BASIC STUDY ON ESTIMATION METHOD OF RETURN PERIOD AND VARIATION RANGE OF SEVERE STORM SURGE EVENT

Sota Nakajo[1], Nobuhito Mori[2], Kim Soo-Youl[3], Tomohiro Yasuda[4], Fumihiko Yamada[5],Hajime Mase[6]

Probability risk assessment of storm surge is difficult because the number of historical data of tropical cyclone is not enough for local region. Most hazard maps for storm surge were designed based on the assumption that intense tropical cyclone approached in target area. However, its return period and variation range of storm surge have not been considered carefully so much. In this study, we examined them by using stochastic tropical cyclone model and physical storm surge model. Target area was Yatsushiro bay in west Kyushu Island in Japan. From physical storm surge simulation over about 300 cases, we decided the severe storm surge scenario and the variation range of maximum storm surge height caused by change of translation speed and radius of tropical cyclone. Finally, by using stochastic tropical cyclone model, the return period of severe storm surge event was estimated about 370 year.

Keywords: Storm surge; Return period; Stochastic tropical cyclone model

INTRODUCTION

The risk of storm surge is important information for design of coastal structure, but its probability assessment is difficult. For example, several tropical cyclones have approached around Kyushu Island in Japan every year, but devastating tropical cyclones were not so many. In the past, typhoon Bart attacked Kyushu Island in 1999 and 12 people were killed by storm surge. Maximum surge height was about 2 m plus tide level at Yatsushiro bay. Current hazard map at Kumamoto prefecture was designed based on the assumption the intense tropical cyclone approached to Kyushu Island with similar track as Bart. Its intensity was assumed to the same to typhoon Vera (1959) which was the most destructive tropical cyclone in Japan. However, we have no information about the return period of this severe situation. Therefore, although this assumption may be enough to decide temporary design criteria, it is difficult to explain the engineering appropriateness of its decision.

Storm surge damage is very sensitive to not only its intensity but also its track, translation speed and scale. If you estimate the occurrence probability of severe storm surge event by extreme value statistical analysis by using only historical data of tropical cyclones passed through around target area, results might include large uncertainty. Because the number of tropical cyclones is not enough decisively at local bay.

One of the method to solve this problem might be use of stochastic tropical cyclone model. Several stochastic model have been proposed before (For example, Vickery et al. (2000) and Emanuel et al. (2006)). And we have presented our global stochastic tropical cyclone model (GSTCM) (Nakajo et al. (2014)). In our model, the entire developing process from generation to disappearance is simulated. Modeled tropical cyclone parameters are three, minimum SLP, translation speed and direction. We assumed the probability density function (PDF) of change rate of tropical cyclone parameters depends on the value of previous time step. This assumption plays an important role in statistical determination of tropical cyclone parameters at next time step in our model. The reproducibility of tropical cyclone parameters depends on the method to estimate PDF. In our previous study, it was shown application of cluster analysis improve the GSTCM. Details were also presented in previous ICCE proceedings Nakajo et al. (2012).

From this background, we examined the tropical cyclone scenario which might cause severe storm surge event at local bay by using physical storm surge model based on historical tropical cyclone data. In this paper, 'tropical cyclone scenario' means temporal variation of tropical cyclone properties. Then we estimated its return period by using stochastic tropical cyclone model. Yatsushiro bay in Kyushu Island was chosen as research subject of this study. Especially, the variation range of maximum surge height depending on tropical cyclone parameters and the way to estimate the return period which is depending on tropical cyclone parameters were explained in this paper.

[1]Department of Civil and Environmental Engineering, Kumamoto University, Japan
[2]DPRI, Kyoto University, Japan
[3]Department of Social Systems Engineering, Tottori University, Japan
[4]DPRI, Kyoto University, Japan
[5]Department of Civil and Environmental Engineering, Kumamoto University, Japan
[6]DPRI, Kyoto University, Japan

