was used to determine scenarios of translation speed, minimum central pressure and track for risk assessment of storm surge at Tokyo Bay. The numerical simulation of waves and flows was conducted by solving non-linear long wave equations. The maximum surge height shows that the typhoon passing through along northeast directional track is dangerous for Tokyo Bay. This trend confirms the previous risk assessment was reasonable. However, it has been shown that the typhoon passing through along north directional track is also dangerous although the frequency is low. Especially, it is interesting that the typhoon passing through along northwest directional track causes distinctive resurgence and harbor oscillation.

*Keywords: storm surge; Tokyo Bay; harbor oscillation; tropical cyclone*

### INSTRUCTION

Tropical cyclone has brought us many disaster events in the world. For example, in 1959, Isewan typhoon (Vera) attacked Ise Bay in Japan, and very severe storm surge occurred. This hazardous tropical cyclone track data has been used as typical design scenario in Japan. By the way, the capital of Japan, Tokyo, has not experienced a severe storm surge in the last 50 years. Exceptionally, typhoon Kitty (1949) caused 1.4 m anomaly tide at Tokyo. However, in 1917, severe storm surge flood occurred at Tokyo and Chiba prefectures by strong typhoon, and 1,300 persons were killed or lost. The maximum wind speed and minimum pressure of those days were 43 m/s and 952 hPa at Tokyo. Therefore, the risk of storm surge at Tokyo area is not low. Tokyo Bay has a largest metropolitan area in the world behind it, and the mouth is open to the south. We should consider the risk of low frequent hazard if the exposure is significant large. Besides, in the future climate, sea surface temperature would rise around Japan Islands (for example, Mizuta et al., 2017). This future change would cause increase of the frequency of tropical cyclone hazard around Tokyo area.

In the official government storm surge assessment, typhoon track has been assumed to be representative by three types like Fig. 1. However, they are linear and imaginary tracks, and actually the frequency of their tracks are not considered. The damage caused by tropical cyclone is very



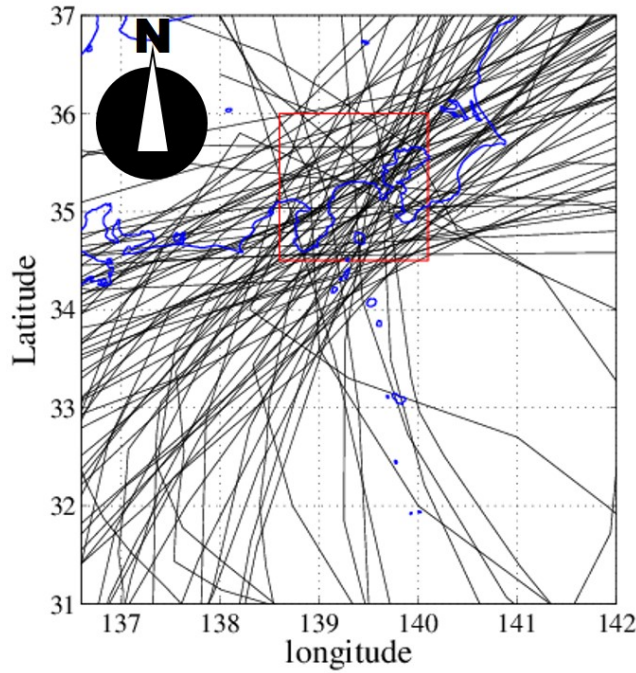
**Figure 1. The scenarios of hazardous typhoon track estimated by government disaster planning. This figure was made from material of disaster assessment report (Ministry of Land, Infrastructure and Transport, 2009)**

<sup>1</sup> Urban engineering, Osaka City University, Sumiyoshi-ku Sugimoto 3-3-138, Osaka, 559-8585, Japan

<sup>2</sup> CTI Engineering Co., Ltd., Chuo-ku Nihonbashi, Hamamachi 3-21-1, Tokyo, 103-8430, Japan

<sup>3</sup> Management of Social systems and Civil Engineering, Tottori University, Koyamacho, Minami 4-101, Tottori, 680-8550, Japan

<sup>4</sup> Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan



**Figure 2. Historical typhoon tracks (82 cases, from 1927 to 2011) passed through an area (red line) including Tokyo Bay**

sensitive to its track. Fig. 2 shows actual tropical cyclone tracks passed around Tokyo Bay during 1927-2011. We selected these corresponding tropical cyclone data from IBTrACS database (Knapp et al., 2010). Certainly, many tracks are similar to three model courses government proposed. However, they are not all. Besides, we should examine the effect of translation speed of tropical cyclone. In the government assessment, the translation speed was assumed to same to that of the typhoon Vera. However, this typhoon did not pass through Tokyo Bay, therefore we should estimate the statistically reasonable value in target area.

