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A new framework for the assessment of potential future disasters caused by typhoons using multi-model ensemble experiments

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Abstract. Assessing future changes in typhoon-related hazards is essential for climate adaptation. We develop an event-based storyline framework coupling high-resolution meteorological simulations with river discharge and storm-surge models to quantify future risks under specified warming levels. Using Super Typhoon Hagibis (2019) as a case study, we conduct multi-model, multi–initial-condition ensemble experiments to account for structural model uncertainty and internal variability. Three meteorological models are run with 27-member initial-condition ensembles to drive three river models and two storm-surge models. Experiments cover the present climate and two warming scenarios (+2 K, +4 K). Across ensembles, Hagibis intensifies under warming: precipitation and near-surface winds strengthen, along with lower central pressure relative to present-climate runs. Consistent with these changes, many river basins in eastern Japan exhibit increased discharge, amplifying flood risk, and coastal models indicate larger storm surges. For Typhoon Hagibis, we quantify uncertainties in peak discharge and maximum storm-surge level. The multi-model combination widens uncertainties by sampling structural model differences, thereby spanning a wider range of plausible outcomes. Thus, our multi-model, multi–initial-condition framework provides a more comprehensive assessment of future typhoon-related risks than single-model experiments.

1 Introduction

It has been described in IPCC AR6 WG1 (IPCC, 2021) that global warming has already caused widespread changes in the world. Climate change strengthens extreme phenomena and increases their frequency of occurrence. For the disaster risk reduction, preparing the climatic hazard information is an important issue for the local government. Thus, we need to test and revise our existing hazardous case, owing to the increase in the frequency and severity of extreme events caused by future climate change. Conventionally, we adopt the largest recorded flood as a hazard information. However, as climate change proceed, extreme events (such as typhoons or heavy rainfall events) become more severe and happen more frequently in the future environment (IPCC AR6 WG1/2) (IPCC, 2021, 2022). We have to include the influence of climate change when we estimate the hazardous case in the future climate condition.

In this paper, we estimate the future change of disastrous weather phenomena, like typhoon and typhoon induced heavy precipitation events. These episodes are basically a meso-scale phenomena. Furthermore, to estimate river flood and storm surge hazards, inner variability of precipitation and wind speed information is important within the meso-scale. Hence, to estimate the impact of climate change, high temporal and spatial resolution information is needed here. As a result, high resolution model's in-detail (meso-scale) results are indispensable. Here, event-based storyline (Ev-SL) approach is an efficient approach to handle those cases. There are already many studies of Ev-SL from the standpoint of climatic hazard (e.g., Ito et al, 2016 SOLA, Takemi, 2019 SOLA, Kanada et al, 2017b SOLA). And in this study, to address scenario uncertainty, two series of experiments were carried out using warming scenario of +2K and +4K, showing that stronger warming would bring about stronger changes.

The Ev-SL approach needs to focus on a specific disastrous event. Thus, we handle here a disastrous super typhoon Hagibis (2019), which hit Japan and brought flash floods (e.g. Takemi and Unuma, 2020). When focusing on a specific event like Typhoon Hagibis, it's crucial to ensure that the present event is realistically represented. Fortunately, many meteorological bureaus have forecasted Typhoon Hagibis, and we can examine various ensemble results (e.g., [TIGGE] (http://gpvjma.ccs.hpcc.jp/TIGGE/tigge_TC.html)). These results clearly show that if the forecast starts before the point of recurvature, there are two distinct trajectories: one group predicts the typhoon will hit Japan, while another group forecasts it will head straight to the China continent. It suggests us the importance of starting point of integration.

Due to the disastrous nature of Typhoon Hagibis, several studies have already been conducted (e.g. Kawase et al., 2021; Kanada et al., 2021; Tanaka et al., 2023). These studies used high-resolution models starting only two days before the typhoon's landfall in the Kanto area of Japan. These models successfully represented the current track and intensity of the typhoon. Additionally, they introduced the Ev-SL or Storyline event attribution approach and found changes in the typhoon's characteristics under climate change. Kawase et al. (2021) used a 5 km grid NHM model and discovered an intensification and increase in precipitation in the Tohoku-Kanto area due to climate change over the past 40 years. The precipitation intensification was greater than predicted by the Clausius-Clapeyron relation, influenced by the central mountains of Honshu Island. Kanada et al. (2021) used an atmosphere-ocean coupled model (CReSS NOAHS) driven by a 1 km grid resolution to predict increased precipitation in a +4K environment. They explained that the precipitation intensification was due to the typhoon's deceleration in a +4K climate scenario. Their model included the effect of Ekman pumping, which reduces typhoon development when it is strong and moves slowly. Tanaka et al. (2023) estimated precipitation changes under future climate conditions for 42 river basins in Eastern Japan, using the same scheme as Kawase et al. (2021). They also found a super Clausius-Clapeyron precipitation increase. In all three studies, the initial conditions were set two to three days before the

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typhoon's landfall. However, these studies (or most typical impact studies in a literature) employed their own or familiar models, which cannot access the uncertainty range of models employed.

Our paper aims to achieve more robust results and provide information adaptable for risk estimation by adopting an ensemble experiment result. Weekly ensemble simulation has been adopted to get natural variability. And multi model ensemble (MME) has been used to count the influence of model insufficiency. Both trials are done to get potential disaster cases. All the models are cutting edge ones. And this scheme is already operationally done in TC forecast. Kanada et al (2017a) has already done MME calculation for the super typhoon Vera (1959), and show us a robust result of the intensification of the super typhoon in the future. Although MME and initial value ensemble handle another uncertainty (as can be seen in Hawkins and Sutton, 2009), when looking them from the standpoint of potential future risk, it can be handled together.