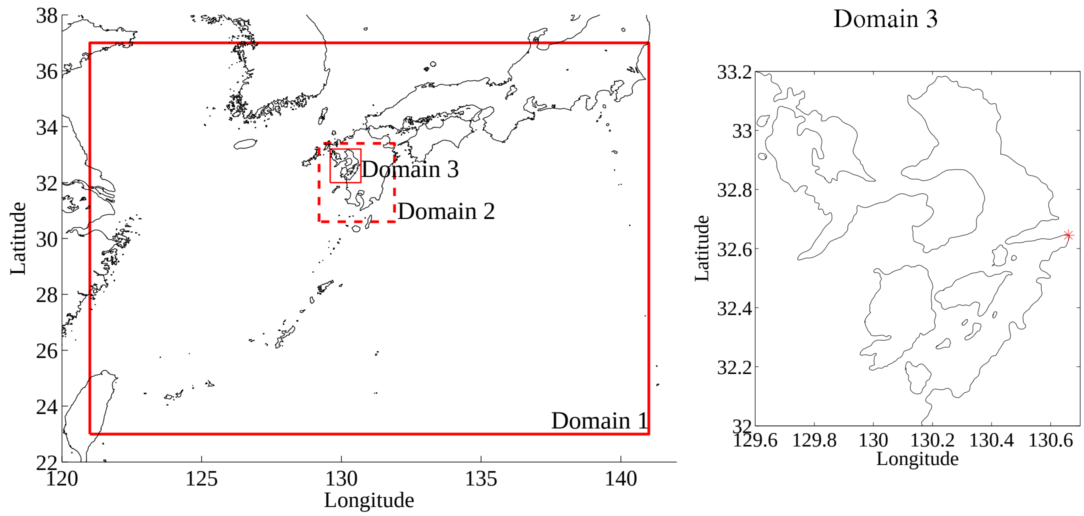

Figure 1: Calculation area

METHODOLOGY

Physical storm surge model

External force of storm surge phenomena are wind and atmospheric pressure depression. Then water flow in the sea and wave action of various scale generate storm surge. Therefore, use of three dimensional meteorological model and three dimensional oceanic model might be recommended in order to simulate more accurate storm surge. However we neglected investigation of accuracy of model in this study because first purpose of this study is just selection of tropical cyclone scenario. Storm surge phenomena was simulated by solving two dimensional nonlinear shallow water equation using SuWAT model developed by **?**.

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

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{d}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{d}\right) + gd\frac{\partial \eta}{\partial x} = fN - \frac{1}{\rho_w}d\frac{\partial P}{\partial x} + \frac{1}{\rho_w}(\tau_s - \tau_b + F_x) + A_h\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{NM}{d}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{d}\right) + gd\frac{\partial \eta}{\partial y} = -fM - \frac{1}{\rho_w}d\frac{\partial P}{\partial y} + \frac{1}{\rho_w}\left(\tau_s - \tau_b + F_y\right) + A_h\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right) \tag{3}$$

$$\tau_b = \rho_w g n^2 \frac{Q|Q|}{d^{7/3}} \tag{4}$$

$$\tau_s = \rho_a C_D W_{10}|W_{10}| \tag{5}$$

Here η is a water level from basic water surface, M and N are components of depth-integrated velocity. Shear forces acting on sea bottom and surface τ_b and τ_s were defined equation (4) and (5) respectively. n is the Manning's coefficient of roughness and Q is depth-integrated velocity. C_D is the surface drag coefficient and W_{10} is a wind speed at 10 m above the sea surface.

Actually, tidal variation has been modeled in SuWAT by imposing boundary condition from result of ocean tidal model (Matsumoto et al. (2000)). However, deciding of timing of landing of tropical cyclone is a difficult problem to search for severe storm surge scenario when tidal variation is considered in simulation. We judged that the nonlinear interference between tidal variation and wave of storm surge was able to be neglected in this study. The wave action smaller than grid scale can be simulated by simulation of wave model SWAN (Booji et al. (1999)) in SuWAT. Then wave setup effect in coastal area and variation of coefficient C_D depending on a wave height are considered in SuWAT. However, in order to calculate many cases, these wave effects were also neglected in this study. In addition, flooding over land was not considered, therefore surge waves reflected at boundary line between land and water.

Table 1: Calculation conditions

Grid arrangement	Three layers and two-way nesting	
Calculation area	First domain	121.0-141.0°E, 23.0-37.0°N
	Second domain	129.2-131.9°E, 30.6-33.4°N
	Third domain	129.6-130.7°E, 32.0-33.2°N
Grid size	First domain	6000 m
	Second domain	810 m
	Third domain	270 m
Surface drag coefficient	Honda and Mitsuyasu (1982)	
Manning's coefficient of roughness	$n = 0.025$	
Tropical cyclone model	Fujita (1952)	

Instead of a three dimensional meteorological model, an empirical tropical cyclone model proposed by Fujita (1952) was used to calculate distribution of atmospheric pressure and wind speed.

$$P = P_\infty - \frac{\Delta P}{\sqrt{1 + (r/R_{max})^2}} \tag{6}$$

$$V_{gr} = r\left[\sqrt{\frac{f^2}{4} + \frac{\Delta P}{\rho_a r^2 \left(1 + (r/R_{max})^2\right)^{-3/2}}} - \frac{f}{2}\right] \tag{7}$$

Here P is a sea level pressure (SLP) and V_{gr} is a gradient wind speed. ΔP is a depth of minimum SLP at center of tropical cyclone from ambient pressure field, r is a distance from center of tropical cyclone and R_{max} is the radius of maximum wind speed. The effect of land topography is not reflected in wind speed and pressure field. Then the ambient wind effect was added to a gradient wind as function of translation speed of tropical cyclone.

Figure 1 shows a calculation area. Three domains were used for nesting simulation. Minimum grid scale of domain 3 was 270 m. Target area of this study, Yatsushiro bay, is shown by an asterisk. Between these grids, simulation results were transferred interactively.

