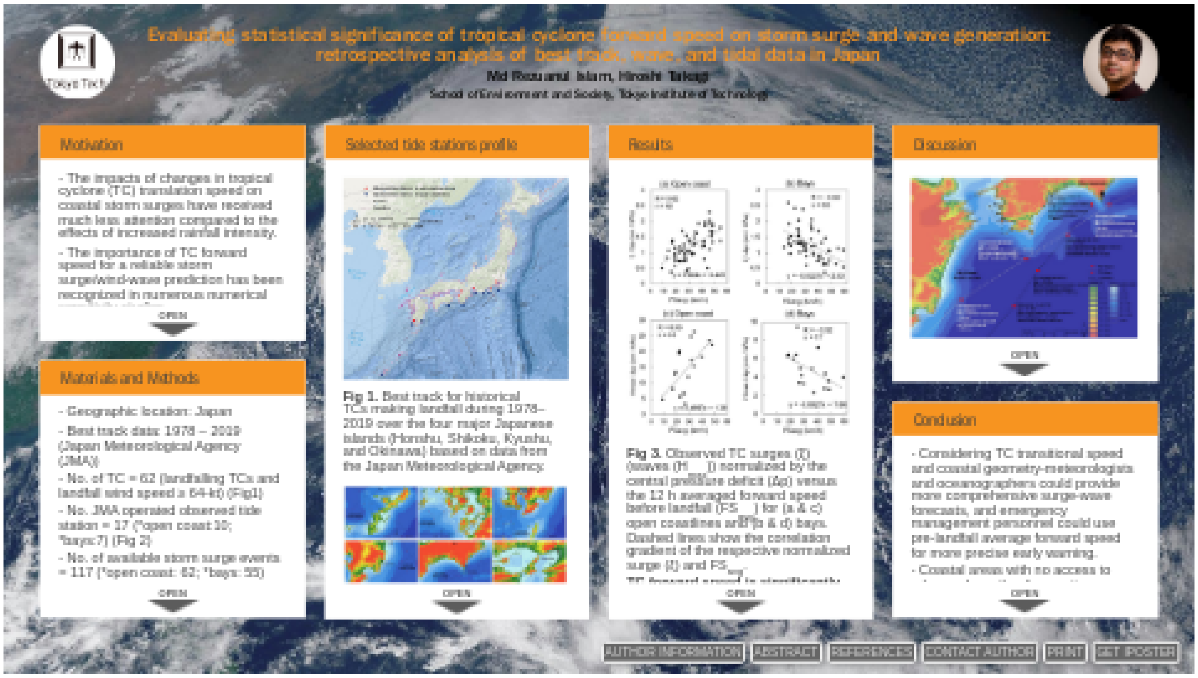
Evaluating statistical significance of tropical cyclone forward speed on storm surge and wave generation: retrospective analysis of best track, wave, and tidal data in Japan



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INTRODUCTION AND MOTIVATION

- The impacts of changes in tropical cyclone (TC) translation speed on coastal storm surges have received much less attention compared to the effects of increased rainfall intensity.

- The importance of TC forward speed for a reliable storm surge/wind-wave prediction has been recognized in numerous numerical sensitivity studies.

- Most of these numerical results are in contrast to each other and the interaction between TC forward speed and storm surge (wave) has not been validated using long-term tidal observations over a large area (i.e., for a country or globally).

Motivating question

Whether there is a statistically significant relationship among TC forward speed, storm surge (wave) and coastal geometry, considering the difference either semi-enclosed bays or open coasts.

MATERIALS AND METHODS

- Geographic location: Japan

- Best track data: 1978 – 2019 (Japan Meteorological Agency (JMA))

- No. of TC = 62 (landfalling TCs and landfall wind speed ≥ 64-kt) (Fig1)

- No. JMA operated observed tide station = 17 (*open coast:10; *bays:7) (Fig 2)

- No. of available storm surge events = 117 (*open coast: 62; *bays: 55)

- No. of available significant wave height = 35 (*open coast: 18; *bays: 17)

*Open coast: open to the ocean (i.e., North West Pacific); Bays: regions surrounded by two land areas that form a concave-shaped coastline.