To obtain useful information for risk assessment, driving impact models is indispensable. For instance, Takayabu et al. (2015) used a storm surge model for Super Typhoon Haiyan (2013), which caused about 7000 fatalities in the Philippines. As many victims are caused by storm surge occurred in Tacloban Bay, they drove a storm surge model to estimate the wave height. This paper is the first one which handle the disaster risk of such severe storm at once. However, as it applied only single impact model, there exists limitation to estimate the robustness of the disaster. In our study, we drive three typhoon models: NHRCM (Sasaki et al., 2011), WRF (Skamarock et al., 2008), and CReSS (Tsuboki, 2023), adopting 27 ensemble cases. From the standpoint of disaster estimation, we use a multi-model experiment and also prune the cases. Subsequently, we use three river models and two storm surge models to estimate the impact of possible scenarios, including LLHI (Low Likelihood and High Impact) cases (Wood et al, 2023).

This system, which includes an impact study in this way, and which determines the robustness and potential cases of the solution is unprecedent. We designed the Ev-SL approach as follows, enable us to assess potential future risk. First: We adopt a weekly ensemble simulation model as a parent model. Second: Here, multi model ensemble has been done. And finally, several impact models have been driven to find the potential disaster cases. There were always some trials to each content as introduced in this section previously, but in this paper all trials have been done all at once.

In Section 2, we describe the experimental framework, which features a multi-model and multi-initial condition ensemble experiment to cover the spread mentioned above. Section 3 presents major results obtained from the experiment. Section 4 discusses how to effectively utilize the multi-model and multi-initial condition ensemble data. By employing this comprehensive approach, our study aims to provide valuable information for risk assessment and disaster preparedness in the face of typhoons like Hagibis.

2 Methodology

2.1 Introducing parent mode

The dynamical downscaling (DDS) procedure adopted in this study is shown schematically in Fig. 1. The parent model is the Japan Meteorological Agency (JMA) weekly ensemble prediction model (GSM). The horizontal resolution of the model is

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1.25 degrees, and it has 27 members, prepared using a singular vector method (Buizza and Palmer, 1995). Time integration starts about two days before the landing of the typhoon Hagibis to the Japan Islands.

2.2 Dynamical downscaling method

For DDS procedure, cascade nested models are used. It is 20km grid model (NHRCM20), and 5km grid model (NHRCM05). To reproduce the TC tracks of the parent model, spectral nudging has been done above 15000m level. And Kain-Fritsch convective parameterization scheme (Kain and Fritsch, 1990, 1993) have been adopted. Finally, it has been downscaled by using three cutting edge Convection Permitting Models (CPMs) with the grid spacing of 2km. They are NHRCM02, WRF, and CReSS (the spec of these three models has been indicated in supplementary Tab. S1). As we need to represent the strength and meso-scale structure of the TC, we need such fine resolution CPM models. At the final stage we narrow down from all 27 ensemble cases to five cases. That's because we should focus on the specific event of Typhoon Hagibis hits Kanto area. The 20-km resolution simulation using NHRCM was initiated at 00 UTC on October 10. The 5-km simulation began at 06 UTC on the same day, followed by the 2-km simulations using three different models, which started at 12 UTC on October 10.

2.3 Event Based Storyline approach

For integrating under the future environment, we applied Pseudo Global Warming (PGW) downscaling method (Schär et al, 1996), where the boundary conditions are assumed to be a linear coupling of the GSM data and the difference component of the climate change of air temperature and sea surface temperature (SST) between the +2 or +4 K future and 2023. Such differences are got from d4PDF mega ensemble data sets (Mizuta et al,2017), and averaged over the 2-km resolution experimental domain and applied in the analysis.

2.4 Impact models

Using the outputs of the meteorological model simulations with 2 km resolution, we drove impact study models, i.e., three hydrological models and two storm surge models as shown in Fig. 1.

2.4.1 Hydrological models

Here we use three hydrological models, Rainfall-Runoff-Inundation: RRI model, 1K-DHM, and CaMa-Flood (the specs of these three models are shown in supplementary Table S2). The RRI model is a two-dimensional distributed model that simulates rainfall-runoff and flood inundation simultaneously (Sayama et al, 2012). The outputs of the model are river discharge, water level, and flood inundation depths. The model takes into account subsurface flow processes including unsaturated and saturated subsurface flow and vertical infiltration. In this study, the RRI model was applied to the eastern part of Japan covering Kanto, Tohoku, and part of Hokuriku regions with 5-sec spatial resolution (approximately 150 m) (Sayama et al, 2020). 1K-DHM (Tanaka and Tachikawa, 2015) is a distributed hydrological model based on a kinematic wave flow approximation that considers subsurface flow. The model was implemented with 30-sec spatial resolution (approximately 1

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km). For the CaMa-Flood (Yamazaki et al., 2011) simulation, we used a part of the Today's Earth Japan system (Ma et al, 2021), in which the land surface model MATSIRO (Takata et al, 2003) is performed forced by the meteorological data first, and the CaMa-Flood to simulate the dynamics of river flow and the inundation is conducted using the MATSIRO water runoff outputs as the forcing data.

The forcing data for the RRI and 1K-DHM are precipitation. For the MATSIRO/CaMa-flood model, atmosphere variables (the surface temperature, surface specific humidity, surface wind speed, downward short wave and long wave radiation and cloud cover) are added as the forcing data for MATSIRO. The feature of the model among the three hydrological models is the fine spatial resolution, which enables us to assess flood discharges even in tributaries and the consideration of flood inundation, which affects the downstream flood discharge.

