B213

Scenario-based Evaluation of Coastal Flooding and Economic Loss under Typhoon Intensity

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Introduction

Changes in typhoon intensity are known to strongly influence storm surge heights in coastal regions, and numerous studies have focused on quantifying this relationship. However, surge amplification alone does not fully explain real flood damage, because actual losses increase abruptly once flood defenses and coastal protection facilities are exceeded. In other words, while storm surge responds continuously to typhoon intensity, inundation and economic damage often exhibit threshold-driven, nonlinear behavior. This gap indicates that analyses based solely on typhoon intensity or surge height are insufficient for evaluating coastal hazard risk. Therefore, this study aims to investigate the cascading amplification from typhoon intensity to storm surge, inland inundation, and ultimately economic loss. A scenario-based numerical framework is applied to Tokyo Bay, Japan, to clarify how incremental changes in typhoon intensity can trigger disproportionate increases in flooding and damage once critical defense limits are surpassed.

Method

A coupled modeling system was developed using the WRF model for meteorological forcing and the JAGURS-surge model for storm surge and inundation simulation. Typhoon Faxai (2019) was selected as the control (CTL) run for all scenario-based simulations. **Figure 1** illustrates the historical relationship between minimum pressure and maximum wind speed. Based on this relationship, twenty-four intensity scenarios were generated by systematically varying pressure and wind speed from –50% to +30% in 10% increments. These scenarios include pressure-only (green dashed box), wind-only (blue dashed box), and combined pressure-wind cases (red dashed box). High-resolution nested grids (up to 90 m) were used to capture localized flooding processes. For each scenario, peak surge height, inundation area, and inundation depth were calculated and translated into grid-based economic losses using national damage estimation guidelines, enabling a direct evaluation of the full damage cascade.

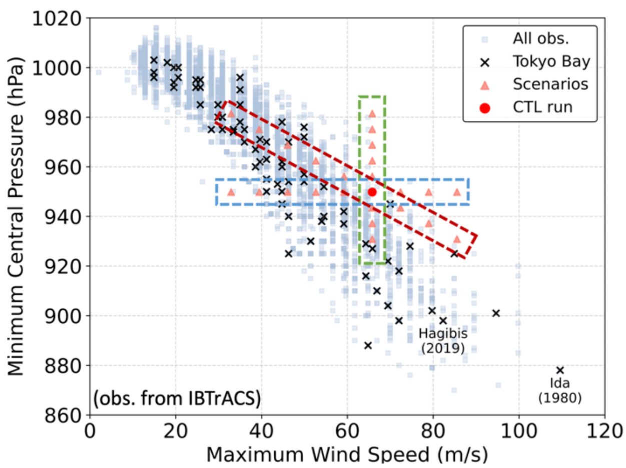

Fig 1. Typhoon intensity scenarios based on pressure-wind relationships

Results and Discussion

Scenario experiments show that changes in typhoon intensity propagate through the coastal system in a strongly nonlinear manner. Wind speed variations produced localized surge amplification within Tokyo Bay, while pressure changes mainly caused broad, basin-scale water level shifts. When both effects were combined, surge heights increased beyond the linear sum of individual contributions, highlighting nonlinear surge dynamics under intensified forcing.