- TC forward speed was estimated by linearly interpolating the speeds at two positions along each TC track.

- Storm surge (wave) was scaled by dividing the peak surge (wave) by TC central pressure deficit, Δp (= 1013 – pressure at the center of the TC at landfall time) to eliminate the effect of TC intensity.

- The Pearson correlation coefficient (R), was used to measure the strength of the linear association between the observed TCs' forward speed and normalized peak storm surge (wave) height.

SELECTED TIDE STATIONS PROFILE

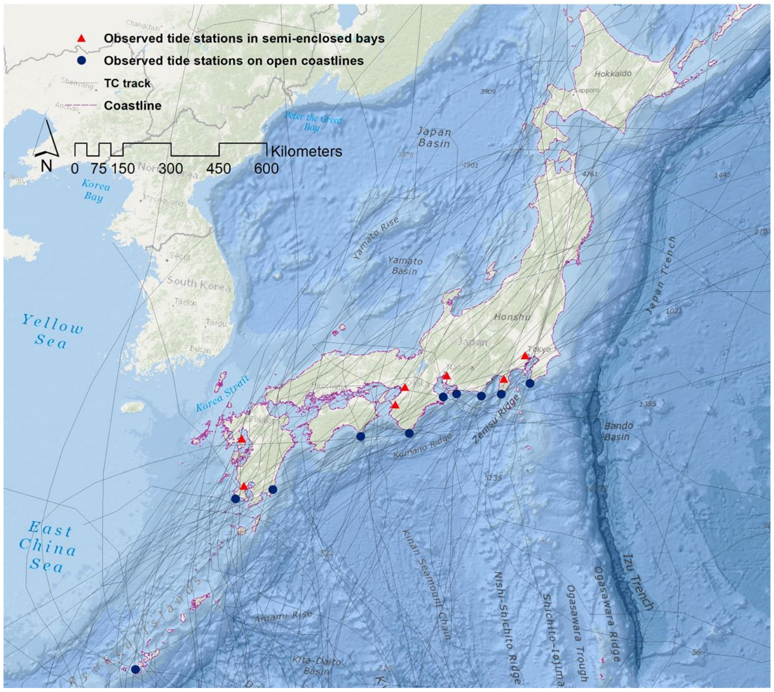

Fig 1. Best track for historical TCs making landfall during 1978–2019 over the four major Japanese islands (Honshu, Shikoku, Kyushu, and Okinawa) based on data from the Japan Meteorological Agency.