2.4.2 Coastal models

To evaluate the future change of storm surge caused by the strong wind and low surface pressure of Hagibis, two numerical models simulating the storm surge: SuWAT and GeoClaw are introduced in our experiment (the detailed setting of surge models is shown in supplementary Tab. S3). The ocean flow, waves, and sea level are driven by the surface wind and sea level pressure, which are given by 2 km grid meteorological simulations: NHRCM02, WRF, and CReSS. SuWAT is a fully coupled model of storm surge and ocean waves based on the non-linear shallow-water equation and spectral wave model (Kim et al., 2008), and takes into account atmospheric pressure, wind stress, and wave radiation stress (wave effects on current) but the wave model was excluded in this simulation. We applied SuWAT to five domains with spatial resolutions ranging from 2430 m (D1) to 30 m (D5), with two-way nesting. The astronomical tide was excluded for computation and survey for simplicity, although the maximum astronomical tidal range is about 0.93 m from T.P. (Tokyo Peil (T.P.): Standard (zero) of latitude of land (topographical maps, etc of Geospatial Information Authority of Japan)).and was close to mean water level at the landfall of Hagibis. GeoClaw, which was developed by Mandli and Dawson (2014), employs adaptive mesh refinement (AMR) algorithms, enabling it to resolve disparate spatial and temporal scales. GeoClaw solves nonlinear long-wave equations using the finite volume method based on the Riemann solver (see LeVeque 2002 for details). We updated the GeoClaw to be forced by the atmospheric model result with the similar resolution setting as the SuWAT model. The other numerical conditions including topography and bathymetry were same to the SuWAT model. In all the coastal models used in this study, topographic data were generated based on 10-meter mesh data provided by the Chubo (Central Cabinet), and levees were not taken into account.

2.5 Model validation and climate change assessment

To give a reliable conclusion about the future climate change and its impacts on the typhoon-related hazards, it is critical to reproduce the actual typhoon Hagibis and the hazards: floods and storm surge. We verify the reproducibility of our models based on some observed data. The meteorological models and the reproducibility of the TCs (Tropical Cyclones) are verified based on the JMA best track data (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html) in terms of

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the TC intensity and the track. The tide-level data of JMA is used as the reference data for the storm surge models. The impact of future climate change on floods is analysed by focusing on the relative future change (not the absolute value is used here) of river discharge without using any observation data as a reference because the reproducibility of river discharge comparing with the observation is not enough to be analysed. The relative future change of extreme discharge was investigated by many previous studies (e.g., Nohara et al., 2006 and Hirabayashi et al., 2013). The location analysed for the future change of hazard is selected where the severity of flood and storm surge is prominent. The eight river systems: Tama River, Ara River, Tone River, Naka River Kuji River, Shinano River, Abukuma River, and Naruse River (Fig. 6), are used for the analysis in the present study according to the impact of this Hagibis event and the importance of its flood prevention. As Hagibis passed the Tokyo Bay, the storm surge at the innermost location of Tokyo Bay (Fig. S4) is analysed and its future change is assessed.

3 Results

3.1 Reproducibility of Typhoon Hagibis

The high reproducibility of the typhoon model provides high reliability when assessing the impact of global warming and estimating how typhoon-related disasters will change in the future. Figure 3a shows all typhoon Hagibis tracks from the 27 ensemble present experiments (NHRCM05), as well as its best track. The model results closely follow the best track, although the spread extends approximately between 137.5°E and 140°E around the latitude of Tokyo Bay (35.5°N). Since NHRCM uses spectral nudging, the tracks shown in Fig. 3a do not differ significantly from those of the Global EPS (Tokuhiro, 2018), whose track reproduction accuracy is considered high. Likewise, the results of the 2 km model, shown in Fig. S1 also exhibit high track reproduction accuracy, though due to the absence of spectral nudging in CReSS, a slight deviation in the track is observed (Fig. S1c).

Next, the central pressure of the typhoon is examined. Since the reproduction of central pressure strongly depends on model resolution (Takayabu et al., 2015) and cannot achieve the observed intensity without sufficient resolution, Figure 3b presents the results from the highest-resolution, the 2 km resolution simulation (NHRCM02). When comparing the central pressure of the typhoon between the current climate model results (shown by the dashed line) and the observations (shown by the thick solid line), the comparison is conducted at the same latitude, as the northward movement speed of the typhoon differs among the ensemble members and from the observations. At the start of the 2 km simulation, the central pressure is higher than the observed values, which is believed to result from the downscaling from the coarser (5 km) model results. However, at the latitude of Tokyo Bay, the models successfully reproduce a sufficiently low central pressure. After the typhoon makes landfall, the central pressure increases, indicating the weakening of the typhoon, similar to the actual observations. These behaviors are essential for accurately reproducing actual disasters, such as the storm surge at Tokyo Bay and the floods in eastern Japan, using storm surge models and hydrological models (Fig. 1).

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3.2 Intensification of Typhoon Hagibis Due to Global Warming

We applied the PGW method to the same five ensemble cases, each of which was run using three different CPMs, to simulate the future Typhoon Hagibis in a +2K and +4 K warmer world. Figure 4 summarizes the results of the current climate model and the +4K PGW method simulations for the aforementioned 15 cases, showing changes in TC central pressure, maximum wind speed when passing over Tokyo Bay, as well as accumulated precipitation over the simulation period in the Kanto-Tohoku region. The TC central pressure decreases by 10.9 hPa (4.07 hPa) in the +4K (+2K) world, although there is a large spread among ensemble runs and differences among the CPMs (Fig. 4a). As surface pressure decreases in the future case, the maximum wind speed also increases; it becomes 2.97 m s-1 (2.75 m s-1) stronger in the +4K (+2K) world (Fig. 4b). As indicated in Fig. 4c, accumulated rainfall in the Kanto-Tohoku area (as indicated by the black rectangle in Fig. 2) increases by 19.8% (7.42%) in the +4K (+2K) world. All three of these results indicate the strengthening of typhoons due to global warming, suggesting that storm surges and flooding will also become more hazardous accordingly. Another important finding from Fig. 4 is that there is a large spread in the results of both the current and PGW experiments due to differences in the initial conditions and the CPMs. This spread represents the uncertainty in typhoon intensity and accounts for the uncertainties in simulating typhoon-related disasters, as explained in the following subsection.

3.3 Flood hazard

This study investigates the future changes in flood severity due to the intensification of typhoons caused by global warming, using 45 ensemble members generated from 15 meteorological forcing datasets and three hydrological models. Figure 5 presents the hydrograph of Tone-river as an example of the results, and its location is shown in Figure 6. Although the hydrograph results exhibit a large spread, the peak discharge in the future climate is significantly higher than that in the present climate at the 99% confidence level. It is also clearly shown that the flood peak occurs earlier in the future due to the acceleration of TC translation and the early peak of precipitation in the future climate simulation. Since the timing of the decrease in discharge does not change significantly, the total discharge in the future experiments increases. These trends: an increase in peak discharge and a longer duration of high discharge, are commonly observed at other observation sites (Fig. S3), which leads to an increased risk of flooding across a wide range of eastern Japan.