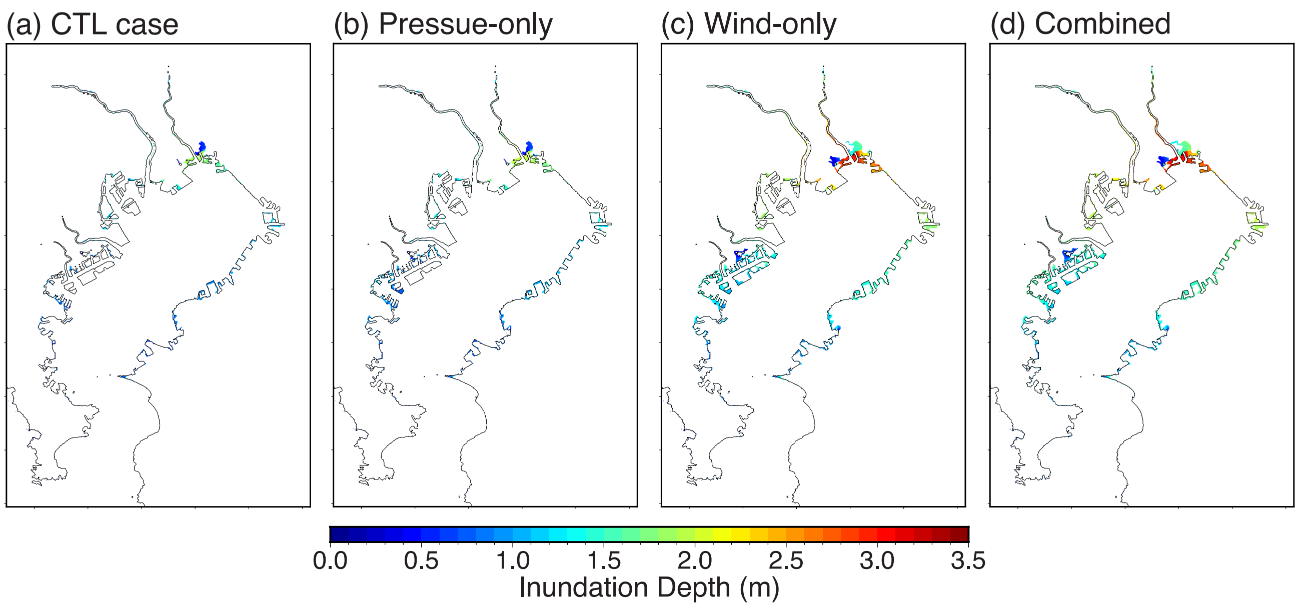

Fig 2. Spatial distribution of inundation depth for CTL, pressure-only, wind-only, and combined scenarios.

However, the most significant amplification occurred not at the surge level but during the transition from surge to inland inundation. Once water levels exceeded seawall crest heights, flooding expanded rapidly into low-lying urban areas, resulting in qualitative shifts in inundation patterns. **Figure 2** compares the inundation extent and depth under the extreme +30% intensity scenarios with the CTL case (**Fig. 2(a)**). Under the combined scenario (**Fig. 2(d)**), the inundation area more than doubled relative to the control case, and deep flooding (>2 m) propagated widely inland. This change in the inundation depth distribution, rather than inundation area alone, played a decisive role in the escalation of economic damage.

Figure 3 presents the cascading response of coastal flooding and economic loss to typhoon intensity variations. While surge height increased by 61.1% in the strongest scenarios, economic losses rose by 199.7%, indicating strong nonlinear amplification. A critical threshold emerged between +10% and +20% intensity, beyond which flood defense exceedance and deep inundation caused abrupt escalation of damage. These results demonstrate that coastal flood losses are controlled by threshold-driven processes rather than proportional surge amplification alone.

Conclusion

This study indicates that evaluating coastal hazard risk requires explicit consideration of the cascading amplification from typhoon intensity to storm surge, inundation, and economic loss. Scenario-based evaluations reveal that once protection limits are exceeded, damage increases abruptly and nonlinearly, even for moderate additional increases in intensity. These findings demonstrate the limitations of surge-only assessments and emphasize the necessity of integrated, scenario-based approaches for hazard risk assessment and adaptation planning in coastal megacities under climate change.

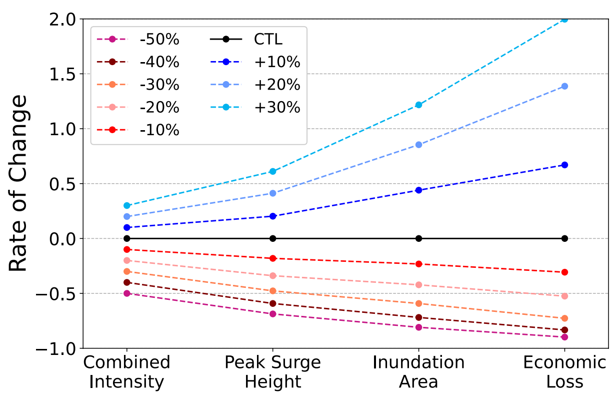

Fig 3. Cascading amplification from typhoon intensity to peak surge, inundation area, and economic loss