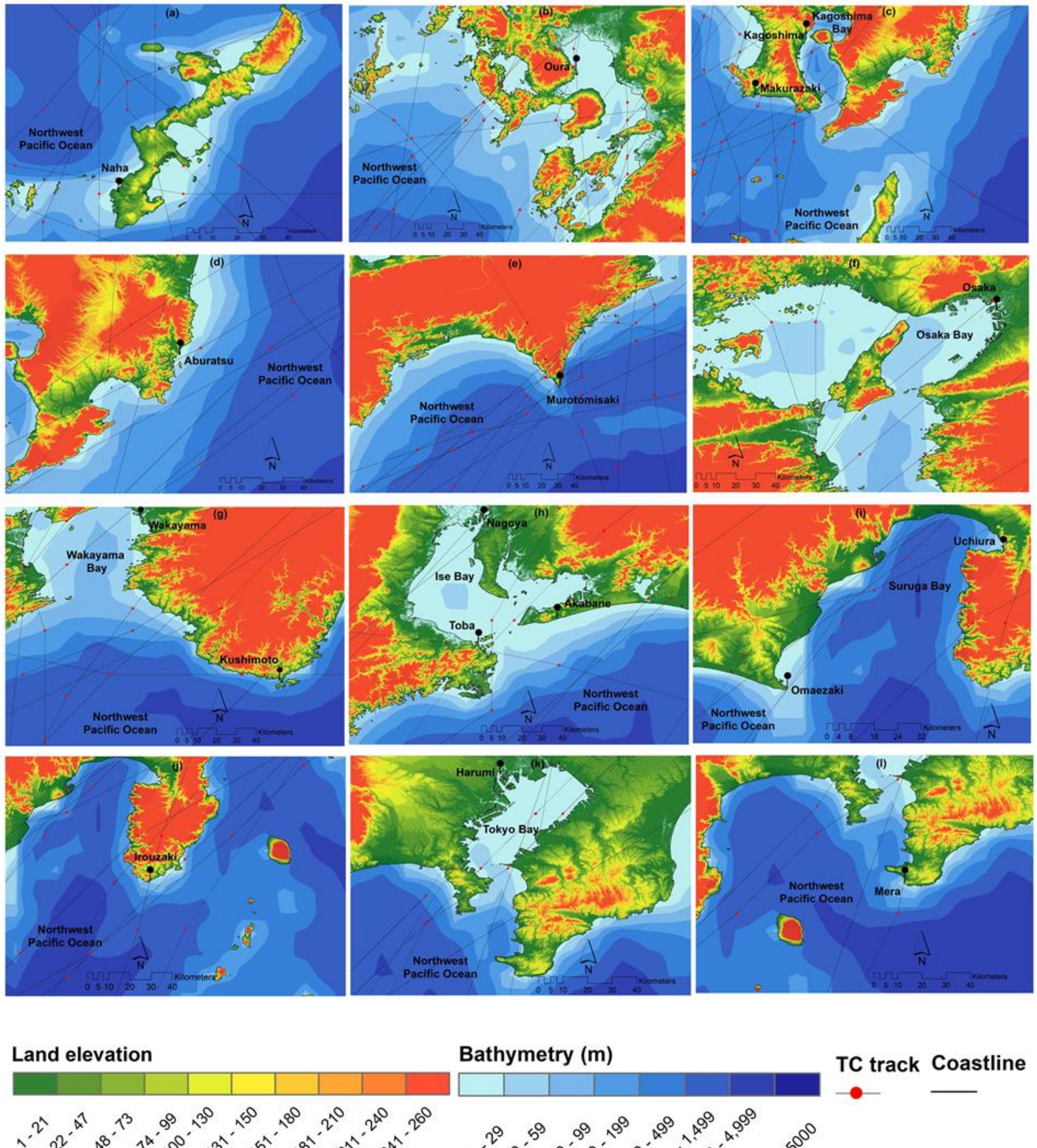

Fig 2. Location map of observed tide stations (a) Naha, Okinawa island; (b) Oura, Kyushu island; (c) Makurazaki and Kagoshima, Kyushu island; (d) Aburatsu, Kyushu island; (e) Murotomisaki, Shikoku island; (f) Osaka, Honshu island; (g) Wakayama and Kushimoto, Honshu island; (h) Toba, Nagoya, and Akabane, Honshu island; (i) Omaezaki and Uchiura, Honshu island; (j) Irouzaki, Honshu island; (k) Harumi, Honshu island; (l) Mera, Honshu island;

