Assessment of Compound Flooding Risk in Ise and Mikawa Bays, Japan Using a Framework of Atmosphere-Ocean-River Coupling

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Abstract

The present study evaluated the compound flood risk of 11 different-sized rivers in the estuaries of the Ise and Mikawa Bays, Japan, using an integrated framework of atmosphere-ocean-river developed in this study. First, the framework was developed by incorporating the river channel into a coupled model of surge-wave-tide to include the interaction of the storm surge runup and river flow. In addition, the framework was validated by the Typhoon Trami (2018)-induced meteorological field, discharge, and storm surge with high accuracy. Then, the time difference between the storm surge and discharge at the estuary (TDSD) was investigated assuming six typhoons with different tracks and similar distributions of intensity and precipitation using Typhoon Hagibis (2019) as a case study. It was found that the TDSD reveals a high positive correlation with the length of the river channel (correlation coefficient: 0.90). Also, the smaller rivers were more prone to simultaneous storm surge and high river flow. The river with the smallest TDSD average in 6 cases of sensitivity experiments was 70 minutes, and it was clarified that the storm surge and high river flow occur simultaneously (within 15 min) in the most severe case (the smallest TDSD case). As a result, it was found that the small- and medium-sized river with a standard deviation of 49.5 minutes has a small TDSD regardless of the typhoon track, resulting in a higher risk of compound flood in comparison to the large-scale rivers with that of 102 minutes.

1. Introduction

Intense typhoons can cause storm surges that run up in rivers and overflow riverbanks, resulting in land floods. Such flood becomes severer when the storm surge runup coincides with peak river flows due to heavy precipitations. The simultaneous occurrence of two hazards is inferred to lead to compound floods (Wahl et al., 2015; Sebastian et al., 2021; IPCC, 2021). Wahl et al. (2015) reported that increasing tropical cyclone intensity increases the risk of the combined storm surge and river flood in the coastal area. Sebastian et al. (2021) pointed out that conventional risk assessments cannot adequately qualify the precipitation and storm surge-induced compound flood and may underestimate the damage. The Intergovernmental Panel on Climate Change AR6 (IPCC, year) also highlights the urgent need for countermeasures against compound flooding.

The Northwest Pacific Ocean is one of the most active areas for typhoons. In particular, the number of typhoons making landfall in Japan and approaching 300 km off Japan is three per year and 11.7 per year since 1991, respectively, according to Japan Meteorological Agency (JMA). Among the historical typhoons, Typhoon Jebi in 2018 generated a record-breaking 3.29 m storm surge height in the Osaka Bay area, while Typhoon Nancy (1961) produced the previous highest surge height of 2.93 m in the Bay (Mori et al. 2019). Mori et al. (2019) reported that Typhoon Jebi produced multiple hazards-induced floods: wave overtopping/runup, river overflow, surge overflow, surge runup in rivers, sewer backflow, and high wave, for instance. The Jebi-induced surge ran up the Yodogawa River, and its water level approached the embankment height by approximately 1 m. This event clearly demonstrates the compound flood risk of the storm surge and river flow in Osaka Bay (JMA, 2018; Mori et al., 2019). Although compound flooding by storm surge and river flow has not occurred, Typhoons Faxai and Hagibis in 2019 caused serious
disasters in Japan in recent years (Shimozono et al., 2020; Suzuki et al., 2020). Faxai induced a record-breaking storm disaster that occurred mainly in Chiba Prefecture, causing a large-scale power outage (JMA, 2019). Furthermore, flood damage due to waves and storm surges occurred in the coastal area of Kanagawa Prefecture. Hagibis recorded the highest historical total precipitation observed at 613 locations in northern and eastern Japan (JMA, 2019). The Hagibis induced storm surge and -wave inundated coastal areas and made roads to be sunk in Shizuoka Prefecture.

Typhoon disasters are becoming more serious, and it is not surprising for compound floods to occur at any time. In addition, Japan is considered to have a high risk of compound flood owing to its topographical characteristics. Rivers in Japan have an extremely high river regime coefficient due to their steep topography and are characterized by a rapid rise in water level due to precipitation associated with typhoons. In addition, the three major bays (Ise, Tokyo, and Osaka Bays) have the potential for large-scale storm surges because of their shallow terrains. Furthermore, because various small- and medium-sized rivers go through residential areas, it has been confirmed that the water level change and warning are critical issues for vulnerability to typhoons. Thus, the potential risk of compound flood due to the storm surge and high river flow in the Japanese coastal area is extremely high.