In this study, we assessed the potential of storm surge at Tokyo Bay based on actual observed track data and statistics of tropical cyclone properties. By the way, in 2018, typhoon Jongdari passed through unique course. This typhoon passed through southern coastal area of Japan to the westward although the ordinal typhoon around Japan translates to the eastward by the effect of westerlies. These reverse travel tropical cyclones have been also observed in the North Atlantic Ocean (Hurricane Lenny, 1999). These tropical cyclones are not many but we should estimate the potential of storm surge event would be caused by them.

## METHODS

**Storm surge simulation.** The government equations of storm surge simulation in this study were nonlinear shallow water equations.

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} & \frac{\partial M}{\partial t} + \frac{\partial}{\partial x} \left( \frac{M^2}{d} \right) + \frac{\partial}{\partial y} \left( \frac{MN}{d} \right) + gd \frac{\partial \eta}{\partial x} \\ & = fN - \frac{1}{\rho} d \frac{\partial P}{\partial x} + \frac{1}{\rho} (\tau_s - \tau_b) + A_h \left( \frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} \right) \end{aligned} \quad (2)$$

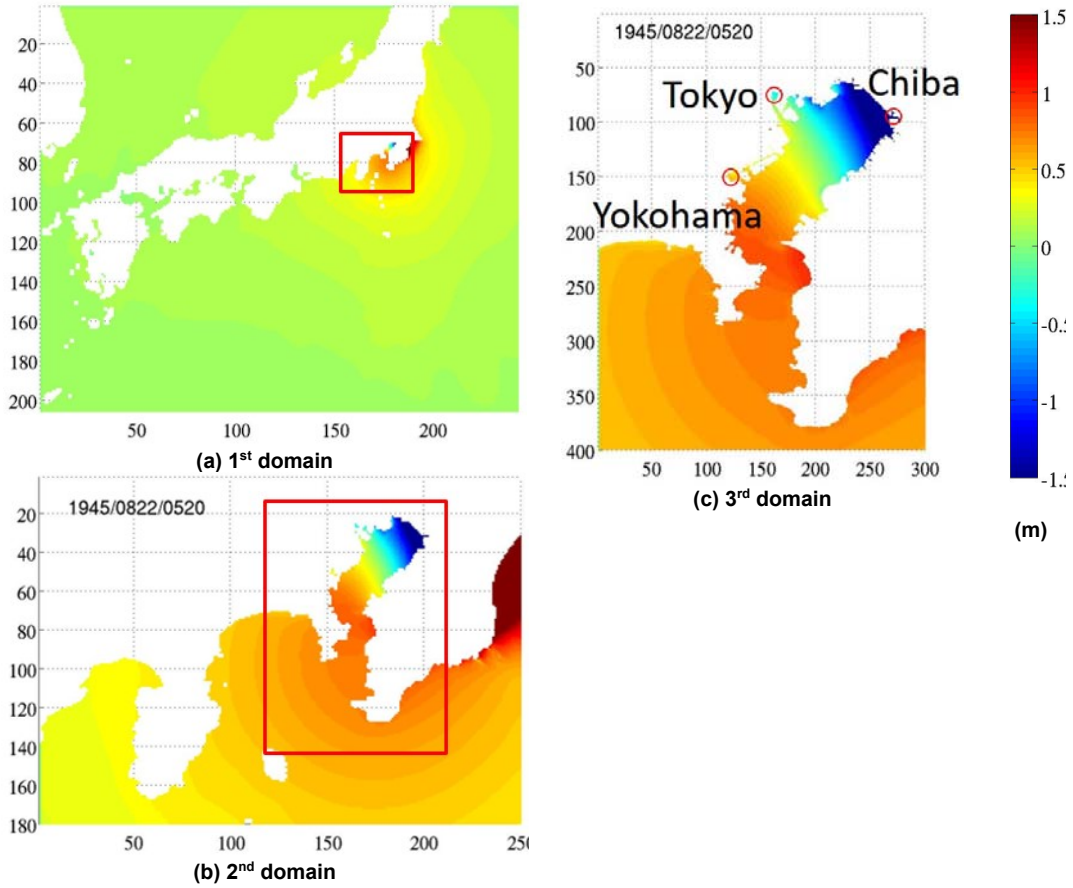


Figure 3. Calculation domains and a snapshot of anomaly of tide

$$\begin{aligned} & \frac{\partial N}{\partial t} + \frac{\partial}{\partial x} \left( \frac{NM}{d} \right) + \frac{\partial}{\partial y} \left( \frac{N^2}{d} \right) + gd \frac{\partial \eta}{\partial y} \\ & = -fM - \frac{1}{\rho} d \frac{\partial P}{\partial y} + \frac{1}{\rho} (\tau_s - \tau_b) + A_h \left( \frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2} \right) \end{aligned} \quad (3)$$

