Influence of Typhoon Moving Speed on Maximum Storm Surge Height in a Bay Facing the Open Ocean

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BACKGROUND

Storm surges may bring catastrophic damage to coasts by the abnormal increase in sea level. In semi-enclosed, shallow water areas such as Tokyo Bay, the increase of sea level due to wind tends to be significant. Due to this characteristic, the fast-moving typhoon can be regarded as a potential candidate for possible maximum storm surge in Japan. The moving speed of Super Typhoon Vera in 1959 (i.e. 73 km/h), which caused the worst storm surge in Japan, is about two times faster than the average around Japan (Yamaguchi et al. 2020) but is typically used in storm surge simulation by parametric typhoon models (e.g. assessing the risk of storm surge inundation at coasts (MAFF and MLIT 2023), designing coastal defence structures (OCDI 2020)).

However, this may not be true in bays facing the open ocean. High waves are likely to enter such bays, and storm surges due to wave setup can be predominant, meaning that fast-moving typhoons do not necessarily cause significant storm surges. The relationship between the moving speed and maximum storm surge height in such bays, however, seems not to be well studied. Therefore, the authors examined this relationship through the hindcast of storm surges induced by super Typhon Jebi in 2018 and numerical experiments. Typhoon Jebi brought catastrophic damages to the coastal areas of the Kansai region (Mori et al. 2019).

METHODS

The storm surge in Hidaka Bay (i.e. Gobo), facing the Pacific (Figure 1), was simulated by the two-way coupling ROMS and SWAN using the coupled ocean-atmosphere-wave-sediment transport modelling System (COAWST) (Warner et al. 2010). In the hindcast, 10 m wind and sea level pressure fields from two models were used as the external forcings: a parametric typhoon model account for the super gradient wind (SGW) (Fujii and Mitsuta 1986) and the Meso Scale Model (MSM) simulated by the Japan Meteorological Agency (JMA). The JMA best track data gave the model parameters in SGW (i.e. location and central pressure); the maximum wind speed radius and the pressure deficit were estimated by fitting the Holland pressure profile with a parameter $B = 1$ to the observations on land (Iwamoto et al., 2020). In the numerical experiment, 15 hypothetical typhoon fields were simulated by SGW with a central pressure of 910 hPa and a maximum wind speed radius of 75 km, following the practical guideline of making a storm surge hazard map (MAFF and MLIT 2023). Five straight typhoon tracks were set by shifting the typhoon track before Typhoon Jebi made landfall by 25 km in east-west directions (white thin lines in Figure 1), and the moving speeds were set as 30, 50, and 70 km/h, respectively.

The computational domains comprised five grid systems, from the entire northwestern Pacific Ocean to Hidaka Bay, reducing the grid size to a minimum of 30 m. The raw tidal record observed at Hidaka Bay was obtained from JMA. After excluding the astronomical tide from this record, the residual was treated as the observed storm surge.

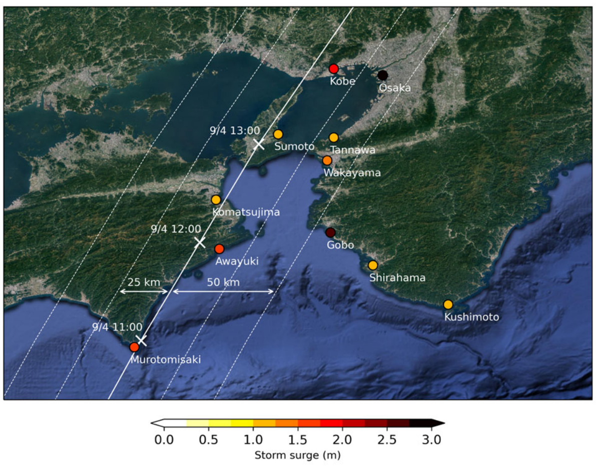

Figure 1 – Maximum storm surge height distribution induced by Typhoon Jebi in 2018. The location of coloured dots corresponds to the tide stations. The solid white line is the observed typhoon track, and the thin white lines are the tracks used in the numerical experiments.

RESULTS AND DISCUSSION

The accuracy of the two meteorological fields was assessed by comparing the time series of 10 m wind speed and sea level pressure around Hidaka Bay. During the typhoon passage (0600 to 1800 JST, September 4), the average of the Root Mean Square Error (RMSE) and Mean Error (ME) for sea-level pressure in MSM were 1.41 hPa and 0.28 hPa, while those in SGW were 2.74 hPa and -1.33 hPa. For 10 m wind speed, MSM had RMSE and ME of 5.66 m/s and 1.84 m/s, while SGW had 10.71 m/s and 7.91 m/s. This result shows that MSM and SGW performed well, particularly in reproducing the typhoon pressure field.