Several studies on compound floods have been conducted (e.g., Ikeuchi et al., 2017; Kumbier et al., 2018; Pasquier et al., 2019; Yin et al., 2021; Toyoda et al., 2021). Ikeuchi et al. (2017) conducted a flood simulation to investigate the simultaneous occurrence of storm surges and river flows in Bangladesh during Cyclone Sidr, reporting that the storm surge induced-inundation depth in the estuary increased by more than 3 m compared to the inland flood induced-one. In addition, it was found that the compound flood makes the inundation depth 0.7 m higher in the area farther from the estuary. Kumbier et al. (2018) also reported that storm surge and rainfall runoff for inundation evaluation during storms should be simultaneously considered for the 2016 storm event (south-eastern Australia, Shoalhaven estuary), clarifying that the inundation area and depth may be underestimated by approximately 30% (up to 1.5 m), if rainfall-runoff is not considered. Toyoda et al. (2021) targeted Typhoon Jebi (2018) which caused a severe storm surge runup at the Yodogawa River in Osaka Bay, Japan. They reported that it is essential to consider the impact of the storm surge runup in the river to evaluate the Jebi induced-combined inundation due to storm surges and river flow using a coupled surge and wave model and regional climate model that consider a storm surge runup in rivers.

However, these studies used insufficient methods in physics for the coastal area: ignoring the effect of the wave on the sea surface level and the effect of the topography on the meteorological field and focusing on only large rivers. In other words, the potential risk of the small and medium-sized rivers was not investigated. Furthermore, several studies (e.g., Mori et al., 2019; Yin et al., 2021) investigated the protection level of a large-scale river that is sufficiently set high, severe floods in the large river are unlikely to occur, except in extreme events. On the other hand, such compound floods in small and medium-sized rivers are not fully understood.
The purpose of the present study is to quantitatively evaluate the risk of compound floods during typhoons in the Ise and Mikawa Bays in Japan (Fig. 1a). To achieve this, first, we developed a framework (section 2) of surge, wave, precipitation, river flow, and wind and pressure using a coupled model of tide, surge and wave (SuWAT), dynamical meteorological model (WRF / HTM) and rainfall-runoff-inundation model (RRI). The typhoon meteorological field is simulated by the dynamical meteorological model, and rainfall-runoff is simulated by RRI, and these results are input to SuWAT to evaluate compound floods. The framework of the integrated atmosphere-ocean-river model was used to simulate river flows in 11 rivers in total (five large-scale rivers, and six small and medium-sized rivers). Then, we conducted a hindcast experiment (section 3) for Typhoon Trami (2018) and initial condition sensitivity experiments based on the Typhoon Hagibis (2019) on the difference between the typhoon track and peak times of storm surges and high river flow (section 4). The sensitivity experimental results from Yoshino et al. (2021) were used for the analysis in section 4. In the sensitivity experiments, typhoons with similar rainfall distributions and intensities were simulated on different tracks to clarify the possibility of the simultaneous occurrence of storm surges and river flows in each river and the difference in compound flood risk for each river scale.

2. A Framework Of Atmospheric-river-ocean

A framework of atmospheric-river-ocean was developed by combining a mesoscale meteorological model (Weather Research and Forecasting model, WRF, Skamarock et al. 2008; High-resolution Typhoon Model, HTM, Yoshino et al. 2012), rainfall–runoff–inundation model (RRI, Sayama et al. 2012) and coupled model of surge, wave and tide (SuWAT). The models in the framework were used to accurately hindcast the Typhoon Trami induced wind and pressure, rainfall runoff, and storm surges (Fig. 1). The integrated framework simulations are very costly. In addition, the number of historical events is limited for analysis. For this reason, the evaluation was performed in addition to the results of ensemble experiments on Typhoon Hagibis. The sensitivity experiments to storm surge-river discharge based on Typhoon Hagibis were conducted using the results of typhoon track ensemble experiments by the HTM from the previous study (Yoshino et al. 2021). The two models of WRF and HTM were used to reproduce the wind and pressure fields induced by Trami and Hagibis, respectively. Section 4 describes the sensitivity experiments in detail.

2.1 Weather, Research, and Forecasting model (WRF)

The WRF model was used to simulate the meteorological fields of typhoons (Table 1). It is a non-hydrostatic mesoscale model developed by the National Center for Atmospheric Research (NCAR; Skamarock et al., 2008) and is used for a wide range of analyses of tropical cyclones (e.g., Ninomiya et al., 2017). In this study, Typhoon Trami was simulated using analytical data from the WRF model. We focused on the reproducibility of the typhoon intensity and track to evaluate the storm surge caused by Typhoon Trami.
Three nesting domains (D1, D2, and D3) were used as the WRF computational domains. D1 (7.29 km grid) covered almost the entire Japan region. D2 (2.43 km grid) was set up inside D1, and D3 (0.81 km) was set up inside D2. They were used to calculate the meteorological fields of storms at the Ise and Mikawa Bays at a higher resolution. The simulated period was from 0:00 UTC on September 28, 2018, to 0:00 UTC on October 2, 2018 (section 3.1). The initial and boundary conditions were the final analysis data (FNL) of the National Centers for Environmental Prediction (NCEP) on a 0.25-degree grid. High-resolution merged satellite data, and in-situ data of Global Daily Sea Surface Temperature (HIMSST, JMA 2016) were used as the sea surface temperature (SST) data, which were interpolated every 6 h (original temporal interval is daily, and horizontal resolution is 0.1°). Therefore, NCEP FNL data were used as the atmospheric field, and HIMSST was used as the SST in this study. Further details of the simulation settings are presented in Table 1.