RESULTS

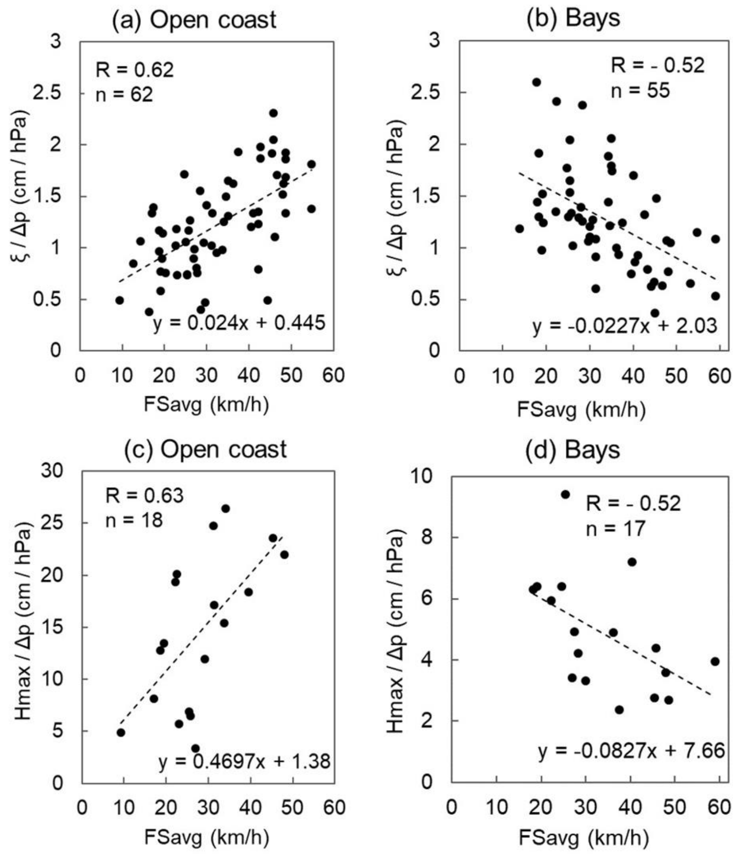

Fig 3. Observed TC surges (ξ) (waves (H_{max})) normalized by the central pressure deficit (Δp) versus the 12 h averaged forward speed before landfall (FS_{avg}) for (a & c) open coastlines and (b & d) bays. Dashed lines show the correlation gradient of the respective normalized surge (ξ) and FS_{avg}.

TC *pre-landfall forward speed is significantly correlated with maximum storm surge (wave) height. Coastal morphology was the determining factor for the correlation between storm surge (wave) and TC forward speed. Fast-moving TCs tended to amplify the storm surge (wave) along open coastlines, but reduce it in semi-enclosed bays (Fig 3).

*pre-landfall forward speed (FS_{avg}) and landfall forward speed both exhibited a similar result

For Fig. 3 (a, b), the influence of coastal morphology was most prominent for TCs with a central pressure lower than 956 hPa (Fig 4).