$$\tau_b = \rho g n^2 \frac{Q|Q|}{d^{7/3}} \quad (4)$$

$$\tau_s = \rho_a C_D W_{10} |W_{10}| \quad (5)$$

where,  $M$  and  $N$  are the vertical integrated velocity of  $X$  and  $Y$  direction.  $\eta$  is the water surface elevation,  $d$  is the water depth,  $f$  is the Coriolis parameter,  $P$  is the atmospheric pressure and  $\rho$  is the sea water density and  $A_h$  is the horizontal eddy diffusive coefficient.  $\tau_b$  and  $\tau_s$  are the bottom and surface shear stress respectively.  $Q$  is the vertical integrated velocity vector.  $n$  is the Manning coefficient ( $=0.02$ ).  $W_{10}$  is the wind speed at 10 m height.  $C_D$  is the drag coefficient calculated by empirical equation (Mitsuyasu and Honda, 1982). However, we limited the maximum value of this coefficient when the wind speed becomes larger than 35 m/s in this study.

The external force information for these nonlinear longwave equations, wind and atmospheric pressure field, was made by the empirical typhoon model equations (Fujita, 1952). The detail of tropical cyclone track data is shown in next paragraph. Calculation domains are shown in Fig. 3. We used three different scale grid for acceleration of simulation by using two-way nesting technique. The resolution of domains are 6,000 m, 810 m and 270 m, respectively. In this study, the astronomical tide effect was not considered for convenience. The running up of wave on land was also neglected in this simulation.

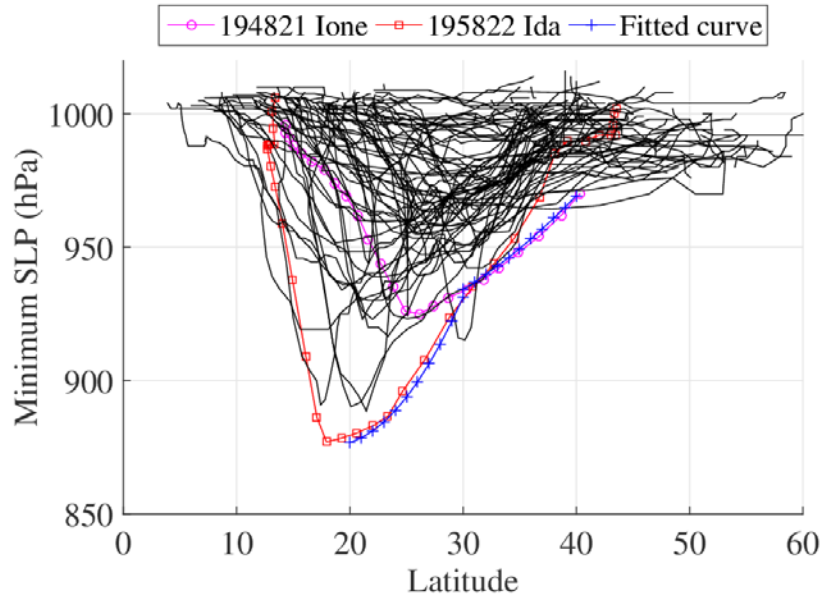


Figure 4. The latitudinal variation of central pressure of historical tropical cyclones

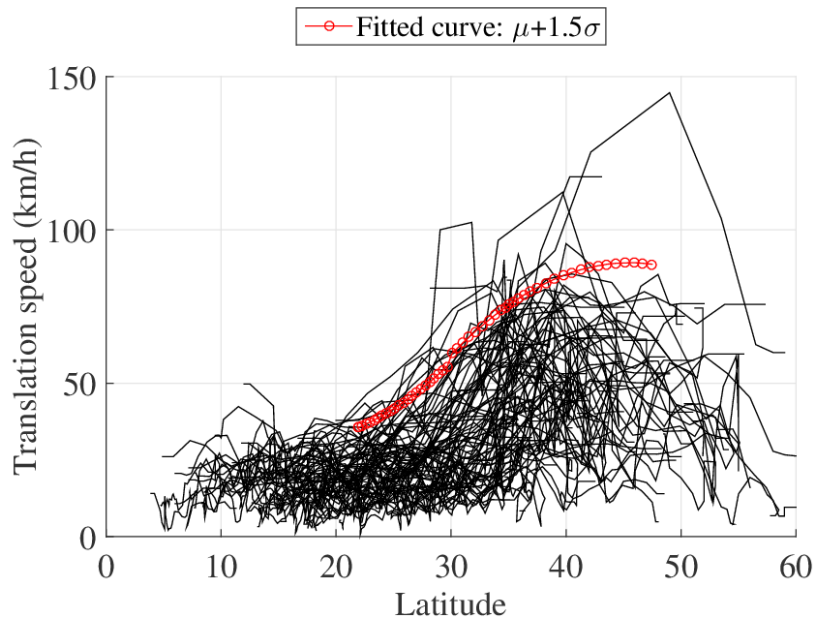


Figure 5. The latitudinal variation of translation speed of historical tropical cyclones

**Tropical cyclone scenario.** In order to estimate possible tropical cyclone scenario at Tokyo Bay, we selected historical tropical cyclone data passed target area (138.6-140.1°E, 34.5-36.0°N) from IBTrACS v03r04 database (Knapp et al., 2010). The period of these data is from 1927 to 2011. As a result, 82 tropical cyclones corresponded to this condition.