2.2 A high-resolution typhoon model (HTM)

In sensitivity experiments (section 4.2), the HTM was used to simulate typhoon tracks based on Typhoon Hagibis as the dynamical meteorological model (Table 2). The HTM, a type of RCM, is developed for sensitivity experiments on typhoon tracks (Yoshino et al., 2012; Yoshino et al., 2015). The HTM is based on the Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Fifth-Generation Mesoscale Model (MM5) (Dudhia 1993) and is a three-dimensional, nonhydrostatic, fully compressible, cloud-resolving atmospheric model used to capture mesoscale and local scale meteorological phenomena. Additionally, several types of physical parameterizations were incorporated into the original MM5. Particularly, ocean mixed layers (Shade, 1999; Emanuel et al., 2004), dissipative heating (Bister et al., 1998; Zhang et al., 1999), and sea spray processes (Fairall et al., 1994; Wang et al., 2001) have been implemented to express realistic typhoon intensity and structural characteristics accurately. The accuracy of HTM has already been proven in previous studies (e.g., Toyoda et al., 2022). Toyoda et al. (2022) conducted replication and pseudo-global warming experiments for 49 typhoons that made landfall in Japan from 2000 to 2017 and reported that the reproducibility of the HTM was very high and that both weak and strong typhoons could be reproduced.

Two typhoons, Trami and Hagibis, were taken in the sensitivity. Typhoon Trami has an easterly track and is less likely to cause large storm surges 2 m high in Ise Bay, even when several tracks are considered. Therefore, Hagibis was selected as the case study for the sensitivity experiments because its northerly track caused heavy rainfall and storm surge. Although different typhoon cases are used, we believe the results are consistent on the compound flooding risk assessment of storm surges and high river discharges in both typhoon cases.

2.3 Computational configuration for rainfall-runoff

In the present study, 11 rivers were selected as the target rivers (Fig. 1). Five were large-scale rivers, and the others were small and medium-sized rivers. All river flows were simulated using the rainfall-runoff-inundation model (RRI). The RRI model is an integrated 2D hydrological and hydraulic model developed by Sayama et al. (2012), simulating rainfall-runoff and flood inundation simultaneously. The model can
simulate discharge using rainfall data. In the RRI model, the flow on the slope grid cells and the river channel are calculated using 2D and 1D wave-diffusive models, respectively. The model also simulates lateral subsurface and vertical infiltration with surface flows.

Because of the steep slope in mountainous regions, the lateral subsurface flow is more important, so it was calculated as a discharge-to-hydraulic-gradient relationship. The vertical infiltration flow was estimated using the Green-Ampt model (Rawls et al. 1992). The model calculating the slope grid cell flow uses mass balance and momentum equations for a gradually varying unsteady flow. The flow in the river grids was calculated using a 1D wave equation. The cross-section of the river was assumed to be rectangular, with width $W$, depth $D$, and embankment height. The width and depth parameters were determined through the upstream contributing area $A$ (km$^2$) of Equations (1) and (2).

$$W = C_w A^{sw}$$

1

$$D = C_d A^{sd}$$

2

The simulation results of the RRI were sensitive to the cross-sectional parameters of the river. The river width parameters at each estuary site were obtained from Google Earth and the depth and catchment area were provided by administrations. The Ibigawa/Nagara rivers and the Gojo/Shinkawa/Syonai rivers are located in the same basins. Therefore, the same settings were used for those basins. For the detailed river parameters, the configuration identified from land use data was used (Table 3).

The topographical data input in the RRI simulation included the digital elevation model, flow direction, and flow accumulation pixels obtained from the J-FlwDir (Yamazaki et al., 2018). This database provides data with resolutions of 1 and 3 arcsec. In the current study, the 3 arcsec data were used for the large-scale rivers, and the 1 arcsec data were used for the small and medium-sized rivers. In addition, land information mesh data (100 m grid) from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) were used for the distribution of land-use (https://nlftp.mlit.go.jp/ksj/index.html). The default land use is classified into 12 types. However, in order to facilitate the calibration of the parameters, we consolidated them into the five types during the calculation: rice paddy, farmland, mountain, urban, and water area (Konja et al. 2019).

