Assessing climate change impacts on extreme rainfall and severe flooding during the summer monsoon season in the Ishikari River basin, Japan

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Abstract:

This study investigates the change in extreme rainfall and river flooding for a large river basin due to climate change during the summer monsoon using a large ensemble dataset (d4PDF) coupled with the Integrated Flood Analysis System (IFAS). Frequent severe flooding causes significant damage in Japan. Therefore, we aim to provide useful information to mitigate flood damage. The study area is the Ishikari River basin (IRB) in Hokkaido, Japan. We used the d4PDF 5-km downscaled rainfall data as input for the IFAS model. The results showed that, for a given increase in extreme rainfall, the discharges from the IRB and its main sub-basins increase to a greater extent. The differences between the time of peak discharge at the reference stations in each tributary and the time of peak water level at the confluence points in the main river are evaluated. Climate change effects are significant in the southern sub-basins, wherein the amount of extreme rainfall increases by 29%–35%, whereas the river discharge increases drastically (37%–56%). Additionally, the time difference decreases by 1.02–2.14 h. These findings will help policymakers develop future flood control measures in flood-prone areas.

KEYWORDS river flooding; extreme rainfall; time difference; Ishikari River basin; d4PDF; IFAS

INTRODUCTION

According to the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC), severe natural disasters due to extreme climate have become more frequent since 2000 (IPCC, 2012). Floods are considered as extreme weather events that occur frequently and cause severe damage (Doocy et al., 2013; Hirabayashi and Kanae, 2009). Although several factors contribute to flooding, heavy or prolonged rainfall is considered the most critical factor that causes floods. The IPCC 5th Assessment Report (IPCC, 2013) indicated that rainfall is expected to increase in Asia during future summer monsoon seasons, and extreme rainfall is likely to become more frequent. Increasing rainfall, especially extreme rainfall, has enhanced the risk of floods in the future (Higashino and Stefan, 2019; Hirabayashi et al., 2008).

In Japan, extreme flood events from heavy rainfall have been recorded regularly in recent years. For example, large-scale flooding due to heavy rainfall occurred during July 5–8, 2018 in western Japan, causing extensive damage over numerous prefectures and resulting in 224 deaths, 21,460 collapsed houses, and 30,439 inundated houses. In the Oda River and its three tributaries, levees were breached at eight points due to the “backwater phenomenon” in which the tributary river floods synchronized with the main river flood (River Council for Social Infrastructure Development, 2018). Considering various climate change scenarios, several studies have predicted increased rainfall in the future (Kitoh et al., 2009; Kim et al., 2010). Kim et al. (2010) indicated that rainfall in Hokkaido is expected to increase by 6.1% and 10.6% in the near and extended future, respectively. Additionally, Yamada (2019) reported that extreme rainfall will be more extensive under future climate conditions.

Attempts have been made to develop flood adaptation strategies to address the critical effects of climate change on the risk of river floods. Several studies have been conducted in important river basins internationally (e.g. Shrestha and Lohpiaisankrit, 2017; Try et al., 2020), as well as regionally in Japan (e.g. Sato et al., 2012; Tachikawa et al., 2009; Hoshino and Yamada, 2017). A study by Tachikawa et al. (2009) indicated that severe rainfall would increase in the Yoshito River basin, and the peak flood discharge would increase to a greater extent in the future. Additionally, the trend of extreme rainfall events increasing in a short period of time should be considered. Sato et al. (2012) indicated that climate change is projected to change river discharges significantly, especially in northern Japan.

Thus, understanding the change in the amount of rainfall, especially considering future extreme rainfall events, and assessing its effect on the risk of river floods in vulnerable basins is necessary to create effective flood control plans. This study investigates the changes in the risk of river flooding associated with climate change in the Ishikari River basin (IRB), a socioeconomically important basin in Hokkaido, Japan. This study is the first to assess the changes in extreme short-term rainfall and extreme river flooding events during the summer monsoon in the IRB as...
well as in its main sub-basins (IM-SBs) using an Integrated Flood Analysis System (IFAS) coupled with a large-ensemble rainfall dataset (d4PDF) with a high resolution of 5 km (Yamada et al., 2018). Additionally, the differences between the time of peak discharge at the reference stations (TOPD-RS) in each tributary and the time of peak water level at the confluence points (TOPWL-CP) in the main river are evaluated. The shorter the time difference, the greater the flood risk. These results will provide additional information about the effect of climate change on the risk of river floods, and thus guide climate change adaptation and flood damage mitigation strategies in vulnerable areas.