Table 1 shows a summary of calculation conditions. We used surface drag coefficient C_D modeled by Mitsuyasu-Honda equation (Mitsuyasu and Honda (1982)). However we decided the upper limit of this coefficient when wind speed is over 35 m/s. The Manning's coefficient of roughness n was constant at all area.

Accuracy check of storm surge model Accuracy of surge simulation was checked by hindcasting of storm surge caused by typhoon Bart in 1999. The observation value of maximum surge height was 1.8 m at Matsuai district in Yatsushiro bay. Figure 2 shows temporal variation of surge height at Matsuai district in simulation. The peak value of simulation was 2.1 m. From this result, we estimated that an error range of surge height is about 0.3 m.

Characteristics of tropical cyclone around target area and method to decide the scenario of tropical cyclone

We examined severe storm surge scenarios from results of physical model simulation using synthetic tropical cyclone data which had the same track to historical tropical cyclone. First, we searched tropical cyclones passed through around target area (129.5-131.0°E, 32.0-33.0°N). As a result, 63 tracks were picked up from 83 years data (1927-2009) of tropical cyclone database, IBTrACS v03r04.

Figure 3 shows latitudinal changes of minimum SLP of historical tropical cyclones passed through around Yatsushiro bay. Specially, some representative tropical cyclone data are shown with markers (Forrest(1983), Mirelle(1991), Sanba(2012)). Actually, typhoon Sanba was not passed through target area although it passed near area. But it added to this figure because it was very intense tropical cyclone recently. From this figure, we can understand the characteristics of intensity of tropical cyclone. For reference, typhoon Vera which was used for assumption of hazard map of storm surge had 940 hPa when it was landing.

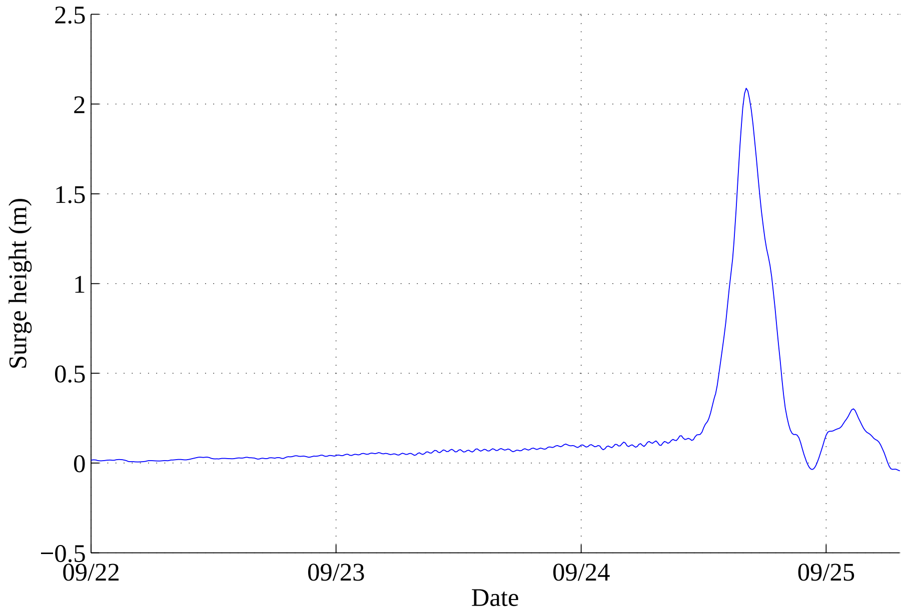

Figure 2: Temporal variation of surge height at Matsuai district (Simulation)

Yatsushiro bay is located at north latitude about 32 degree. Therefore, it shows that previous assumption of hazard map is more dangerous condition than historical data. In this study, we decided the virtual scenario of minimum SLP in our individual way. Blue and green lines are historical data of typhoon Forrest and Mirelle respectively. These are strongest tropical cyclone in low and middle latitude region in historical data. Their variations can be approximated by quadratic regression curve (magenta line). We used this variation of minimum SLP as virtual tropical cyclone scenario. The intention of our method is that we have to understand that former tropical cyclone passed through target area might cause severe storm surge event if conditions are right.

In Figure 4, a blue line shows latitudinal change of translation speed of typhoon Mirelle. This typhoon accelerated after passing through north latitude 25 degree because it was affected by westerlies presumably. Then it had a large translation speed around target area (32°N). The value of large translation speed means existence of large ambient wind speed. Therefore, this change is appropriate to a candidate of severe storm surge event. We approximated this variation by a linear regression curve (red line). In addition, we prepared three scenarios of translation speed in order to estimate the influence of translation speed. Each translation speed at north latitude 32 degree was 60, 40 and 25 km/h, respectively.

In the empirical tropical cyclone model, a scale of tropical cyclone can be changed by the radius of maximum wind speed R_{max}. However, authorized information of R_{max} did not existed. We referred previous studies (For example, Hashimoto et al. (2003)) and decided its range.