The simulation period in the hindcast experiment in section 3.2 was 17 days, from September 15, 2018 to October 2, 2018. The simulation period in the initial condition of the sensitivity experiments in section 4.2 was four days, from October 9, 2019 to October 13, 2018. Each simulation has a period for a spin-up calculation of more than one day. In the sensitivity experiments for the track estimation, a spin-up is shortly set in a range that does not disrupt the calculation accuracy due to the limitations of the HTM simulation setup.
The eXtended Radar Information Network (XRAIN) was used to estimate precipitation volumes, provided by the Data Integration and Analysis System (DIAS) with a resolution of 250 m grid at 10-minute intervals. Although it is possible to obtain precipitation data from the WRF, their time-series values were highly biased by the model. Therefore, XRAIN was used in the hindcast experiment to reproduce the rainfall-runoff with high accuracy. Evapotranspiration was given as an approximate daily average of 2 mm/day in the Chubu region, according to Kobatake (1989). Although this setup is coarse, it has been confirmed that the values do not significantly affect the calculation results.

2.4 Computational configuration for surge-wave coupling model

The storm surge was calculated using the coupled model of surge, wave and tide (SuWAT) developed by Kim et al. (2015). The SuWAT model is based on a nonlinear shallow water equation that considers atmospheric pressure-driven surge, wind stress, and wave radiation stress. Six domains nesting were used with spatial resolutions of 7290 m (D1) to 30 m (D6). The storm surge model considered the wave-induced forces from the radiation stress in the momentum. The calculation domains of D1 to D4 are common, while the domains of D5 and D6 cover the Ise and Mikawa Bays, respectively (see Figs. 1b and 1c). The bathymetry was grided using the terrain data from the Central Disaster Prevention Council. The 11 river channels were incorporated in the innermost domain in order to calculate the surge runup in the rivers imposed by river flow rates from the upstream rivers. The simulation period was from 0:00 UTC on September 29, 2018, to 0:00 UTC on October 2, 2018 (section 3.3), and was from 0:00 UTC on October 10, 2019, to 0:00 UTC on October 13, 2019 (section 4.2) for Typhoons Trami and Hagibis, respectively. In addition, a 24-h spin-up calculation was conducted before the start of the main simulation. The meteorological field to be input was the WRF pressure and wind fields output values (10-min intervals), and the RRI output was set as the lateral boundary condition (10-min intervals). The radiation boundary condition proposed by Flather (1994) was applied to the boundary between the RRI and SuWAT following the method of Kim et al. (2011). A seamless connection was achieved by converting the constantly changing discharge calculated from the RRI into the water level according to the river channel topography (river width and water depth) in the SuWAT using Eq. (3).

\[ H_t = \frac{Q_t}{\Delta t \times Width \times Depth} \]

where \( H_t \) (m) is the converted water level at time \( t \), \( Q_t \) (m\(^3\)/s) is the river flow at time \( t \) (output from RRI), \( \Delta t \) (sec) is the simulation time step, \( Width \) (m) is the river width (30 m multiplying the number of meshes), and \( Depth \) is the river depth at the boundary mesh. In addition, the coupling between the two models is unidirectional from RRI to SuWAT. Note that SuWAT considers the astronomical tide for the hindcast experiment, but its impact was very small. In addition, exclude the impact of the astronomical tide for sensitivity experiments because these experiments are not the real case. Therefore, it is discussed only the water level anomaly excluding the astronomical tide level in this study.
By combining the meteorological, rainfall-runoff, and wave/storm surge models described above, it is possible to build an integrated atmosphere-sea-river model and solve the precipitation and storm surges associated with typhoons (Fig. 2). The following is a description of our simulation framework: 1) First, the meteorological model is prepared for the typhoon meteorological field; 2) Next, each time step of rainfall distribution in the meteorological field is used to simulate the rainfall-runoff using RRI. This process is performed for each watershed. 3) The meteorological fields and hydrographs prepared in Steps 1) and 2) are forced to SuWAT as input and boundary values. The above three steps consist of the framework that assesses the compound flood due to the storm surge and high river flow in the coastal urban area. Note that the three models are offline coupled in this study.

### 2.5 Outline of hindcast and ensemble experiments

Two different simulations were carried out in this study. Sections 3 and 4 describe the numerical experiment in detail: Section 3 discusses the results of the hindcast experiment for Trami, and Section 4 investigates the results of the sensitivity experiment for Hagibis.

The objective of Section 3 is to confirm the validation of the RRI and SuWAT. We used the WRF meteorological field in this experiment to calculate the wave and storm surge. On the other hand, XRAIN was used to obtain the time series of precipitation because the WRF-estimated precipitation has a large bias, such as peak time deviations and inconsistency of distribution, and it is concerned with the large uncertainty in the RRI. Hence, in Section 3, XRAIN was used for precipitation, and in Section 4, the HTM results of all meteorological fields (precipitation, pressure, and wind) were used.