Fig. 4 and Fig. 5 show the latitudinal change of these selected tropical cyclone properties, central pressure and translation speed. In Fig. 4, two characteristic strong tropical cyclone data were colorized, typhoon Ione (1948) and Ida (1958). In this study, we assumed the central pressure and translation speed are able to be described by function of latitude. Actually, the central pressure depends on the sea surface pressure and it depends on the latitude. The translation speed also depends on ambient wind, for example westerlies, therefore it depends on the latitude roughly. At every latitude, we estimated the scenario of tropical cyclone properties cause severe storm surge. The fitted curves in Fig. 4 and Fig. 5 are our estimated tropical cyclone scenario. The change of the central pressure corresponds to an envelope curve of historical data. We estimated this curve by quadratic polynomial equation of the latitude. Then the change of translation speed corresponds to the line of  $\mu+1.5\sigma$ . We have no necessity

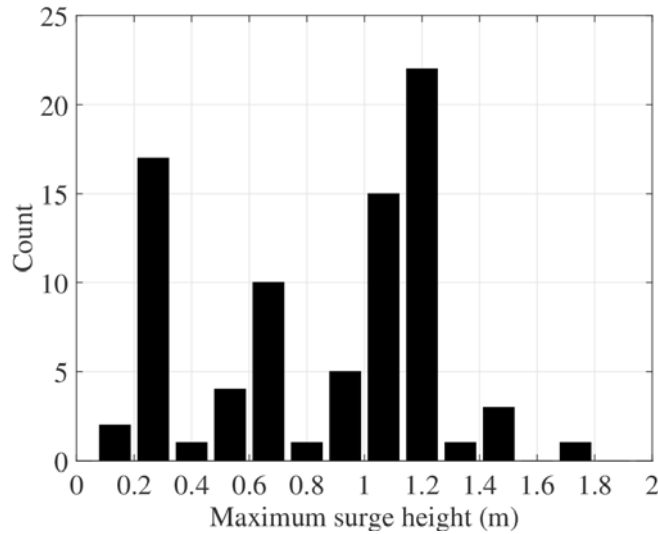


Figure 6. Histogram of maximum surge height at the inner part of Tokyo Bay ( $R_{max} = 40$  km)

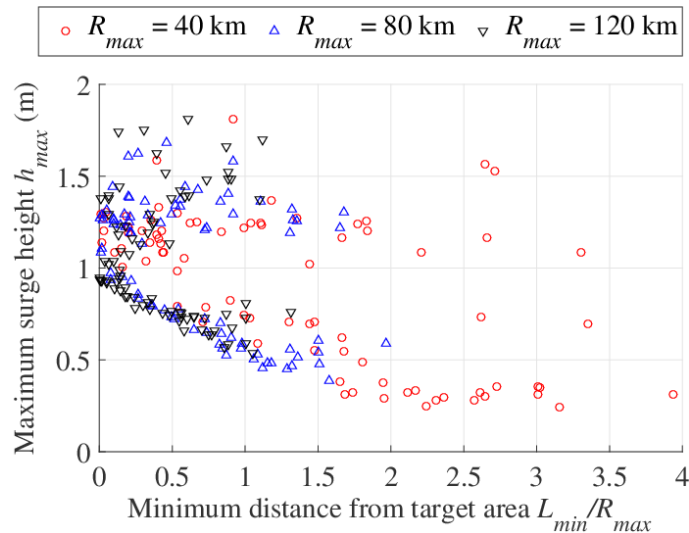


Figure 7. Minimum distance from target area and maximum surge height (Tokyo)

of this decision and this is very subjective. However, there is no doubt that these conditions are significant dangerous scenario for storm surge at Tokyo Bay.

Of course, we can estimate some extreme value of them. However, in this study, we estimated the dangerous scenario of tropical cyclone occurs in moderate frequency. Therefore, the worst-case scenario would be more dangerous than this assumption. By the way, the mean water depth of Tokyo Bay is about 17 m. The theoretical translation speed causes large Proudman resonance is about 45 km/h. The latitude of Tokyo Bay is about 35 degrees. Therefore, the speed around Tokyo Bay is larger than this resonance condition. However, we assumed the resonance effect is not so large in this study. We used historical tracks around Tokyo Bay for storm surge simulation, and these tropical cyclone development process were implemented as a latitudinal function. The maximum wind speed radius of tropical cyclone model was changed in parametric way,  $R_{max} = 40, 80$  and 120 km. Therefore, totally 246 cases of storm surges were simulated in this study.