Figure 6 illustrates the projected future changes in peak river discharge for eight rivers in the Kanto and Tohoku regions. The observation sites for each river are shown by red points in the top-center figure of Fig. 6. It is evident from the figure that, peak river discharge is likely to increase, thereby raising the risk of flooding, depending on the degrees of global warming; the change averaged across the eight observation sites, is +10% (+23%) in a +2K (+4K) future world. The advantage of the multi-model and multi-initial condition ensemble framework is clearly demonstrated by the two error bars attached to each bar in the chart. The right one shows the max-min spread of the multi-model ensemble experiments, i.e., the range between the maximum and minimum peak discharge among all 45 ensemble members (multi-model spread). On the other hand, the left one represents the max–min spread of the initial-condition ensemble, calculated separately for each of the three models and then averaged. This can be regarded as the expected ensemble spread in the case where only a single model is used (single-model spread). By definition, the multi-model spread is larger than the single-model spread; however, the magnitude of the difference is particularly pronounced. For example, in the case of the Naruse River (the top right-hand corner of Fig. 6), the former indicates a more than threefold increase in peak discharge under future (+4K) climate conditions, which is a change that may only be detected through a multi-model approach. The multi-model maximum is regarded as the highest possible river discharge derived from multiple models, and it can be seen to increase significantly as global warming progresses from the present to the +2K and +4K future experiments.

3.4 Storm surge

We evaluate the future changes in storm surge risk driven by the strong surface winds and low sea level pressure of tropical cyclones (TCs). Similar to flood hazards, storm surges are assessed using 15 meteorological forcing datasets and two coastal models (Fig. 1). The results are presented for each combination of a specific meteorological model and a specific storm surge model, with the five-member initial condition ensemble averaged for each combination.

The spatial distribution of maximum tidal level deviation at Tokyo Bay is shown in Supplementary Fig. S4. These models simulate the coastal waters along the complex shoreline of Tokyo Bay in detail. To assess the risk of storm surge in the coastal area of Tokyo, the sea level at a location (139.46°E, 35.39°N) in Fig. 3a and S4 is analysed with tidal gauge observation data. Figure 7 shows the time series of the storm surge height for the observation (black line) from JMA and the present (blue) and +4K (red) future experiment results. The shaded area represents the range between the maximum and minimum values across ensemble members at each time step, filled in blue and red for the +4K and present experiments, respectively. The ensemble means for each experiment are also shown as solid lines, using the same colors as the corresponding shaded areas. It is evident that the timing of the storm surge and the magnitude of sea level rise are very well reproduced. The timing of the storm surge in the model is accurately reproduced. Although the storm surge height tends to be underestimated when considering the ensemble mean, the ensemble maximum closely matches the observed value. This suggests that employing a large ensemble enhances the capability of reproducing extreme events such as the actual storm surge, as previously described. A comparison of the ensemble means results between the present and future (+4K) climates shows no significant differences, e.g., peak surge level, except that the timing of the peak is shifted earlier in the future experiments, which is likely due to the faster translation of the typhoon Hagibis and is consistently demonstrated in the river discharge results shown in Fig. 5.

Since storm surge height is highly sensitive to the typhoon track or position (Otaki et al., 2021), it is plausible that the ensemble-mean time series shows no significant future change e.g., the peak level, given that the typhoon does not follow exactly the same path as in the present simulations and that each ensemble member reaches its peak at a different time. To more specifically account for disaster risk under future climate conditions, Fig. 8 shows the ensemble-mean peak storm surge levels (bar chart), along with the single-model and multi-model spreads represented by error bars, as in Fig. 6. A pronounced increase in the ensemble-mean peak storm surge level is observed in the +4K experiment. Similar to the results for river discharge (Fig.6), the multi-model spread is larger than the single-model spread, indicating that the uncertainty in storm surge

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projections is more comprehensively captured. Considering the multi-model maximum, which represents the potential future risk among possible outcomes, the storm surges are projected to intensify with the progression of global warming from the present climate to the +2K and +4K experiments, suggesting an increased risk of disaster. The detectability of the potential future risk is enhanced by the introduction of the multi-meteorological and multi-surge models.

4 Discussion and conclusion

Assessing the future changes in hazards arising from extreme meteorological events, e.g., heavy rainfall, flood, and storm surge, is important for enabling society to develop effective adaptation measures. We developed a new experimental framework to analyse future changes in these various hazards through a series of ensemble experiments, in which meteorological simulations are followed by river and storm surge modelling. The advantage of the framework is the use of multi-model and multi-initial-condition ensemble experiments (i.e., multi-multi ensemble experiment), which enables us to assess potential future risk by quantifying the spread in projected hazard severity under future climate conditions. 'Multi-model' is accomplished by using several models: three meteorological models and three river models, and two surge models; multi-initial-condition is given by the ensemble data from Global EPS. As an additional benefit, the framework allows global warming levels to be specified as needed for the assessment. In the present study, we apply levels corresponding to the present climate, +2 K, and +4 K compared to pre-revolution era.

We evaluated the future severity of the target hazards caused by Typhoon Hagibis, one of the super typhoons, landing in Japan in 2019 to show the performance of the framework and the advantages of its multi-model and multi-initial-condition approaches. In the warming environments of +2 K and +4 K, Hagibis is found to be intensified in terms of precipitation and wind, as well as a decrease in central pressure, compared with the present-climate experiments. The intensification of typhoons under global warming has been well established by many previous studies, and our experimental framework successfully reproduced this feature.