Section 4 evaluates the relationship between the typhoon track and the risk of compound flooding at the estuary. For this purpose, the results of sensitivity experiments on typhoon tracks using HTM by Yoshino et al. (2021) were applied. The sensitivity experiments assumed that Typhoon Hagibis passes Ise Bay and Mikawa Bay with various tracks. Hence, observational data such as XRAIN cannot be used when assuming a typhoon track that differs from a real track. Therefore, all meteorological fields must be simulated by a meteorological model. Previous studies (Yoshino et al. 2021; Toyoda et al. 2022) confirmed that HTM could accurately represent precipitation distribution, pressure, and wind fields. Therefore, the model bias is considered small, and the simulated results can be used as input values for RRI and SuWAT.

### 3. Results Of Hindcast Experiments

The section discusses the hindcast results of the meteorological field, river discharge, and storm surge in Ise Bay and Mikawa Bay during Typhoon Trami.

#### 3.1 Validation of meteorological fields

First, we confirmed the reproducibility of the typhoon intensity and track using WRF (Figs. 3 and 4). It was found that there were no significant differences between the simulated track in black in Fig. 3 and the
JMA best track in red, indicating that the typhoon track could be accurately reproduced. The WRF model well simulated Trami’s central pressure at each time in the best track: the simulated central pressure was 962.3 hPa at landfall. On the other hand, the observed one was 960 hPa. Next, we compared the simulated wind speed half a day before and after the typhoon’s closest approach to the six anemometer observations by the JMA (Fig. 4) installed along the Ise and Mikawa Bays. Although there were variations along the stations, the model results show trends revealing the wind speeds exceeding 20 m/s at sites near the typhoon center and wind speeds of 5 m/s or less at sites far from the typhoon one. Because the stations were scattered on the east and west sides of the typhoon track, it can be said that a certain degree of accuracy is guaranteed at any point. The bias error was 1.04 m/s, the root mean square error was as small as 3.56 m/s and the correlation coefficient was as high as 0.78. As a result, the reproducibility of the typhoon meteorological field by the WRF is high.

3.2 Validation of rainfall runoff and river discharge

In the eleven rivers targeted in this study, the simulated peak river discharges of five rivers (Ibigawa River, Nagara River, Kisogawa River, Syonai River, and Toyogawa River) were validated with the observed values as listed in Table 4. The observation stations are Mangoku (Ibigawa River), Sunomata (Nagara River), Okoshi (Kisogawa River), Biwajima (Syonai River) and Tougo (Toyogawa River). It was found that the river discharge peaked after the passage of the typhoon in all five rivers. All these rivers are large in scale and have large catchment areas. The Kisogawa River has the largest catchment area, so it reached its peak discharge approximately half a day after the passage of the typhoon. The peak discharges of all rivers estimated by the RRI were relatively close to the observed peak ones. Although the errors were large at the stations of Mangoku (approximately 20%) and Sunomata (approximately 10%) in the same river basin and other rivers could be reproduced with high accuracy (averaged error: 10.7%). In addition, because the peak times of all rivers well simulated the observations (error was within 1 h), the accuracy of RRI using XRAIN was judged to be sufficiently reliable.

3.3 Validation of storm surge at the Ise and Mikawa Bays

Based on the simulation result in Sections 3.1 and 3.2 described above, the SuWAT results are discussed (Figs. 5 and 6). Figure 5 shows the distribution of the water level deviation in Ise Bay (Fig. 5a) at 12:30 UTC and in Mikawa Bay (Fig. 5b) at 14:10 UTC, September 30, 2018, calculated by the high-resolution of 30 m with seawalls and embankments. The complex coastlines are represented in detail. In addition, the river water flowing from the boundary to the river mouth can be observed. The peak surge anomaly were approximately 1.4 m and 2.0 m in Ise and Mikawa Bays, respectively. The storm surge anomaly was almost uniform, with no difference between the river mouths.

In the time series of the water levels at the estuary of each river (Fig. 6), there was no significant difference between the simulated (solid line) and observed ones (dotted line). Here, the rivers that installed the water level gauge at the estuary are indicated in Fig. 6 (note that some rivers have no measurements). In addition, the observed water level here are the values at 10-min intervals at the river mouth and have not been scrutinized data. The storm surge peak in Ise Bay was around 12:30 UTC on
September 30, and that in Mikawa Bay was at approximately 14:10 UTC on September 30. The calculated peak surge level is generally consistent with the observed one, and the error is within 20 min. Therefore, it can be said that the generated storm surge could be reproduced with high accuracy. The accuracy dropped slightly after the storm surge peak, but it was due to errors coming from the river flow from the boundary. On the other hand, a second peak due to the high-water level was seen at 18:00 in the simulated river flow approximately 3 km upstream from the Toyogawa River estuary (see Fig. 6b; Toyobashi). This phenomenon could not be reproduced by the storm surge model alone, however it was enabled to be reproduced with high accuracy by integrating the river flow in the storm surge model.