**RESULTS AND DISCUSSION**

**The characteristic of tropical cyclone track and maximum surge heights.** Fig. 6 shows an example of maximum surge height at Tokyo (Fig. 3(c)) in the case of  $R_{max} = 40$  km. The value was changed from 0.2 m to 1.8 m in this case even if the central pressure and the translation speed are same. The most frequent value is 1.2 m and this is almost equal to historical record in the last 50 years. In order to define dangerous storm surge event, we compared to the result in case we used the track data



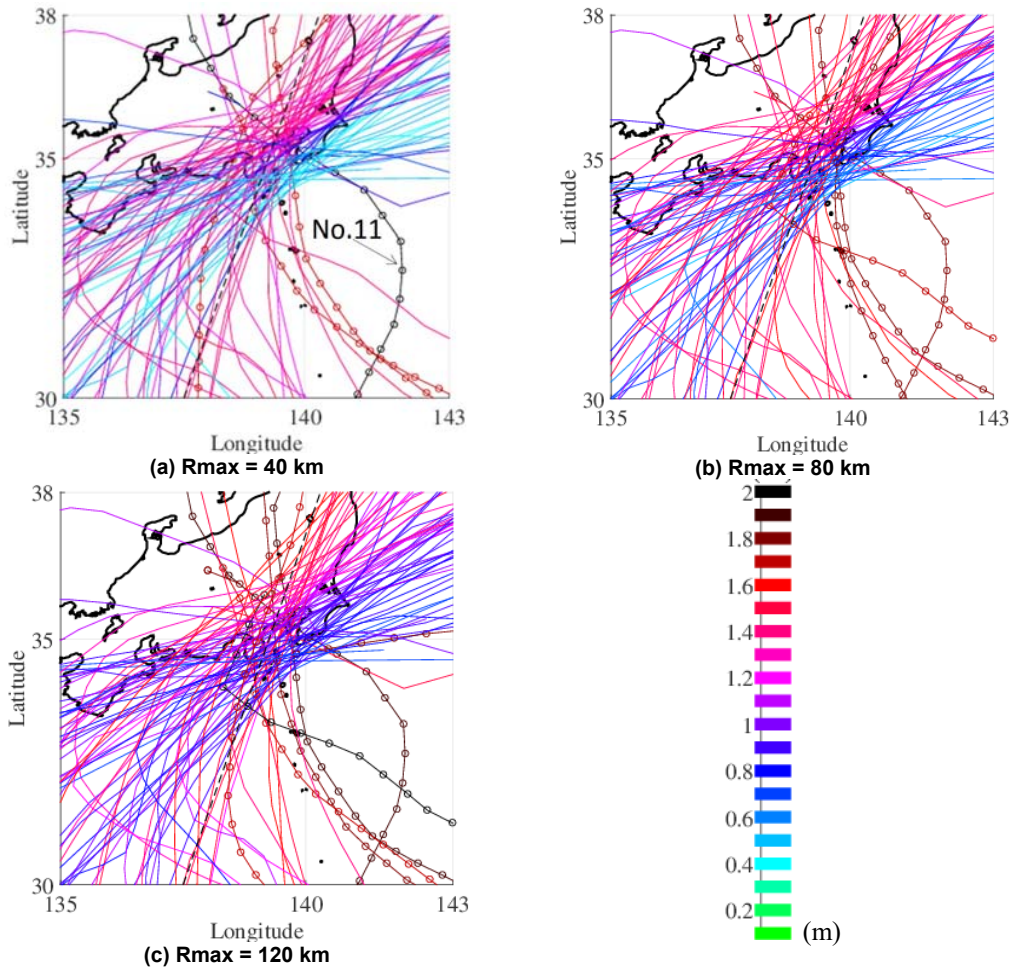


Figure 8. Every tropical cyclone track and maximum surge height at Tokyo caused by them.

of the worst scenario government assumed (MLIT, 2009). The maximum surge height at Tokyo of this additional simulation result was 1.5 m. Therefore, Fig. 6 shows some cases are comparable or exceed this dangerous storm surge event. The maximum value in all case was 1.81 m and this value occurs in case of No. 11 track. This tropical cyclone was generated in 1945. By the way, this typhoon track also shows large storm surge height at Tokyo in the case of other maximum wind speed radius condition.

Fig. 7 shows the relation between the minimum distance  $L_{min}$  from target area and the maximum surge height at Tokyo. In this figure, the minimum distance is normalized by the maximum wind speed radius. As an overall trend, the maximum surge height become large around  $L_{min}/R_{max} = 1.0$ . Generally, the overlap of strong wind zone and the water area in the front of target point brings to a severe storm surge. Therefore, this trend is reasonable result. However, if a tropical cyclone moved to the northeast direction and passed through the southeast side of Tokyo Bay, the suction effect become relatively large. Therefore, those tropical cyclones have the peak value around  $L_{min}/R_{max} = 0.0$ . Besides, it is interesting that, in the case of  $R_{max} = 40$  km, relatively large surge height occurs around  $L_{min}/R_{max} = 2.5$ . In this study, we compared the results using same condition about the central pressure and the translation speed. The range of influence of the wind drift and the suction would become large as the  $R_{max}$  is large. Therefore, the mean surge height become large as the  $R_{max}$  is large. However, the maximum value of all cases occurs in the case of  $R_{max} = 40$  km because the surge height is very sensitive to the track.