**METHODOLOGY**

**Study area**

The study area is the IRB. The river flows through 48 municipalities (including Sapporo, the prefectural capital), accounting for roughly 52% of Hokkaido’s population. The mean annual precipitation in the IRB is 1,300 mm (Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2004). The hydrologic peaks occur from March to May during the snow-melt period, and in August and September during the rainy season. At 268 km in length and with a drainage area of 14,330 km², the river is the longest in Hokkaido and the second largest in terms of basin area in Japan (Japan River Association, 2003). The IRB has experienced severe damage from large-scale historical floods. For example, the flood in August 2016 caused damage of approximately 260 million USD and agricultural losses on 40,258 ha of land (Japan Society of Civil Engineers, 2017). Therefore, the projection of flood risk is significant to reduce future flood damage in this basin. Figure 1 shows the locations of the IRB and IM-SBs.

**d4PDF Dataset**

The “database for Policy Decision making for Future climate change” (d4PDF) contains data from numerous ensemble climate experiments with 60-km resolution on the national scale (Mizuta et al., 2016) and from a regional scale at 20-km resolution (Sasaki et al., 2011). The dataset spans 60 years (2051–2110) and comprises 90 members (total: 5,400 events) for the +4K future climate simulation, and 60 years (1951–2010) and 50 members (total: 3,000 events) for the historical climate simulation.

This study used the d4PDF downscaled rainfall data with 5-km resolution from a previous study (Yamada et al., 2018). The 5-km resolution rainfall data were downscaled from 20-km resolution data via the non-hydrostatic regional climate model (Sasaki et al., 2011). The target period for downsampling was set to 15 days of maximum rainfall for each event in Hokkaido for 3,000 historical simulation events and 5,400 future simulation events (Yamada et al., 2018; Hoshino et al., 2020). After downsampling, the rainfall amount, hourly rainfall intensity, and spatiotemporal distributions of rainfall were similar to those of the recorded rainfall events. Additionally, the downscaled results can represent the topography of the study area more precisely (Yamada et al., 2018). These results suggest that the dataset after downsampling can be used to evaluate the effect of climate change on a regional scale.

In this study, we selected the rainfall data for locations within the IRB. Then, we chose the annual maximum rainfall (mm/72 h) (AMR-72h) for assessing the change in short-term extreme rainfall and its effect on river flooding between the historical and future simulations in the IRB. According to the report (Japan River Association, 2003), the degree of safety for the Ishikari River in Hokkaido was set as 1/150, giving a return period of 150 years. Therefore, this study focused on assessing extreme river flooding events for the top 20 and top 36 rainfall events (T20-T36-REs) out of 3,000 and 5,400 rainfall events corresponding to return periods equal to or more than 150 years for the historical and future simulations, respectively.

**Hydrological model**

This study used the IFAS model developed by the International Centre for Water Hazard and Risk Management (ICHARM). The IFAS uses a Public Works Research Institute (PWRI)–distributed hydrological model developed in the 1990s (Yoshino et al., 1990) as the runoff simulation engine (ICHARM, 2014). A schematic of the IFAS model is shown in Figure S1, and its parameter values are shown in Table SI. It has been used to estimate the flood risk for many river basins globally and has demonstrated good simulation performance (Aziz and Tanaka, 2010; Kimura et al., 2014).

This study used the August 1981 flood to calibrate the hydrological model. The floods in September 2001, September 2011, and August 2016 were chosen to validate the model. These four extreme flood events were large-scale historical flood events that caused severe damage in the IRB. The flood event in August 1981 was particularly large, being the largest flood event observed in the IRB. The simulations were conducted for an additional period of two weeks prior to the main period of flooding events for model warmup and to allow time for the water to reach the downstream area.

We calculated the river discharge at the Ishikari Ohashi station (IOS), which is approximately 26.6 km upstream from the river mouth (Figure 1). The rainfall data for the August 1981 flood were obtained from rain gauge stations provided by the Hokkaido Regional Development Bureau.
To quantitatively evaluate the performance of the IFAS for the historical flood events, we used the Nash–Sutcliffe coefficient ($NS$) (Nash and Sutcliffe, 1970) and the three indices of wave shape error ($E_w$), volume error ($E_v$), and peak discharge error ($E_p$) (Japan Institute of Construction Engineering, 2011; Aziz and Tanaka, 2010), defined as follows.