Next, we investigate the possibility of a compound flood under Typhoon Trami. Figure 7 shows time series of water level and discharge in adjacent large-scale rivers and small- and medium-sized rivers in Ise Bay and Mikawa Bay. Nanashima (Shinkawa River), Touchi (Syonai River), and Minami shibata (Tenpaku River) are located on the coast of Ise Bay. Among them, Touchi is in Syonai river, which is a large-scale river as shown in Fig. 7a. Maeshiba (Toyogawa River), the Jinno-shinden (Yagyu River), and Osaki (Umeda River) are in Mikawa Bay. Toyogawa river is the largest river in Fig. 7b. In Ise Bay, the peak surge level at the estuary appeared at approximately 12:30 to 13:40 (Fig. 7a; lower). However, the peak discharge appeared after 15:00 (Fig. 7a; upper), although it varies with the river. The time difference between the storm surge and high river flow peaks was the smallest at the Minami shibata at approximately 70 minutes, followed by Nanashima at 110 minutes, and finally Touchi at 320 minutes.

It was shown in Mikawa Bay that the peak of the storm surge at the river mouth and the peak discharge both appeared at approximately 14:10 (Fig. 7b; lower and upper, respectively), while the peak discharge at Osaki appeared at approximately 14:40 and Maeshiba at approximately 18:10. The time difference between the storm surge and river flow peaks was the smallest at the Jinno-shinden within 10 min (almost simultaneously), followed by Osaki (approximately 30 minutes), and finally, Maeshiba (240 minutes).

Fortunately, the Trami’s storm surge level was small, 1.4 m at the Ise Bay and 1.9 m at the Mikawa Bay (the historical maximum storm surge level was over 3 m due to Typhoon Vera (1959)), and the compound flood did not occur. However, in the Tenpaku, Yagyu, and Umeda Rivers, the upstream discharges were also large when the storm surge anomaly at the river mouth was large. Yagyu River had a peak at almost the same time, suggesting that the compound flood risk was extremely high. The time difference between the peak storm surge and maximum river discharge was significant in Syonai and Toyogawa Rivers, classified as a large-scale river. On the other hand, Yagyu River was the smallest urban river among the rivers dealt with, and there was the insignificant time difference between the peak storm surge and river flow. Thus, it is considered that the time difference between the maximum level of the storm surge and river flow is strongly correlated with the river scale. The result indicates the potential risk that the storm surge may coincide with the high river flow in the estuary of the small-scale river.

4. Sensitivity Experiments On Peak Time Difference For Storm Surge And Flooding
Section 3 showed that the large-scale rivers tend to have the large difference in the peak time between the storm surge and high river flow, while the small rivers tend to have a small difference. To verify whether this trend is characteristics of the estuaries of Ise and Mikawa Bays, a series of sensitivity experiments was conducted using Typhoon Hagibis (2019) on multiple tracks, using the high-resolution typhoon model (HTM) developed by Yoshino et al. (2012) instead of the WRF. Past cases have shown that storm surges in Ise Bay and Mikawa Bay tend to be larger by typhoons with a northward track (Aichi Pref. Japan, 2021).

4.1 Computational configuration of HTM

Sensitivity experiments to the typhoon track by HTM were originally conducted to evaluate the precipitation distribution and future change in the case of Hagibis hitting the central region of Japan (Yoshino et al. 2021). In the previous study, precipitation by HTM adequately evaluated precipitation by Hagibis comparing from observed value by JMA.

In our study, we extracted 6 cases that cause storm surges in Ise Bay and Mikawa Bay from a total of 61 cases previous study (Yoshino et al. 2021) to evaluate the relationship between typhoon tracks and peak times of storm surges and high river flows (Fig. 8). In these experiments, the area around Japan was simulated at 9 km. In addition, the area in the Chubu region of Japan was simulated at 3 km. For other detailed simulation setups, please refer to previous studies (Yoshino et al., 2021; Toyoda et al., 2022). The HTM can provide the meteorological fields with high accuracy: in particular, the precipitation distribution has no bias. Therefore, the precipitation condition for RRI and the pressure and wind fields for SuWAT are simulated by the HTM (15-minute intervals). The simulation period was 75 h, including before and after the passage of the typhoon (approximately 55 h before and 20 h after the passage). In addition, all six tracks have intensities of 955 to 965 hPa at the time of landfall. The accumulated rainfall is 300 mm in mountainous areas and 100 mm in plain areas (Fig. 9). Using this simulation result, we clarified the compound flood risk by determining the time difference between the storm surge and discharge (TDSD) in each river.