Table 2 shows a summary of scenarios of tropical cyclone for simulation. The scenario of minimum SLP was common, but translation speed and the radius of tropical cyclone were changed. 63 tracks were simulated for each condition.

RESULTS AND DISCCUSIONS

Variation of maximum surge height caused by change of tropical cyclone parameters

Figure 5 shows the relation between maximum wind speed and maximum surge height at target area in case V60-R60, V60-R80 and V60-R100. Each plot is a result of different track and different radius. In the scenario of them, the variation of translation speed are common. The results of same track are connected by different color lines. Line colors show which radius case is highest. The highest maximum surge height was about 3.2 m. For reference, the mark of asterisk in figure shows the result in which the track of typhoon Bart was used. It is shown that the track of typhoon Bart is one of dangerous scenarios although it is not

Table 2: Scenarios of tropical cyclone for simulation of storm surge

Scenario	Translation speed at 32°N (km/h)	Radius of maximum wind speed (km)	Minimum SLP
V60-R60	60	60	Approximated latitudinal variation of Forrest(1983) and Mireille(1991)
V25-R80	25	80	
V40-R80	40		
V60-R80	60		
V60-R100	60	100	

the worst. Maximum surge height has positive correlation to maximum wind speed generally. Then, the radius of tropical cyclone also effects on wind speed. However, maximum change of maximum surge height caused by radius in all cases was about 0.5 m. This result shows most important factor of maximum surge height is track and the radius is secondary factor.

In Figure 6, the relation between minimum distance from target area to center of tropical cyclone L_{min} and maximum surge height. Minimum distance L_{min} is normalized by the radius of maximum wind speed R_{max}. Again, in the scenario of them, the variation of translation speed are common (V60-R60, V60-R80 and V60-R100). For reference, the mark of asterisk in figure shows the result in which the track of typhoon Bart was used. This result shows that even if the scale of typhoon changes, maximum surge height would be the highest when L_{min}/R_{max} is 1.0. However, if its track passed through the south or east side of target area, maximum surge height would be small. Then, we tentatively decided that the severe storm surge level is over 3.0 m in this study. Again, from this figure, we can estimate the severe storm surge event might occur when L_{min}/R_{max} is from 0.5 to 1.5. After above consideration, we decided the tracks which might cause severe storm surge. Figure 7 shows all of them passed through the northwest of target area. In addition, most tracks were approximately parallel to the axis of Yatsushiro bay.

Figure 8 shows the relation between L_{min}/R_{max} and maximum surge height again, in case V25-R80, V40-R80 and V60-R80. Therefore, the influence of translation speed is shown in this figure. However, only the results of representative tracks shown in Figure 7 are shown here. Translation speed has positive correlation to maximum surge height because the increase of translation speed means the increase of ambient wind speed. Even if translation speed changes, maximum surge height is the largest when L_{min}/R_{max} is about 1.0. In addition, the change rate of maximum surge height caused by translation speed was almost constant even if tracks are different.

Return period of the severe storm surge event

The way to decide candidates of tropical cyclone which might cause severe storm surge event

We defined following conditions to calculate return period of the severe storm surge.

(A) Minimum SLP is not larger than 915 hPa.

(B) Minimum SLP when tropical cyclone is close to target area (Yatsushiro Bay) was not larger than 940 hPa.

(C) Track of tropical cyclone is close to that of severe storm surge scenario estimated from SuWAT simulation.

(D) Minimum distance from target point to the track of tropical cyclone is appropriate ($0.5<L_{min}/R_{max}<1.5$).

(E) Translation speed is large enough considering the balance to the minimum SLP.

The threshold value of first condition (A) is correspond to that of reference scenario (see Figure 3) at north latitude 23 degree (south boundary of calculation region). Then, the threshold value of second condition (B) is correspond to that of reference scenario at north latitude at 32 degree. Third condition (C) was decided from observation of representative tracks shown in Figure 7. All tracks have passed through two area which is 1 degree in width, Area 1 (129.0-130.0°E, 31.5-32.5°N) and Area 2 (130.5-131.5°E, 33.5-34.5°N). Therefore, we decided that tropical cyclones passed through these area are candidates satisfied the third condition.