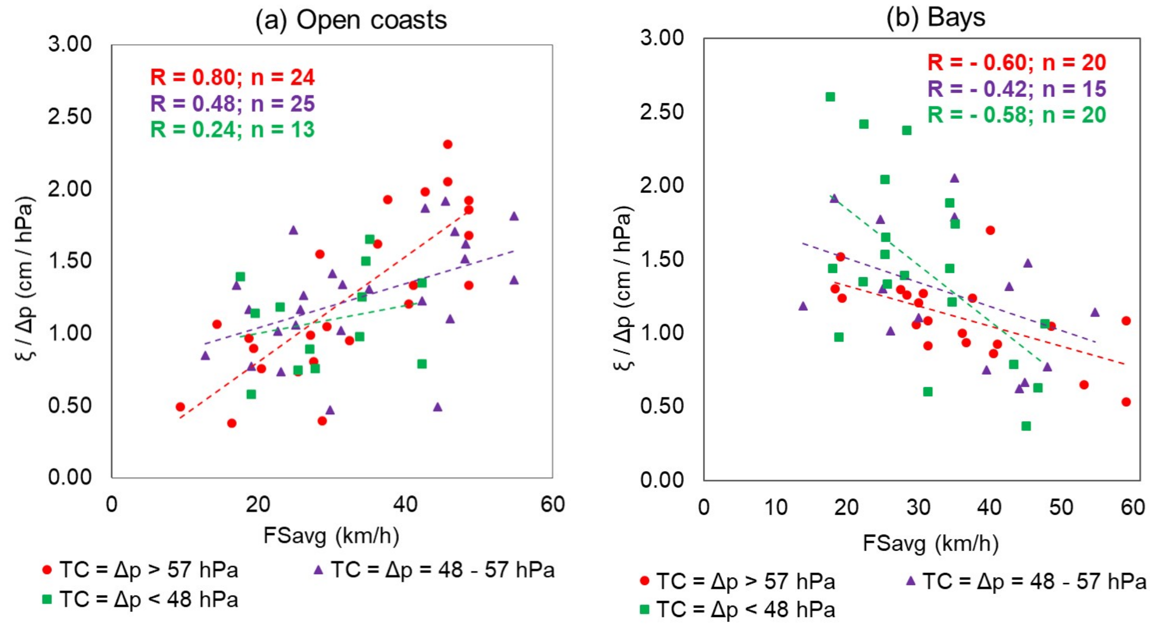

Fig 4. Normalized storm surges (ξ/Δp) versus the 12 h averaged TC forward speed (FS_{avg}), grouped by the central pressure deficit (Δp) for (a) open coastlines and (b) semi-enclosed bays. Dashed lines show the correlation gradient of the normalized surge and forward speed for each group.

Sensitivity of the statistical results

- Correlations corresponding to the 6 h averaged pre-landfall forward speed, 6 h, and 12 h prior to landfall forward speed, were calculated to explore whether any other definition of forward speed would provide better correlations compared to FS_{avg}. These results did not vary markedly from the statistics presented in Fig 3.

- Correlations corresponding to the database but excluding the outliers were made to ensure that the outliers were not skewing the R statistics shown in Figure 3. The resulting R did not change significantly.