Analysis of the impact study model results indicates that many rivers in eastern Japan experienced an increase of river discharge as the result of precipitation increase, which means that the flood risk is enhanced due to global warming. The results of the coastal models suggest that storm surges induced by typhoons in the future are intensified through the TC central pressure decrease and the intensification of surge-driving wind. Although the intensification of each hazard in the future is reported in many previous studies (e.g., Lackman, 2015, Takayabu et al, 2015), our experimental framework provides integrated information on multiple hazards associated with a specified meteorological event, enabling the assessment of socio-economic damages caused by these combined hazards (Owolabi and Sajjad, 2023).

In this study, we sought to capture the potential risks of future typhoon-related disasters as comprehensively as possible by the multi-multi ensemble experiments. To highlight the advantage of the multi-model experiments in the assessments of future change of hazards, we consider two uncertainties: single-model uncertainty and multi-model uncertainty. The max-min spread of multi-model outputs is, in principle, larger than the single-model ones. The max–min spread of multi-model outputs is, by

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definition, larger than that of single-model outputs, and this larger uncertainty helps estimate potential future risks and thereby facilitates appropriate preparedness for disaster risks in advance. The results averaged over the multi-model ensemble are also considered more robust and reliable than those obtained from single-model experiments (e.g., Gleckler et al., 2008). Such advantages of the multi-model approach are incorporated in the present experimental framework, as are the uncertainties associated with initial conditions.

Among the three meteorological models we used, NHRCM and WRF adopt the SST from the parent model as the lower boundary condition, whereas CReSS employs a slab ocean model. (see Tab. S1). In the CReSS simulations, the strong wind of TCs induce Ekman pumping and vertical mixing, entraining colder subsurface water, cooling the SST, and providing negative feedback that weakens the TC intensification. (Kanada et al., 2021, Iizuka et al., 2021, and Ito et al., 2020). Kanada et al. (2021) reported typhoon intensification under global warming, which is consistent with the results obtained in the present study. However, the CReSS simulations here show a smaller future decrease in central pressure compared with the other two models (Fig. 4). This result may reflect the influence of atmosphere–ocean coupling, whereby stronger surface winds in the future enhanced oceanic feedback and suppressed further intensification of the typhoon. The slab model in CReSS is not full-coupled model. Introducing a fully coupled model as one of the multi-model components would broaden the range of model reproducibility in the present experimental framework (i.e., expand the max–min spread), thereby increasing its utility. This is left for future work.

As global warming progresses, the proportion of strong tropical cyclones is projected to increase, as reported in IPCC AR6 WG1 (TS Infographics, 4.1). However, the present study, which employs the Ev-SL method, cannot address changes in the frequency of super typhoons. For this purpose, the Risk-based SL method is more effective in evaluating frequency changes. Therefore, a hybrid approach that combines both methods would be desirable to obtain a more comprehensive understanding of the behaviour of strong tropical cyclones. For this purpose, the information on potential future risks provided by the multi-multi ensemble experimental framework would be valuable.

Code availability.

NHRCM: The underlying software code used in this study is not publicly accessible. This is due to the use of licensed third-party dependencies that cannot be redistributed.

WRF: The model code was obtained from the WRF web site at https://www2.mmm.ucar.edu/wrf/users/

CReSS: The CReSS model used in this study and its user's guide are available on the model website at http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/cress_html/index_cress_eng.html (Tsuboki, 2023).

RRI: The model code is available on the model website at https://www.pwri.go.jp/icharm/research/rri/rri_top.html

1K-DHM: The model code is available on the model website at https://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K-DHM.html (Tanaka and Tachikawa, 2015)

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SuWAT: The source code of SuWAT is opened to the public and commercial sectors; it is available from the Ocean and Coastal Engineering Laboratory, Kumamoto University, Japan, upon request. The model details are available on the following website, https://www.civil.kumamoto-u.ac.jp/sooyoulkim/page-12/page-20/?utm_source=chatgpt.com

GeoClaw: The model code is available on the model website at https://www.clawpack.org/

Data availability.

Japan Meteorological Agency (JMA) best track data: The best track data for typhoons can be obtained from the following website. https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html

GEPS: The data is available by way of "Meteorological Research Consortium", a framework for research cooperation of Japan Meteorological Agency (JMA) and Meteorological Society of Japan (MSJ) at https://www.mri-jma.go.jp/Project/cons/index.html.

d4PDF: The data are available through the Data Integration and Analysis System (DIAS; https://diasjp.net) upon registration for a DIAS account.

Observed tidal data in Tokyo Bay: The data is available at https://www.data.jma.go.jp/kaiyou/db/tide/genbo/index.php

Author contributions. KH prepared the data, executed experiments, analyze the result, and prepared the original draft. IT proposed the concept of the study. HK, TeT, and SK prepared atmospheric models. TS and ToT prepared the river flood models. NM and TM prepared storm surge models. YI prepared the future atmospheric temperature data. MY provided GEPS data. Model execution and visualization has been done by TI, YT, RA, SG, MM, and SS. TN acquire the funding, and administrated the project. All members review and editing the paper.

Competing interests. The authors declare that they have no conflict of interest.