4.2 Results and discussion of sensitivity experiments

Table 5 summarizes the storm surge and discharge peaks for all cases. Note that storm surge here means a storm surge anomaly and ignores the effect of astronomical tide levels. In addition, Nagara River and Ibigawa River conflux near their river mouses where is called "Jonan". Similarly, the Gojo River joins the Shinkawa River, represented by "Nanashima" at its estuary. The yellow-colored cases in the table indicate that the river flow peak did not reach the estuary during the simulation period. Hence, the final time of the simulation period was considered the peak time of the discharge. The red colored number indicates the highest storm surge case or the highest river flow case for each river. The Case 3 has the largest storm surge height in all the rivers. The Case 3 has a track passing from the south to the north on the west side of Ise Bay, and the wind-driven effect was remarkable in the inner bay. The maximum surge level is 2.95 m at the Minami shibata (Tenpaku River). The maximum storm surges were approximately
2.5 m at Nanashima (Shinkawa River) and Touchi (Syonai River), near the port of Nagoya. In Mikawa Bay, a storm surge of more than 2 m was generated by the continuous westerly wind. The storm surge was extremely small at Umenogoh (Nikko River) because the water level gauge point was inside the sluice gate of the estuary. The floodgate was implemented as topography, assuming that they were almost closed. Thus, the storm surge was smaller than that at other locations. These results indicate that the pathways, tending to cause large storm surges in the Ise and Mikawa Bays, were similar. However, the peak discharge rate varied with each case and river. As listed in Table 5, the maximum river-water level occurred in the Case 3 for Jonan (Ibigawa River), in the Case 5 for Yokomakura (Kisogawa River), Touchi (Syonai River), and Minami shibata (Tenpaku River), in the Case 4 for Umenogoh (Nikko River), Nanashima (Shinkawa River), and in the Case 6 for Maeshiba (Toyogawa River), Jinno-shinden (Yagyu River), and Osaki (Umeda River), respectively. The magnitude of river discharge in the estuary varies with the typhoon track because it is affected by both the distribution of precipitation and river size.

Next, the time difference between the peak storm surge and discharge (TDSD) is discussed concerning the river channel extension (RCE). Figures 10 and 11 show scatter plots of TDSD on the vertical axis and RCE on the horizontal axis. Figure 10 shows the results of the sensitivity experiments, where the color of the marker indicates the peak discharge rate. In addition, Fig. 11 shows the observed TDSD of the recent five typhoons that generated storm surge anomaly larger than 1 m in Ise and Mikawa Bays. The same-colored marker indicates the time difference obtained from the identical typhoon. The same symbols point out the same river. Figure 10 indicates that Kisogawa River (square), which had the longest RCE, tends to have a large TDSD on average. On the other hand, Shinkawa River (right-pointing triangle), Tenpaku River (left-pointing triangle), Yagyu River (diamond), and Umeda River (hexagon) with a small RCE tend to have a small TDSD. In particular, in Yagyu River, the average TDSD of all six cases is 70 minutes. Among the TDSDs, the minimum was 15- minutes. Hence, the risk of compound flooding was extremely high. The average TDSD was 614.1 minutes for the large-scale rivers and 180.4 minutes for small and medium-sized rivers, indicating that the high river flows in the small and medium-sized rivers reach the river mouth three times faster than ones in the large-scale rivers. Furthermore, these results indicate that the high river flow in the large-scale river reaches the estuary after the passage of a typhoon because it has a long RCE. On the other hand, the high river flow in the small and medium-sized rivers reaches its mouth after the typhoon's immediate passage from the time of the closest approach of the typhoon. In addition, these similar trends can also be found in Fig. 11, which were created from the observed values. The correlation coefficient between TDSD and RCE is 0.9, indicating a strong positive correlation. Therefore, it can be said that the smaller the river is, the higher the risk of compound flood.

In addition, we calculated the standard deviation between the TDSD and the river extension, the largest standard deviation was found from Syonai River (triangle) with 147.6 minutes, while the smallest was found from Yagyu River with 43.0 minutes. The average of the large-scale rivers (Ibigawa (circle), Kisogawa, Syonai, and Toyogawa (bottom pointing triangle) Rivers) is 102.0 minutes, and the average of the small and medium-sized rivers (Nikko, Shinkawa, Tenpaku, Yagyu, and Umeda Rivers) is 49.5 minutes. The standard deviations and TDSD tended to be smaller in the small and medium rivers in comparison with those in the large-scale rivers, even when the typhoon tracks were different. The small
standard deviations on average indicate that water levels at river mouths tend to be high, regardless of the worst track possibly inducing severer water surface level rise in the bay. Therefore, appropriate actions (e.g., evacuation) should be taken according to prior typhoon forecasts and real-time river-level information. In addition, water level gauges are often not installed at the mouths of small and medium-sized rivers. However, it is necessary to install water level gauges and expand the observation network in the future. Note that the results of this study may differ depending on the structure of the typhoon, its direction of movement, and its moving speed.