Fig. 8 shows every tropical cyclone track and the maximum surge height at Tokyo caused by them. The plot with markers are dangerous storm surge event (over 1.5 m). In this figure, the track of government assumed the worst scenario course is also shown as dashed line. In the whole cases, the typhoon No. 11 shows severe storm surge results. This tropical cyclone approaches from the southeast, and passes through Boso Peninsula, then moves to the northwest. It is interesting that the track of this

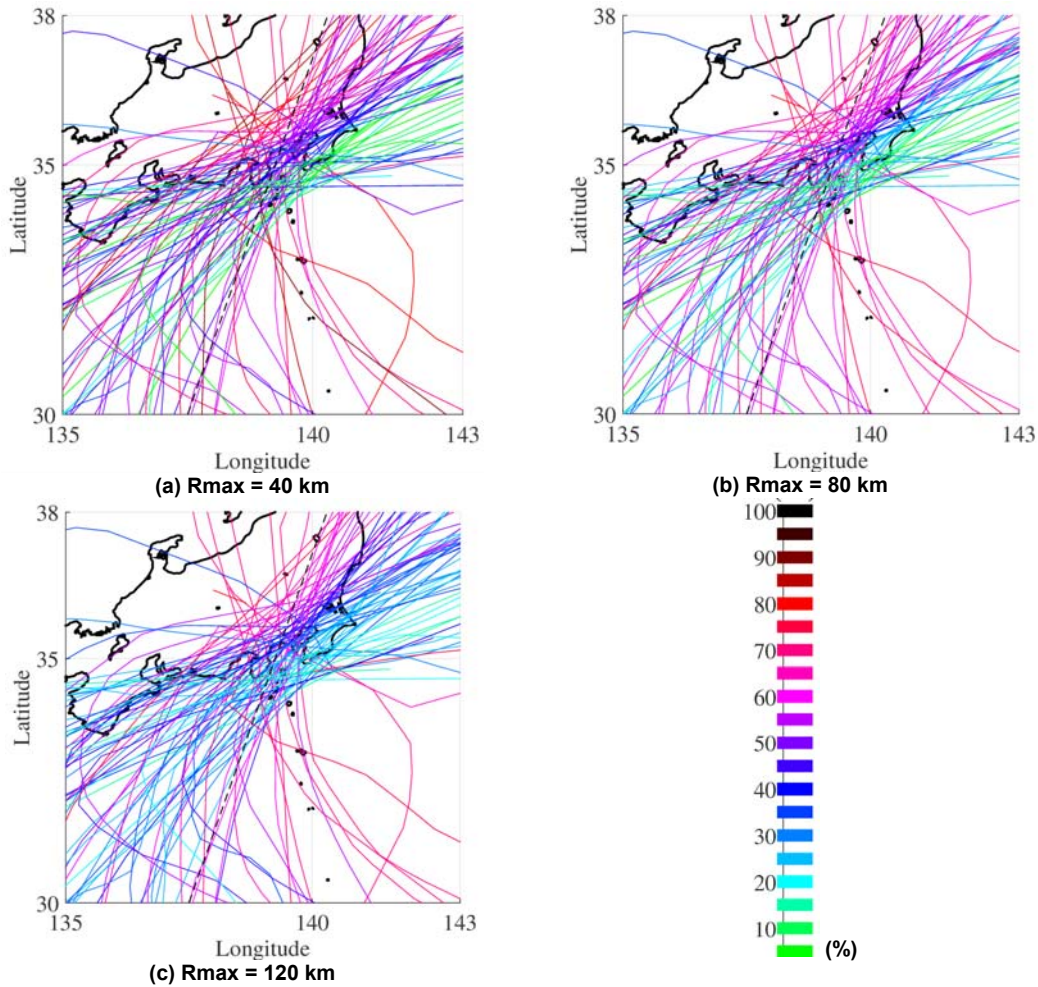


Figure 9. Every tropical cyclone track and the contribution ratio of the wind drift effect.

tropical cyclone is quite different from three model courses government assumed (Fig. 1). By the way, this type of tropical cyclone occurs in Aug. 2018 (the reverse travel typhoon, Jongdari). Fortunately, this typhoon strayed from dangerous course in the end. Therefore, the possibility is not zero although the frequency of this course is low. Besides, relatively large surge height event would be caused by the tropical cyclone approaches from the southeast and moves to the north. Of course, typhoon passing through along northeast direction track is also dangerous for Tokyo Bay. This is consistent with conventional knowledge.