In order to decide the detail of the fourth condition (D), we used the relation shown in Figure 6. The severe storm surge event occurs when the minimum distance satisfied the following condition.

$$0.5 < L_{min}/R_{max} < 1.5 \tag{8}$$

Therefore, we have to get the information of the radius of maximum wind speed R_{max}. However, the radius was not modeled in our stochastic tropical cyclone model. In previous studies, it was shown that the radius of maximum wind speed has positive correlation to minimum SLP. We referred to the technical note of Japanese research institute written by Kato (2005) to consider its relation in this study. They estimated the average and standard deviation of the radius of maximum wind speed, $\mu_{R_{max}}|_{p_c}$ and $\sigma_{R_{max}}|_{p_c}$, as a function of minimum SLP. However, the standard deviation of radius is almost constant not depending on minimum SLP, and it is about 20 km. Consequently, the upper and lower limit of the candidate of minimum distance L_{min} was decided by following equation.

$$0.5\left(\mu_{R_{max}}|_{p_c} - \sigma_{R_{max}}|_{p_c}\right) < L_{min} < 1.5\left(\mu_{R_{max}}|_{p_c} + \sigma_{R_{max}}|_{p_c}\right) \tag{9}$$

In fifth condition (E), we decided the limit of translation speed in consideration of variation of the minimum SLP. The assumption of linear superposition between translation speed and minimum SLP to maximum surge height was used. Figure 9 and Figure 10 show that the variation of maximum surge height depending on minimum SLP and translation speed, respectively. Each variation value shows difference from reference scenario (minimum SLP: 940 hPa at 32°N, translation speed 60 km/h at 32°N). Markers are simulation results and lines are regression curve. There is negative linear relation between maximum surge height and minimum SLP. Then, there is positive quadratic relation between maximum surge height and translation speed. If the sum of variations of maximum surge height is under zero, we decided the tropical cyclone is not the candidate of cause of severe storm surge.

Return period of the severe storm surge event Finally the return period of the severe storm surge was estimated by calculation of conditional probability $P_{condition(X)}$. The tropical cyclones which was created from stochastic tropical cyclone model and satisfied all conditions (A)~(E) were selected as the candidate would cause severe storm surge event. Following equation is used for calculation of conditional probability.

$$P_{condition(X)} = Y_{simulation}\frac{N_{condition(X)}}{N_{total}} \tag{10}$$

Here $Y_{simulation}$ is a total simulation period. 2,500 year simulation of stochastic tropical cyclone model was conducted in this study. $N_{condition(X)}$ is a number of tropical cyclone which satisfied the condition (X). N_{total} is a number of total tropical cyclone during simulation period.

Table 3 shows the return period of each condition. From this table, it is clear that the weight of each condition. The return period of condition (A) and (B) were 23 and 31 year, respectively. These results would be almost agree with observation data (see Figure 3) and our sense. Then, the condition (C) occurred more frequently. This value is almost equal to the rough estimation of return period which can be calculated from the number of tropical cyclone track in Figure 7 (14 tracks) and total period of data (83 year). The condition (D) occurred most frequently in all conditions. However, note that this result includes cases when tropical cyclone passed through east or south side of target area. The return period of the condition (E) was the longest in all conditions. In this study, we decided severe scenario based on observation data. Therefore, it may be reasonable that the order of this return period is almost equal to period of observation data.

Consequently, the return period of severe storm surge was about 370 year. Although the return period of each condition is not so large, that of total condition is relatively large. In future, we have to compare this value to the result of the extreme value statistical analysis of observation data.

CONCLUSION

The severe storm surge scenario at local bay in west Kyushu Island was estimated from many storm surge simulations. Maximum surge height was about 3.2 m at Yatsushiro bay. Then the variation ranges of maximum storm surge height caused by change of translation speed and the radius of tropical cyclone

Table 3: Return period of each condition (year)

Condition	A	B	C	D	E	All
Return period	23.2	31.0	6.6	2.7	59.1	373.1

were enough large. In this case study of severe storm surge event (maximum surge height is over 3.0 m), we decided some conditions of tropical cyclone (track, minimum SLP, the minimum distance from target area and translation speed). By using stochastic tropical cyclone model, the return period of severe storm surge event was estimated about 370 year.

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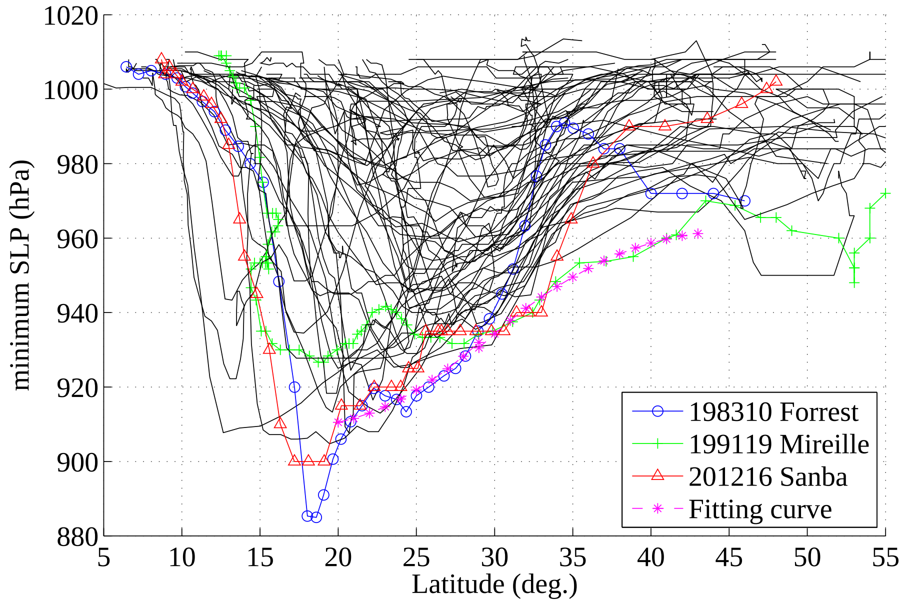