5. Concluding Remarks

The compound flood risk along the estuaries of the different-sized 11 rivers in Ise and Mikawa Bays, Japan, was evaluated using an integrated atmosphere-ocean-river model. First, we hindcasted Typhoon Trami (2018) and succeeded in reproducing the meteorological field, discharge, and storm surge with high accuracy. Furthermore, incorporating the river channel into the coupled model of surge and wave allowed include the effect of the interaction of the surge runup and river flow in the bay. Next, we prepared multiple typhoon tracks with similar intensity and precipitation distributions and conducted a series of sensitivity experiments to investigate the simultaneous occurrence of storm surges and high river flow in the estuary. It was found that there is a strong positive correlation between the time difference between the storm surge and river flow peaks (TDSD) and the river channel extension (RCE). Such a trend was confirmed to be consistent with the observed TDSD. As a result, the smaller the river scale is, the smaller the TDSD is.

Furthermore, the risk of compound flood increases in a small and medium-sized rivers. In addition, the standard deviation of the TDSD between the cases was large for large rivers and small for small and medium-sized rivers. Hence, it suggests that the TDSD is small in the small- and medium-sized rivers, regardless of the typhoon track, and it can be said that the risk of compound flooding is high.

The magnitude and time of the peak surge level were generally uniform within the bay. However, the arrival time and discharge rate of the river flow varied greatly with the river. Therefore, it can be concluded that the small- and medium-sized rivers tend to overlap the storm surge and river flow peaks and are at a high risk of compound flood.

In this sensitivity experiments, we used typhoon meteorological fields with relatively small preceding precipitation. In future work, further studies are necessary to consider typhoons with different characteristics. Also, future climate experiments are essential to assess the effect of climate change on compound floods.

Declarations

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


**Tables**

Tables 1 to 5 are available in the Supplementary Files section.

**Figures**
Figure 1

The simulation areas and list of target rivers for (a) map of Japan and target bays, (b) Ise Bay and (c) Mikawa Bay in this study. Red points in the map indicate gauge points of water level. Rivers in yellow in the list are the large-scale rivers and the others are the small and medium-sized river.
Figure 2

Computational flow of hindcast experiments and initial condition of sensitivity experiments. XRAIN is used for precipitation in the hindcast experiment, and HTM output values are used for precipitation in the sensitivity experiments for the typhoon tracks.
Figure 3

Results of typhoon track (lines) and central pressure (colors). The red dotted line indicates JMA best track data, and the black solid line means a result of WRF. The color bar and each plot color indicate a central pressure for each time step.
Figure 4

Scatter plot between observed and estimated wind speeds for half day. Each symbol indicates each observation site.
Figure 5

Distribution of water level deviations for (a) Ise Bay and (b) Mikawa Bay at the peak time of storm surge calculated by SuWAT.
Figure 6

Time series of water level deviations at the estuary points for (a) Ise Bay and (b) Mikawa Bay. Each solid line indicates simulation results, while each dashed line indicates observed ones. In the legend, rivers that merge at their estuary and flow into the same point are put together. Nikko River is omitted from this figure because the water level gauge at the mouth of the river is located inside the sluice gate.
Figure 7

Time series of river discharges (upper) and water level deviations (lower) for (a) Nanashima in the Shinkawa River, Touchi in the Syonai River, and Minami shibata in the Tenpaku river (b) Toyobashi in the Toyogawa River, Jinno-shinden in the Yagyu River, and Osaki in the Umeda River. Orange vectors indicate the peak time of storm surge and blue vectors indicate the peak time of river discharge. The right vertical axis is used for a river discharge at the Toyobashi.
Figure 8

All typhoon tracks of sensitivity experiments in this study. The westernmost case (red) is Case 1 and the easternmost case (blue) is Case 6.
Figure 9

Distributions of cumulative precipitation (75 hr) in six cases and major river lines. (a)-(f) correspond to Case1 to Case6, respectively. The red-colored river line indicates target rivers.
Figure 10

Relationships between TDSD and RCE by the sensitivity experiments. Color indicates the maximum river discharge rate at the estuary point, and each symbol indicates each river.
Figure 11

Relationship between TDSD and RCE by observed value of recent 5 typhoon cases. Color indicates each typhoon case, and each symbol indicates each river.

Supplementary Files

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