**Wind drift effect and tropical cyclone track.** The relation between the effect of the wind drift and the tropical cyclone track was examined. We assumed the total surge height is composed by a sum of the suction effect and the wind drift effect. The surge height caused by the suction effect  $h_p$  was estimated by the following equation.

$$h_p = 0.01\Delta P \quad (6)$$

where  $\Delta P$  is the depression from ambient atmospheric pressure. We used the pressure value at Tokyo for convenience. Actually, we should use the value at some appropriate offshore point and the maximum surge height does not always occur when the pressure becomes the lowest. Therefore, we assumed actual  $h_p$  has positive correlation to this simple estimation value. Then the contribution ratio of the wind drift effect to the maximum surge height  $R_w$  was estimated by the following equation.

$$R_w = (h_{\max} - h_p) / h_{\max} \quad (7)$$

Fig. 9 shows every tropical cyclone track and the contribution ratio of the wind drift effect. This figure shows that the maximum surge height quite correlates to the wind drift effect. Especially, in the

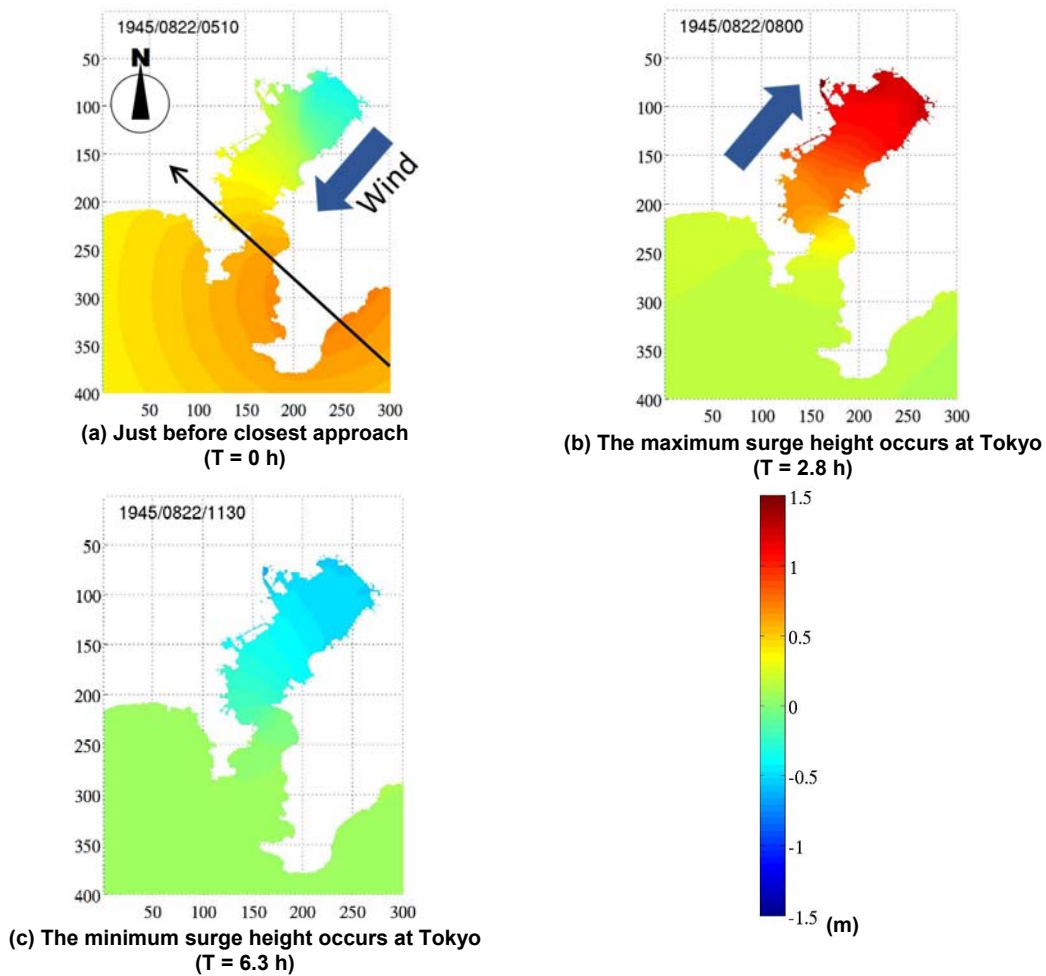


Figure 10. Temporal variation of surge height distribution around Tokyo Bay in the case of No. 11 tropical cyclone. The arrow in (a) shows tropical cyclone track.

case of No. 11, the ratio reaches to about 60 to 80 %. The difference of  $R_w$  tends to become small as the maximum wind radius is large.