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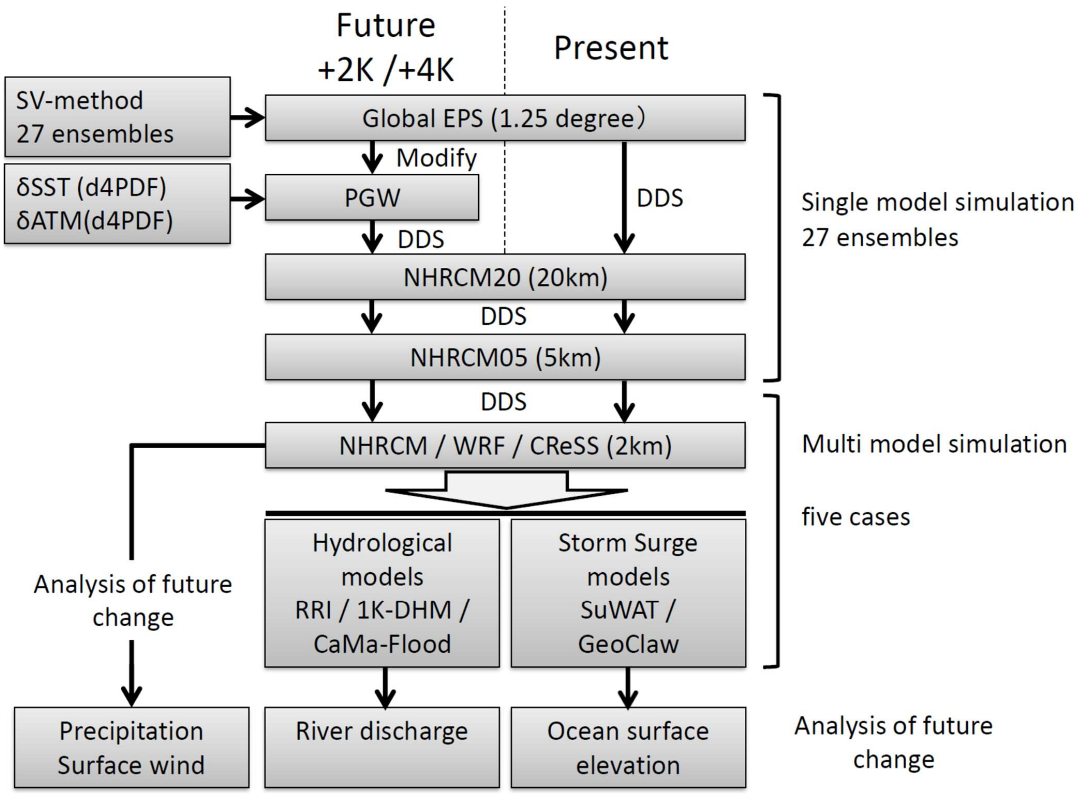

Figure 1: The framework of the multi-model and multi-initial-condition experiments.

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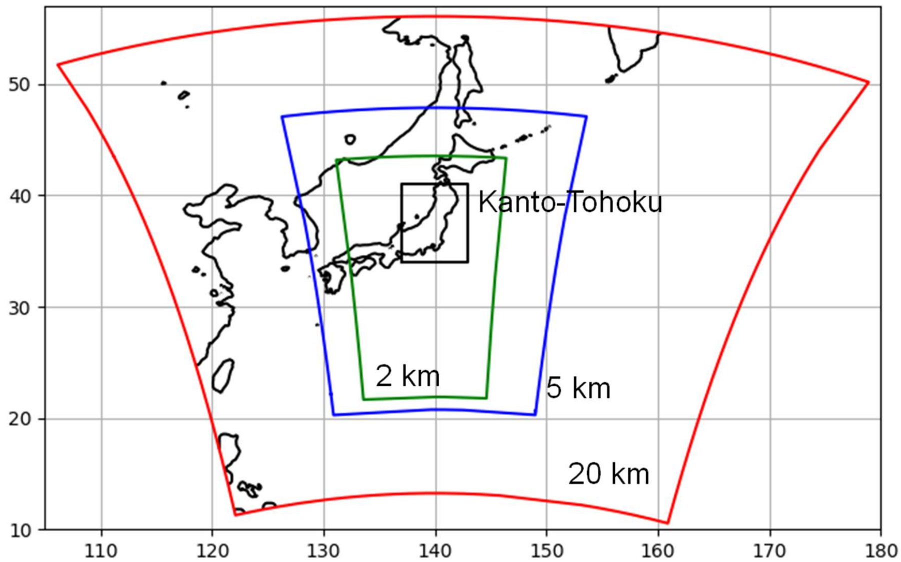

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Figure 2: The computational domains for the meteorological models: red for 20 km resolution simulation, blue for 5 km, and green for 2 km. The black line shows Kanto-Tohoku region for calculating the area-averaged precipitation.

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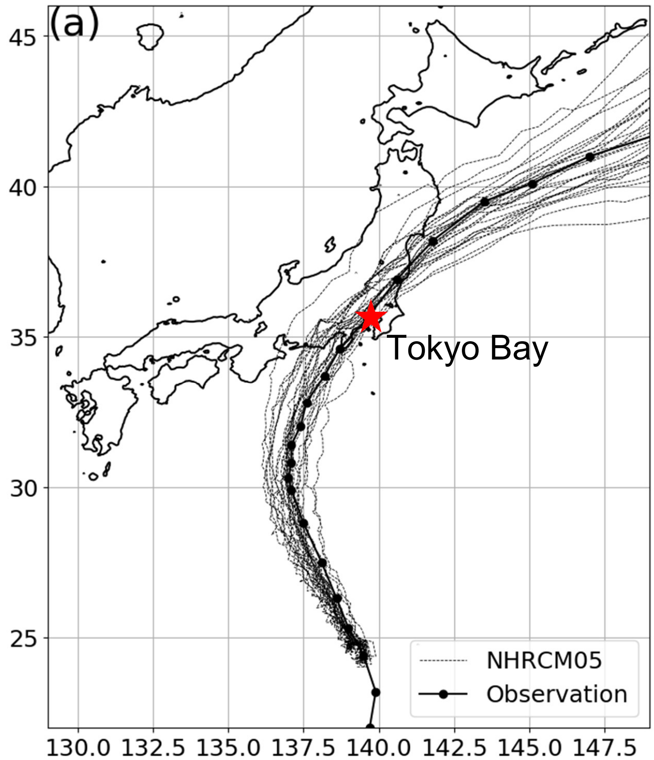