$$NS = 1 - \frac{\sum_{i=1}^{n} (Q_{av(i)} - Q_{oi})^2}{\sum_{i=1}^{n} (Q_{av(i)} - \bar{Q})^2}$$  \hspace{1cm} (1)$$

$$E_w = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{Q_{oi} - Q_{av(i)}}{\bar{Q}} \right)^2$$  \hspace{1cm} (2)$$

$$E_v = \frac{\sum_{i=1}^{n} Q_{oi} - \sum_{i=1}^{n} Q_{av(i)}}{\sum_{i=1}^{n} Q_{av(i)}}$$  \hspace{1cm} (3)$$

$$E_p = \frac{Q_{wp} - Q_{cp}}{Q_{wp}}$$  \hspace{1cm} (4)$$

Here, $Q_{oi}$: observed discharge ($\text{m}^3/\text{s}$); $Q_{av(i)}$: simulated discharge ($\text{m}^3/\text{s}$); $n$: number of data points; $\bar{Q}$: average observed discharge ($\text{m}^3/\text{s}$); $Q_{wp}$: peak value of the observed discharge ($\text{m}^3/\text{s}$); and $Q_{cp}$: peak value of the simulated discharge ($\text{m}^3/\text{s}$). The simulation model is acceptable if $NS > 0.7$; and the smaller the $E_w$, $E_v$, and $E_p$ errors are, the better the model is.

**Analytical procedure**

This study was conducted to assess the effect of climate change on extreme rainfall and severe river flooding in the IRB using the following steps. First, the IFAS model was calibrated and validated against historical flood events. Next, future changes in extreme rainfall were estimated based on the large ensemble rainfall dataset d4PDF. The Student’s t-test was used to find a significant difference between the two sets of samples (observed rainfall data and rainfall data obtained from the historical simulation). The hypothesis of the test is stated as follows.

$${\text{Ho}}: \mu_1 = \mu_2$$

$${\text{H1}}: \mu_1 \neq \mu_2$$  \hspace{1cm} (5)$$

Here, $\mu_1$ and $\mu_2$ are the means of the observed rainfall data and rainfall data obtained from the historical simulation, respectively. The null hypothesis is rejected if the $p$-value is less than the significance level $\alpha$ of 0.05. Additionally, the Student’s t-test was used to find the significant difference between the two sets of samples (historical and future simulations); the hypothesis of this test is stated as follows.

$${\text{Ho}}: \mu_2 \leq \mu_1$$

$${\text{H1}}: \mu_2 > \mu_1$$  \hspace{1cm} (6)$$

Here, $\mu_1$ and $\mu_2$ are the means of AMR-72h in the historical and future simulations, respectively. The null hypothesis is rejected if the $p$-value is less than the significance level $\alpha$ of 0.05.

Then, future changes in extreme rainfall between the T20-T36-REs were evaluated for the IRB and IM-SBs. After validation, the IFAS model was used to estimate the river discharge at 8 reference stations located in the IRB, each IM-SBs, and 7 confluence points (Figure 1) for the T20-T36-REs. Changes in extreme river flooding between the T20-T36-REs in the IRB and IM-SBs were investigated. Finally, the differences between the TOPD-RS in each tributary and TOPWL-CP in the main river were evaluated. The average values of the time differences over all the flood events in each of the sub-basins were estimated and compared between the T20-T36-REs.

**RESULTS AND DISCUSSION**

**Hydrological model calibration and validation**

Figure 2(a) compares the simulated and observed discharges for the flood event of August 1981 after calibration. Figures 2(b), (c), and (d) compare the simulated and observed discharges in the validation process for flooding events in September 2001, September 2011, and August 2016, respectively. The model calibration was performed using a “trial and error” process. As shown in Figure 2, the IFAS closely reproduced the flood duration and peak discharge in most cases. For the August 1981 flood, the simulated discharges showed close agreement with the observed discharges, as indicated by a high $NS$ value of 0.95, an $E_w$ of 0.08, $E_v$ of 0.04, and $E_p$ of –0.01.

In the validation process, the simulated discharges matched well with the observed discharges for the September 2001, September 2011, and August 2016 floods, with high $NS$ values of 0.96, 0.92, and 0.90, respectively. The simulated peak discharges were evaluated to be slightly lower than the observed peak discharges for the September 2011 and August 2016 flood events. However, the statistical performance indices suggested good performance for all cases. The detailed indicators are shown in Table III. These results suggest that the IFAS model can perform reasonably well for the IRB.

**Future changes in extreme rainfall**

Figure 3 shows the relative frequency of AMR-72h in the IRB for the observed rainfall data, and the historical and future simulations. The results indicate that the AMR-72h in the historical simulation and the rainfall amount (mm/72 h) from the observation data have similar frequencies. The result from Student’s t-test demonstrates a $p$-value of 0.214, which exceeds $\alpha$. This result implies that the mean of the observed rainfall data is similar to the mean of rainfall data obtained from the historical simulation.