Figure 3: Latitudinal change of minimum SLP of historical tropical cyclones

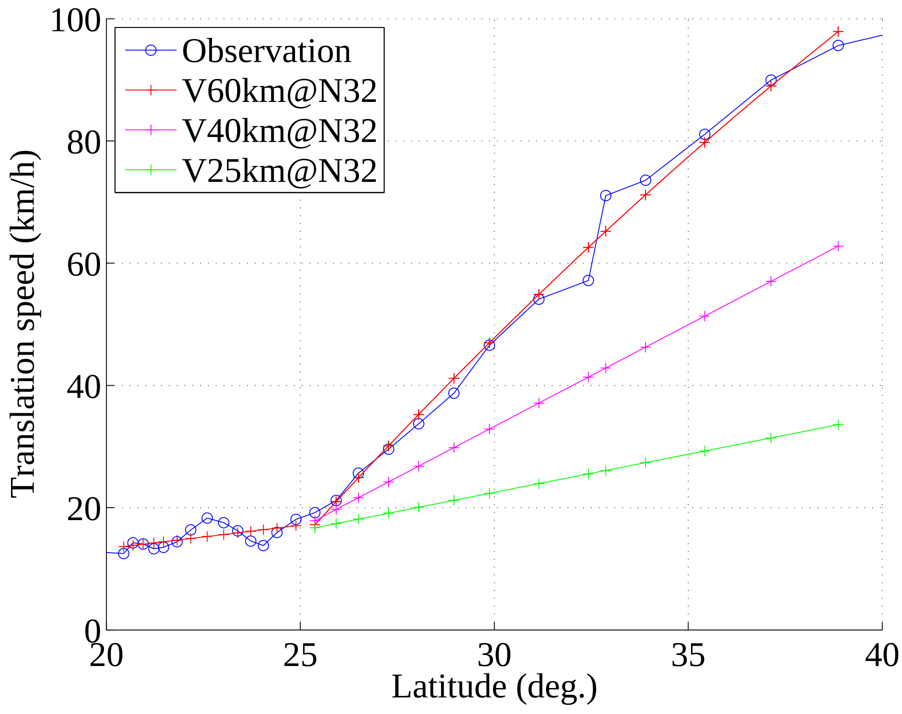

Figure 4: Latitudinal change of translation speed (Typhoon Mireille and simulations)