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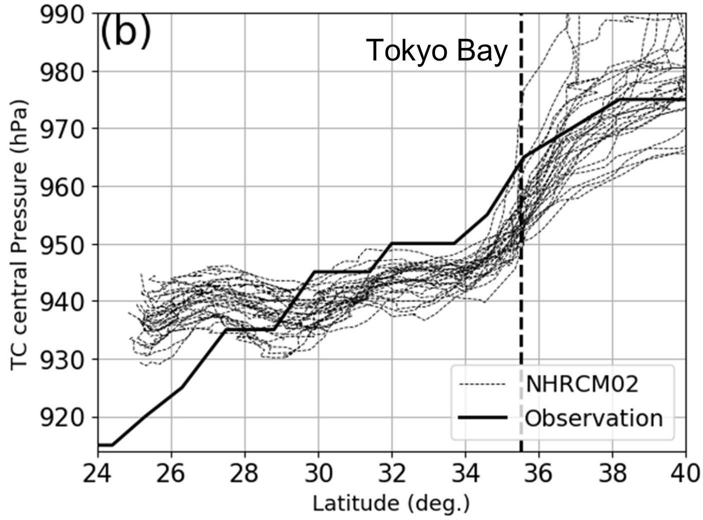
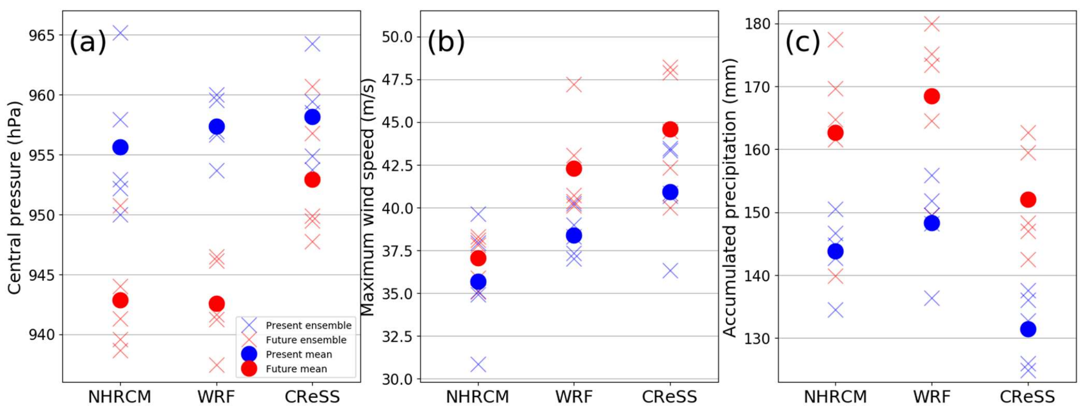


355 **Figure 3: The track of Typhoon Hagibis as reproduced by the present NHRCM05. The dashed lines indicate the results of all 27 ensemble members. The track line in the thick line is the best track data with the dots in the intervals of three hours. (b) Typhoon central pressure calculated using present NHRCM02 (dashed line) and from observation (solid line). The vertical dashed line indicates the latitude of Tokyo Bay (35.5°).**



360 **Figure 4 (a) Typhoon Hagibis's central pressure, (b) the maximum surface wind speed, and (c) the area averaged accumulated precipitation in the present (blue) and future 4K experiments (red). The results of future 2K experiments are shown in Fig. S2.**

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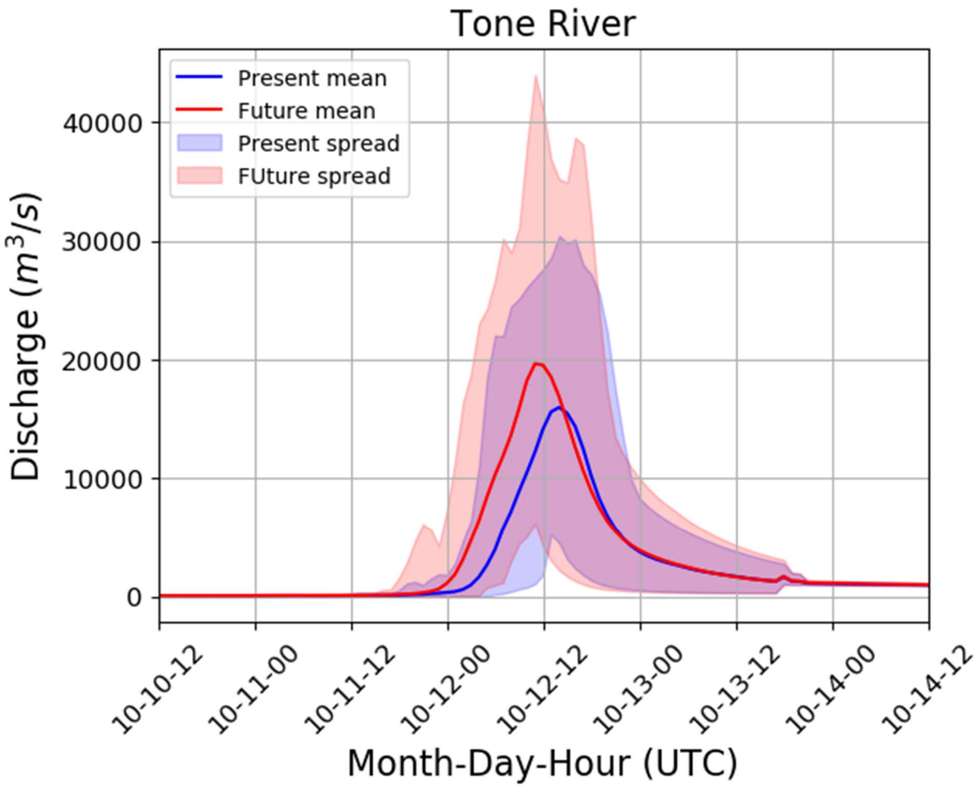

Figure 5: The hydrograph at the Tone River observation site. The shaded areas represent the max-min spread for all ensemble members, and the lines indicate the ensemble mean. The blue color represents the results of the present experiments, while the red color represents the results of the future 4K experiments. The hydrographs at observation sites for other rivers are shown in Fig. 3.