DISCUSSION

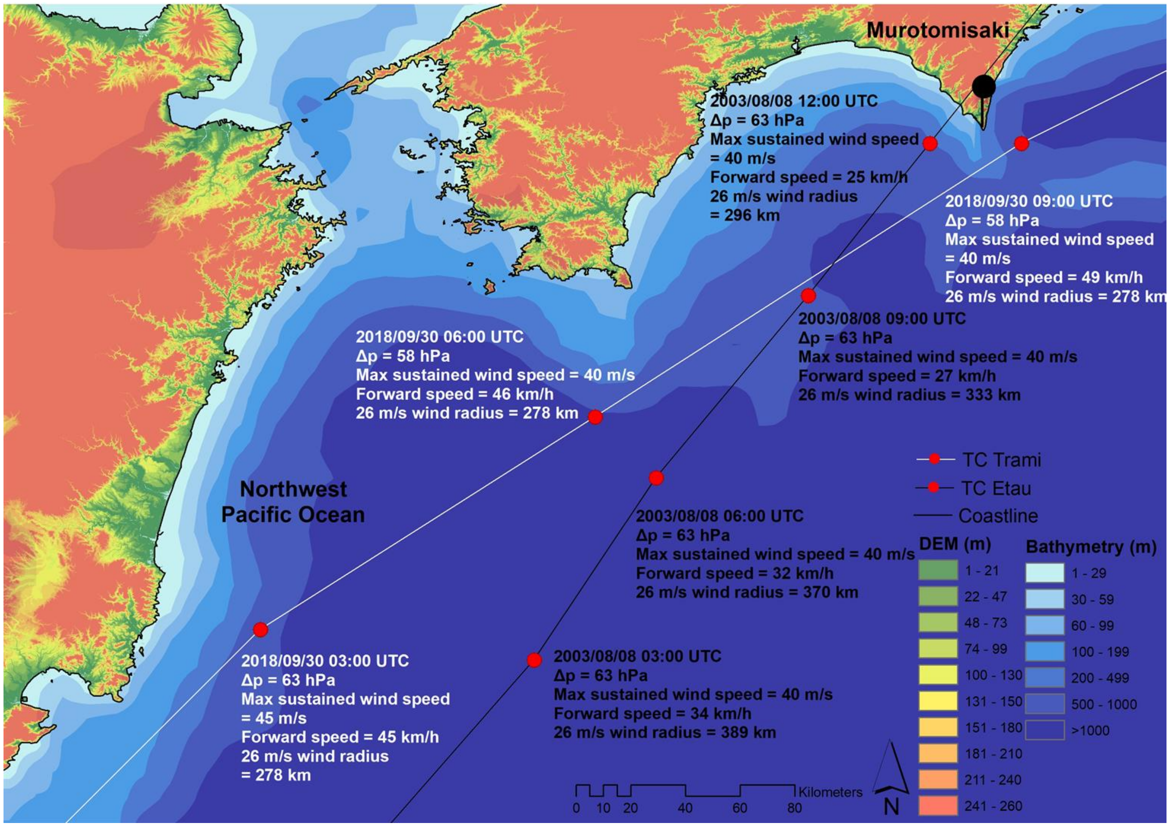

Fig 6. TC Trami (2018) and Etau (2003) as it approached Murotomisaki

- Faster TCs tend to generate greater storm surges which is consistent with the idealized TC studies (e.g. Jelesnianski 1972; Rego and Li 2009; Thomas et al. 2019).

- TCs with a FS_{avg} > 34 km/h (average FS_{avg} of TCs that made landfall in Japan = 34 km/h) generated an average surge height of 0.84 m, while TCs with $FS_{avg} \leq 34$ km/h produced an average height of 0.52 m at open coastlines.

- TC Trami at Murotomisaki: storm surge (wave) = 1.15 m (historically highest) (9.5 m); TC Etau at Murotomisaki: storm surge (wave) = 0.66 m (7.5 m).

- Energizing a shelf wave; storm surges could be amplified when the TC translation speed was similar to the propagation speed of the long wave (linear theory by Proudman (1952)).