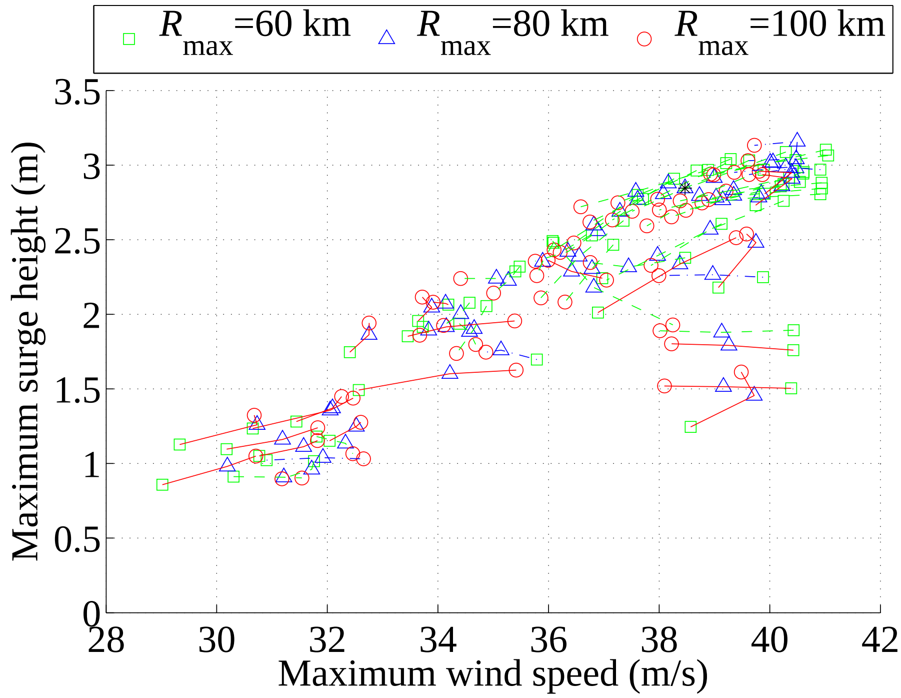

Figure 5: Maximum wind speed and maximum surge height at Yatsushiro bay

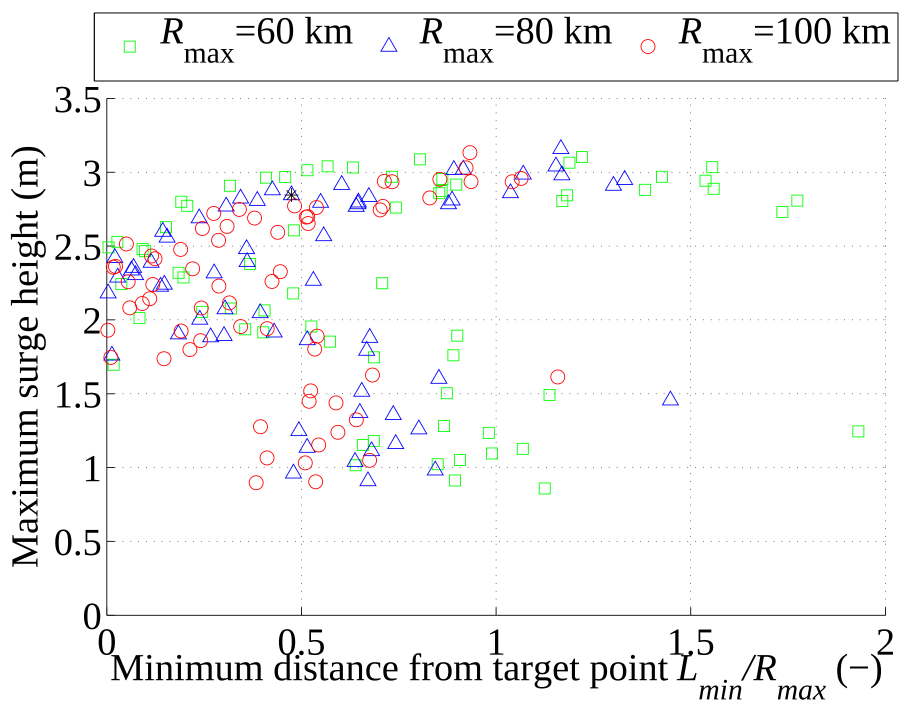

Figure 6: The influence of the scale of tropical cyclone: Maximum surge height and minimum distance from target area to center of tropical cyclone L_{min}

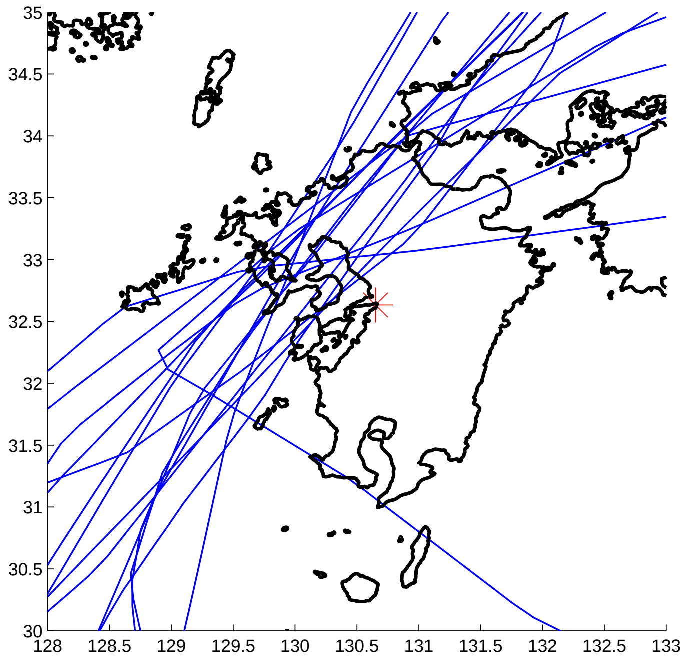

Figure 7: Tropical cyclone tracks might cause severe storm surge at Yatsushiro bay