The coupled ocean-wave model simulated the storm surge well for both meteorological fields (Figure 2); the maximum in both cases was above 1.5 m. In contrast, without considering the effect of waves (i.e. only ROMS), the maximum storm surge heights were up to 0.6 m, and the simulations underestimated the observation by more than 1.0 m. These results indicate that the wave setup was predominant in the storm surge at Gobo over 2.0 m.

From the numerical experiment results, when considering the effects of waves (see the coloured bars in Figure 3), the maximum storm surge height among all 15 hypothetical typhoons was highest (3.86 m) when the moving speed was 50 km/h, passing a similar track to that in Typhoon Jebi. Meanwhile, the maximum storm surge

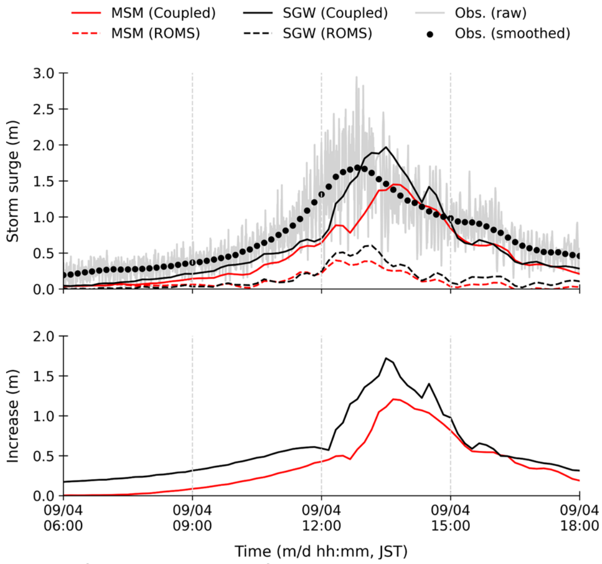

Figure 2 - Time series of observed and simulated storm surges at Gobo, Hidaka Bay. The sampling frequency of the raw tidal observation is 15 s, and the hourly moving average smoothed this data.

heights when the moving speed was 70 km/h were generally smaller, nearly 1.0 m. Also, the results simulated by ROMS alone show much more minor differences in maximum storm surge heights (< 0.2 m, see the hatched bars in Figure 3) depending on the moving speeds. Thus, the differences in considering the effects of waves were primarily due to the wave setup. It should be mentioned that the maximum significant wave height was also smaller throughout the bay, up to 4.0 m, when the moving speed was 70 km/h (Figure 4). This suggests the typhoon-induced waves were not fully developed in the open ocean. In this study, these waves can be regarded as deep water waves; the group velocity C_g can be estimated by Eq. 1,

$$C_g = \frac{1}{2}\frac{gT}{2\pi} \quad (1)$$

where g is a gravitational acceleration (m/s^2), and T is a wave period (s). Assuming that C_g was 70 km/s (~ 19.4 m/s), the corresponding wave period was about 25 s. The typical periods of typhoon-induced waves are less than 20 s, indicating that the typhoon can overtake the wind waves when the moving speed is 70 km/h. Consequently, the offshore waves did not develop sufficiently, resulting in more minor maximum storm surge heights.

CONCLUSION

The storm surge hindcast reveals that the primary factor of the significant storm surge in Hidaka Bay induced by 2018 super Typhoon Jebi can be wave setup. Also, the numerical experiments show that the offshore waves may not develop sufficiently when the typhoons move faster than the group velocity of waves, and the maximum storm surge height may also decrease up to 1.0 m.

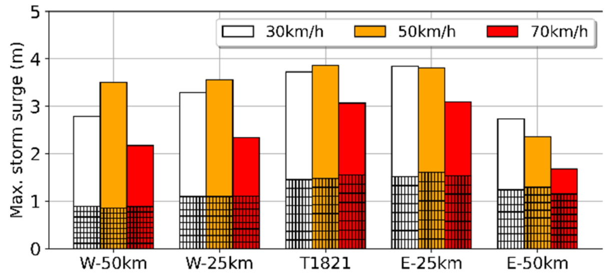

Figure 3 Maximum storm surge heights in Gobo in 15 hypothetical typhoons. The hatches represent the results using ROMS alone.

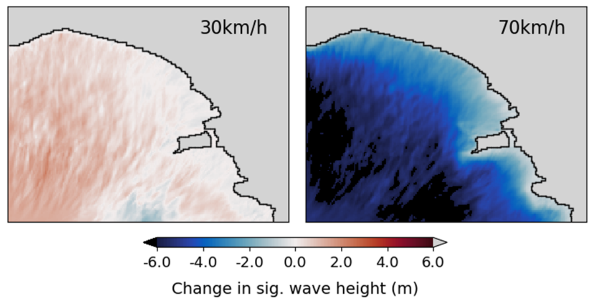

Figure 4 Average changes in maximum significant wave height at 30 km/h and 70 km/h against that at 50 km/h.

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