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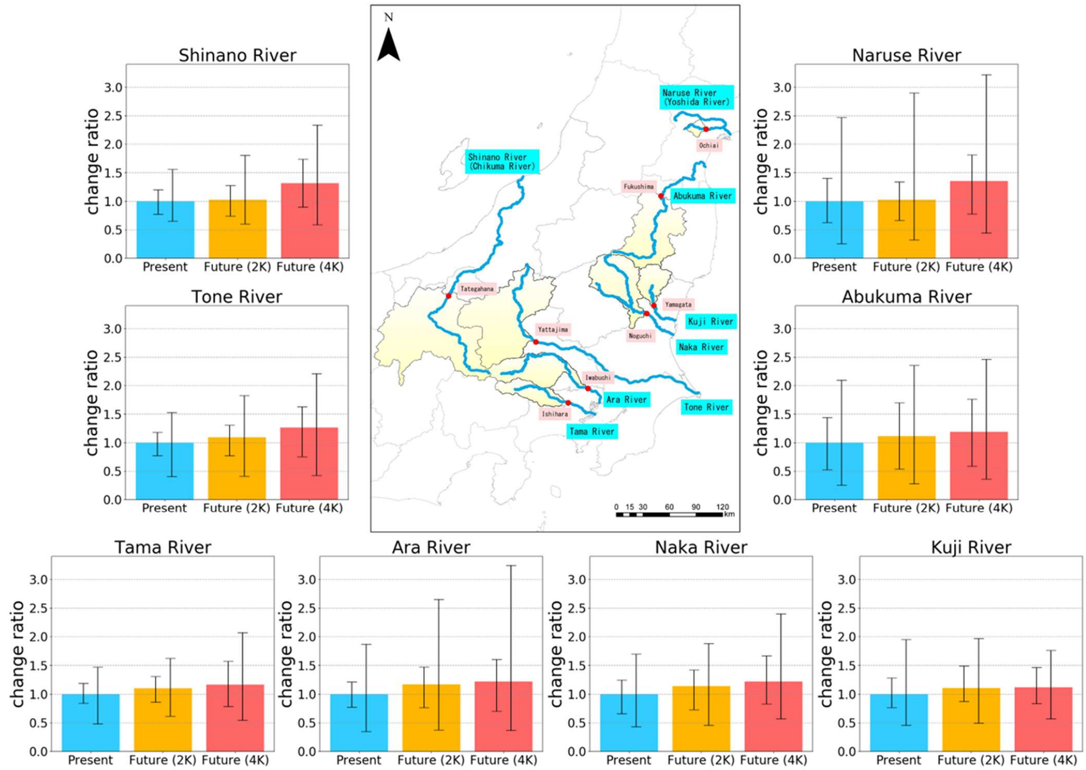

370 **Figure 6: Future changes (2K and 4K) in the maximum discharge of eight river system: The bars represent the ensemble average of 45 sample generated from 15 meteorological forcing datasets and three hydrological models, and the left (right) error bars indicate the max-min range of the single-model (multi-model) ensemble framework At the top center, river information is shown, including the observation point (red dot) and the upstream catchment area (yellow region).**

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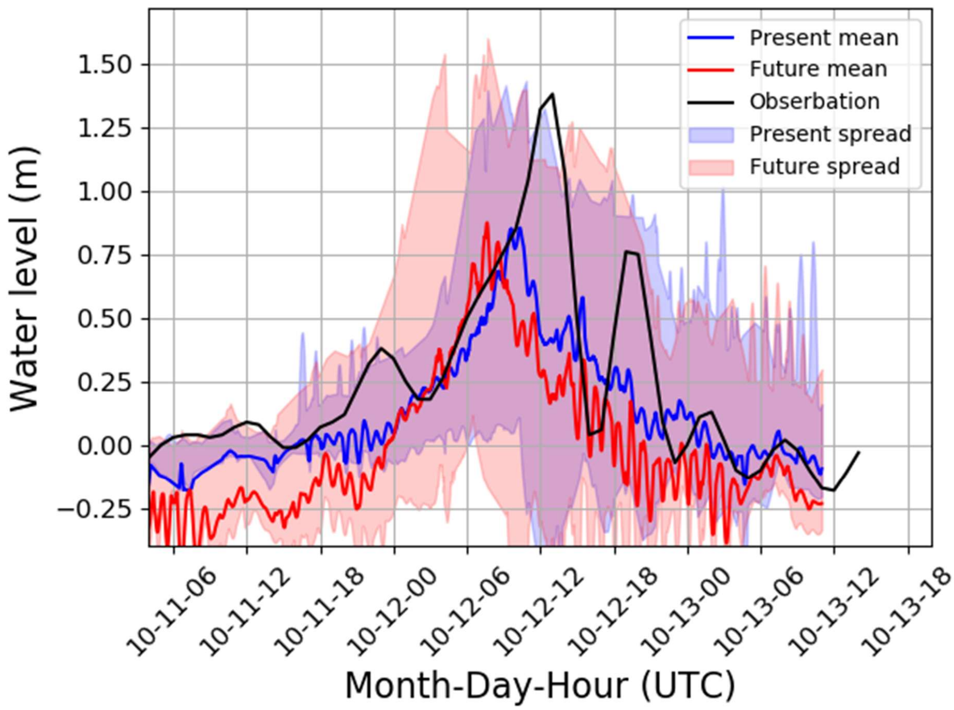
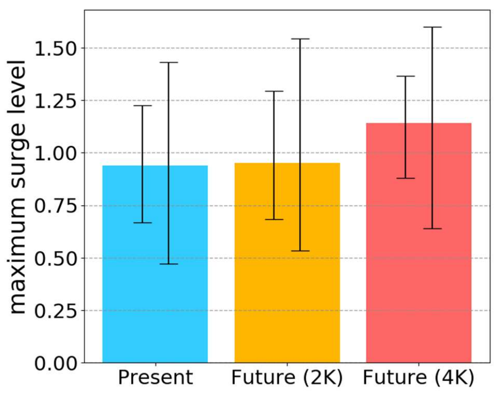


Figure 7: Time series of surge level at Tokyo Bay. The meaning of the lines and shaded areas is the same as in Fig. 5. The results from the 2K experiments are shown in Fig. S5.



375 **Figure 8: Maximum surge level at Tokyo Bay. Bars and error bars are as in Fig. 6.**

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