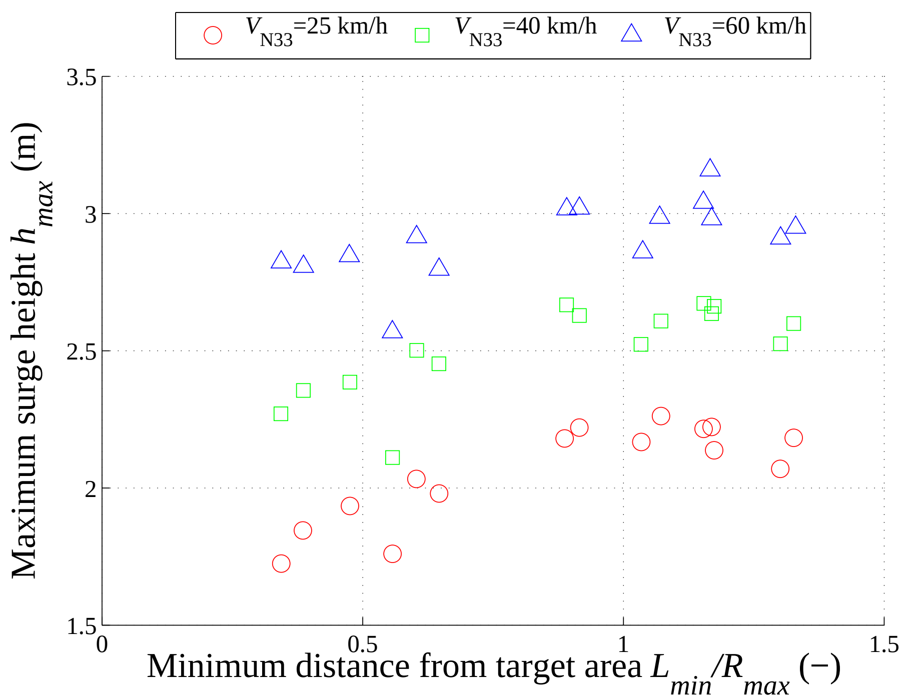

Figure 8: The influence of translation speed: Maximum surge height and minimum distance from target point

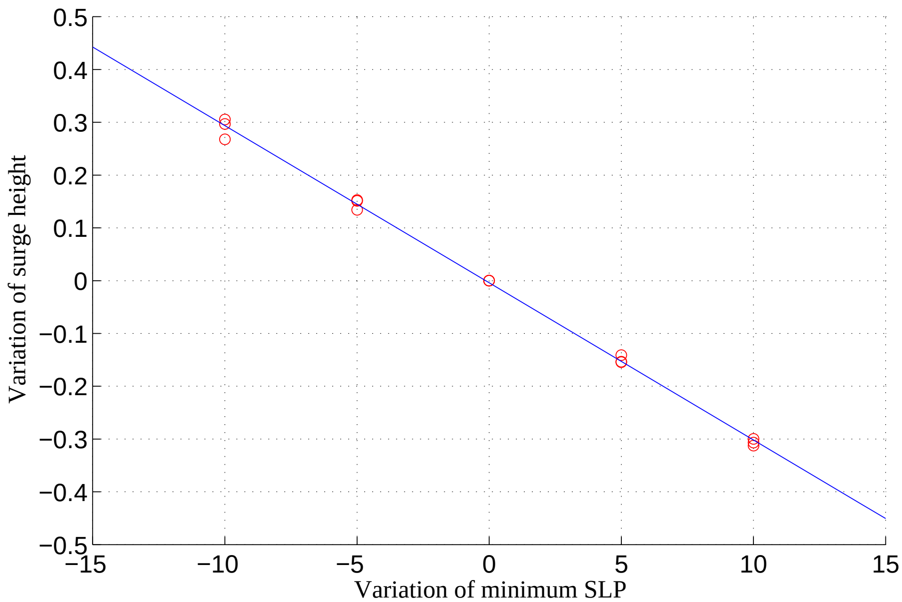

Figure 9: Variation of maximum surge height depending on minimum SLP

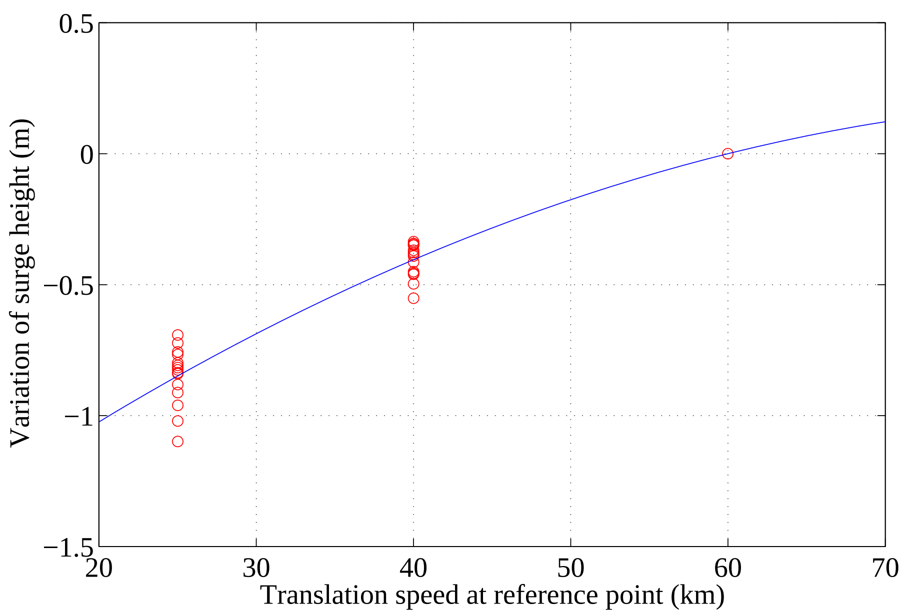

Figure 10: Variation of maximum surge height depending on translation speed