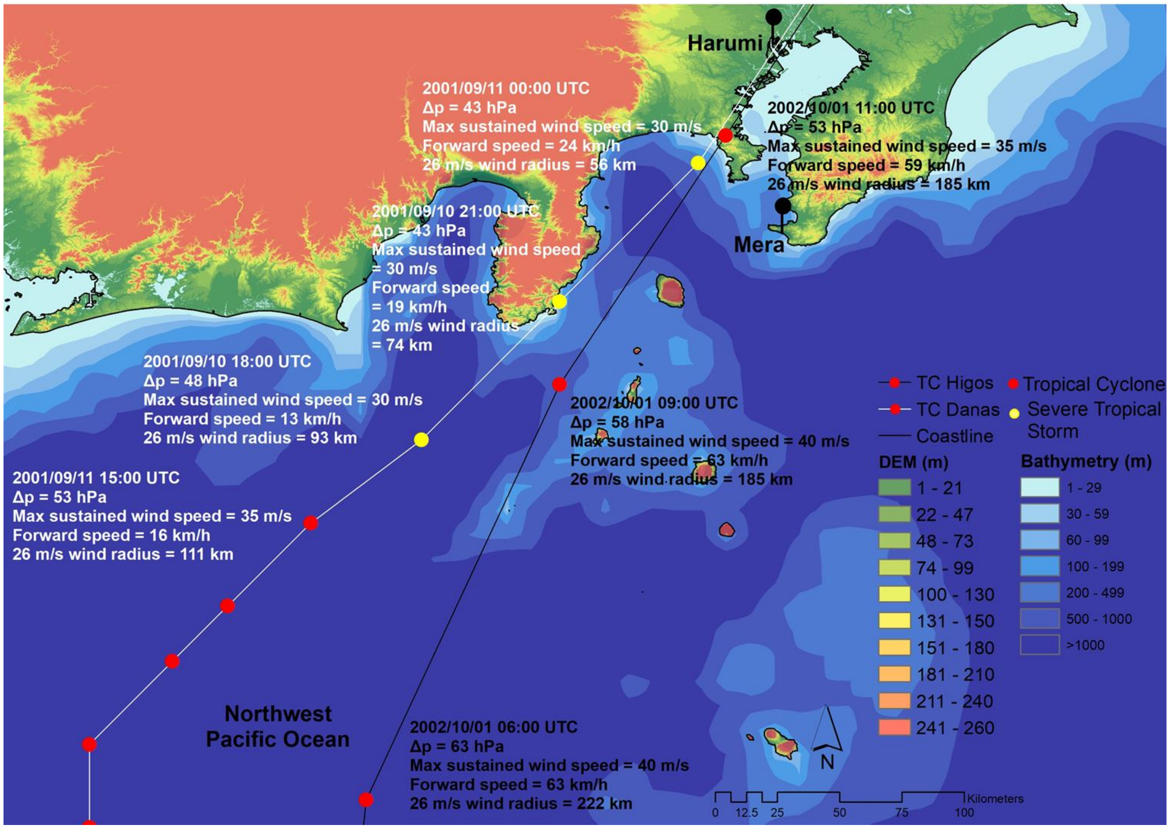

Fig 7. TC Danas (2001) and Higos (2002) as it approached Harumi

- A slower TC can generate a higher surge in a semi-enclosed bay. This agrees with the previous idealized TC studies (Peng 2004; Weisberg and Zheng 2006; Islam and Takagi 2020), but is contrary to the results of Rego and Li (2009) and Wei et al. (2019).

- TCs with a FS_{avg} ≤ 34 km/h generated an average surge height of 0.74 m, while TCs with a FS_{avg} > 34 km/h produced an average height of 0.56 m in semi-enclosed bays.

- TC Danas at Harumi: Storm surge (wave) = 1.12 m (3.1 m); TC Higos at Harumi: storm surge (wave) = 0.63 m (2.29 m)

- TC wind act is larger at the effective cross-shore shallow area; the time scale for mass redistribution within the shallow and geometrically complex estuaries is in the order of hours and somewhat longer than along the open coasts.

- This phenomenon is contrary to the general perception that the coincidence of wind and forward speed vectors generate a larger storm surge.

- However, not all fast/slow-moving TCs generate a higher peak surge because other factors may drive surge variability.

CONCLUSION

- Considering TC transitional speed and coastal geometry-meteorologists and oceanographers could provide more comprehensive surge-wave forecasts, and emergency management personnel could use pre-landfall average forward speed for more precise early warning.

- Coastal areas with no access to advanced weather forecasting models could use these empirical findings along with other TC intensity-related information to estimate the maximum surge-wave heights and improve evacuation plans.

Future work

- Examining the influence of changes in geographic location (i.e., for another country or globally)

- Conducting numerical experiments

- TC forward speed vs coastal flooding volume

DISCLOSURES

No potential conflict of interest was reported by the author(s).

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ABSTRACT

Over the past several decades, scientists have focused on numerical sensitivity analysis to explain the relative importance of tropical cyclone (TC) forward speed on storm surge and wave height predictions. These past studies performed numerical analyses, but the results have not been sufficiently compared with long term observations. In this study, 42 years of tidal records and landfall TC best tracks in Japan were analyzed, demonstrating that TC pre-landfall forward speed is significantly correlated with both maximum storm surge and significant wave height. Coastal horizontal morphology was the determining factor among these correlations. Fast-moving TCs tended to amplify the storm surge along open coastlines (Pearson correlation coefficient, R = 0.62), but reduce it in semi-enclosed bays (R = -0.52). A similar tendency has also been observed for the case of wave height (open coast, R = 0.63; bay, R = -0.52). The negative correlation contrasts with the general perception that the coincidence of TC wind speed and forward speed vectors generates a larger storm surge. The influence of coastal morphology was most prominent for TCs with a central pressure lower than 956 hPa. Tropical cyclone operational forecasts are continuously improving; however, there is still scope to improve the precision of storm surge - wave predictions. These findings may be beneficial in two main areas. Firstly, considering TC transitional speed and coastal geometry (open coastline or bays) - meteorologists and oceanographers could provide more comprehensive surge-wave forecasts, and emergency management personnel could use pre-landfall forward speed for more precise early warning. Secondly, coastal areas at risk with no access to advanced weather forecasting could use these empirical findings along with other TC intensity related information (e.g., wind speed, central pressure, radius) for improvement of early-warning activities.

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