**The mechanism of dangerous storm surge event caused by No. 11 tropical cyclone.** We analyzed the mechanism of dangerous storm surge from simulation results. Fig. 10 shows temporal variation of surge height distribution around Tokyo Bay in the case of No. 11 tropical cyclone. First, the water in Tokyo Bay was pushed toward the entrance of the bay by the eastern wind in the beginning, then after the typhoon passed, the driving force has been released and the western wind promoted the increase of surge height. This is what is called resurgence of long wave. Therefore, distinctive harbor oscillation is a main factor in this case. This characteristic feature would be related to the closed shape of Tokyo Bay and water depth. Besides, the strong opposite wind would also promote the increase of water level.

Fig. 11 shows time series of surge height, the wind speed and the atmospheric pressure at representative points. The closest time of tropical cyclone corresponds to the minimum value of the atmospheric pressure. When the tropical cyclone approaches to Tokyo Bay, the northeasterly wind causes the increase of water level at Yokohama and the decrease of water level at Chiba. After tropical cyclone passed Tokyo Bay, the southeastern wind causes the increase of water level at Tokyo. At Yokohama, the wind speed has double peaks and second peak value after tropical cyclone passes is larger than that of first peak. This is an evidence of strong opposite direction wind causes the increase of storm surge at Tokyo. The variation of water level at Tokyo shows significant secondary long wave overlapped major long wave. The period of major wave is about 6 hours and that of secondary wave is about 1 hour. This result almost consists with the previous knowledge of natural period of Tokyo Bay (Hino et al., 1964).



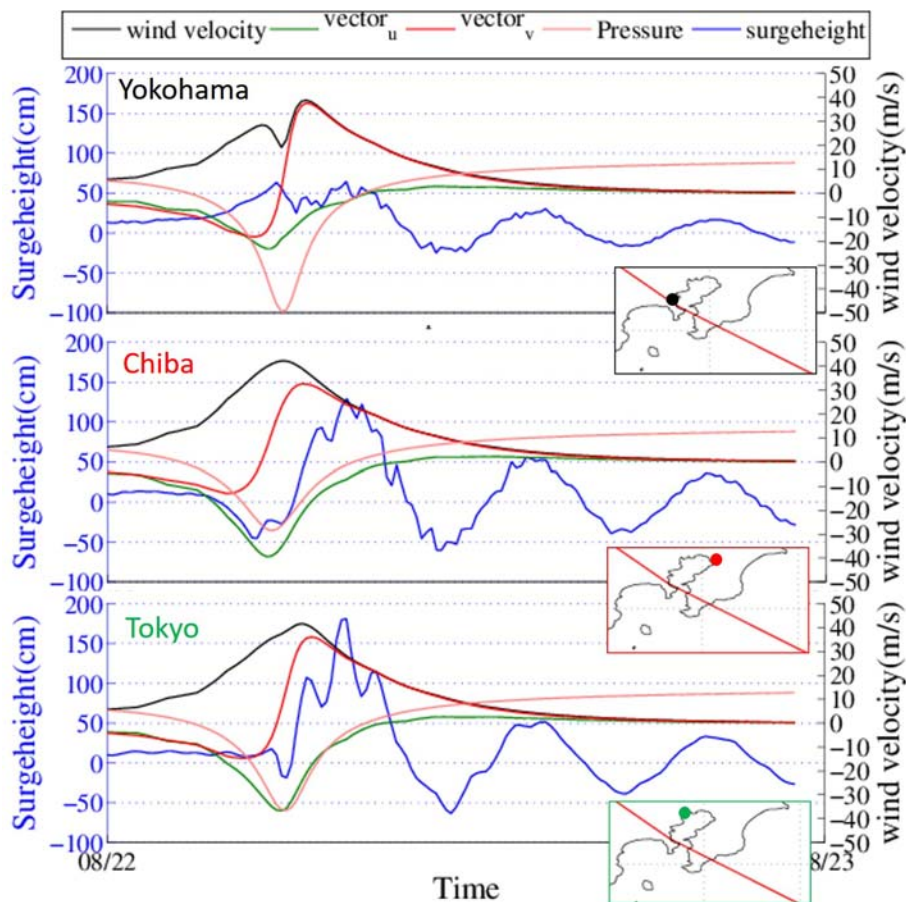


Figure 11. Time series of surge height, wind speed (black; absolute value, green; eastward component, red; northward component) and atmospheric pressure at representative points.

## CONCLUSION

The storm surge potential estimated from the actual historical record is comparable to the governmental planning scenario. Tropical cyclone passing through along the northeast direction track is dangerous for Tokyo Bay. Besides, the north directional track is also dangerous although the frequency of this type is low. Especially, it is interesting that the tropical cyclone passing through along northwest directional track (No. 11 tropical cyclone) causes distinctive harbor oscillation. The water in Tokyo Bay was pushed toward the entrance of bay by the eastern wind in the beginning, then after the typhoon passed, the driving force has been released and the western wind promoted the increase of surge height.

## ACKNOWLEDGMENTS

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