Additionally, the rainfall amount is projected to increase significantly in the future. The mean value of the rainfall amount in the future simulation is 86.3 (mm/72 h), which is 1.13 times that in the historical simulation (76.6 mm/72 h). The Student’s t-test result shows that the $p$-value is less than 2.2×10$^{-16}$, i.e. much smaller than 0.05. This adequately proves the validity of H1. Therefore, the frequency and magnitude of extreme rainfall are expected to increase in the future.
Tables SIII and SIV show the T20-T36-REs for the IRB and IM-SBs. In Figure 4(a), the AMR-72h is expected to increase in the IRB and all IM-SBs. The percentage difference in the median value of AMR-72h between the T20-T36-REs for the IRB and IM-SBs is shown in Figure 4(b). It is shown that the median 72-h value in the IRB is projected to be 21% higher in the future. Additionally, the extreme rainfall is expected to increase significantly in the Chitose, Ikushunbetsu, and Yubari river basins located in the southern part of the IRB, with estimated increases of 35%, 30%, and 29%, respectively. Moreover, the spatial distributions of AMR-72h averaged for the T20-T36-REs, and the percentage difference between the selected historical and future simulations.
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cal and future events are shown in Figure S2. These results also indicate that the increase in extreme rainfall is expected to be particularly significant in the Ikushunbetsu and Chitose river basins.

Future changes in river floods between the T20-T36-REs

Tables SV and SVI show the results of peak discharge for the T20-T36-REs at 8 reference stations in the IRB and IM-SBs. Figure 5(a) shows boxplots of the peak runoff depth (mm/h) for the T20-T36-REs, and Figure 5(b) shows the percentage difference in the median of the peak runoff depth between the T20-T36-REs in the IRB and IM-SBs. These results indicate that the river floods were projected to increase significantly in the IRB and IM-SBs. In particular, the Ikushunbetsu, Yubari, and Toyohira river basins were more likely to experience extremely large river flooding events with peak runoff depths exceeding 25 mm/h.

The percentage difference in the median of the peak runoff depth between the T20-T36-REs indicated that the peak runoff depth is projected to increase by 33% in the IRB. The Ikushunbetsu, Uryu, Sorachi, and Yubari river basins are expected to undergo remarkable increases of 56%, 54%, 54%, and 53%, respectively, in peak runoff depths. In particular, the Ikushunbetsu and Yubari river basins located in the southern part of the IRB are expected to experience a significant increase in extreme rainfall and river floods. However, the river floods from extreme rainfall will increase to a greater extent.

Time difference prediction

The difference between the TOPD-RS in each tributary and the TOPWL-CP in the main river was estimated for the T20-T36-REs. Figure 6 shows the time difference averaged for the T20-T36-REs in each of the sub-basins. The results show a slight increase of 0.19 h and 0.70 h in the future time difference in the Uryu and Sorachi river basins, respectively. Conversely, the time differences in the Ikushunbetsu, Yubari, Chitose, and Toyohira river basins are expected to decrease by 1.30, 2.14, 1.02, and 0.84 h, respectively. The time difference in the Chubetsu river basin was almost unchanged with a slight decrease of 0.05 h. The shorter the time difference, the greater the flood risk. These results can serve as a useful additional reference for flood damage mitigation strategies in vulnerable areas. Particular attention should be paid to the Chitose River basin because it is a lowland area prone to flood damage.

Limitations

Because our approach focused on natural hazards, we ignored future changes in land-use activities and populations. Additionally, we did not consider the existing flood control facilities in the basin. However, we predict that short-term extreme rainfall events will have much greater effects on river flooding than the aforementioned factors.

CONCLUSIONS

The following conclusions were drawn from this study:

– Following validation, the IFAS model can provide reasonable simulations of river discharges in the IRB.
– Severe rainfall and river flooding events are expected to increase significantly in the IRB and IM-SBs in the future. Additionally, the river flooding resulting from

Figure 5. (a) Boxplots of the peak runoff depth (mm/h) for the top 20 and top 36 rainfall events in the Ishikari River basin and in its main sub-basins, and (b) the percentage difference in the median of peak runoff depth between the top 20 and top 36 rainfall events

Figure 6. Time difference averaged for the top 20 and top 36 rainfall events in each of the sub-basins
extreme rainfall would increase to a greater extent than the increase in extreme rainfall in the IRB and IM-SBs. The effect of climate change is significant in the sub-basins located in the southern part of the IRB, where extreme rainfall is expected to increase by 29%–35%, whereas the river discharge is likely to increase drastically by 37%–56%. The difference between the TOPD-RS and TOPWL-CP is expected to decrease by 1.02 h to 2.14 h in these regions. Special attention should be paid to the Chitose River basin, as it is located in a lowland area of the IRB that is prone to flood damage. These results will provide additional information about the effect of climate change on the risk of river flood for establishing climate change adaptation and flood damage mitigation strategies in vulnerable areas.

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SUPPLEMENTS

Figure S1. Schematic of the IFAS model
Figure S2. Spatial distribution of AMR-72h averaged for the (a) top 20 rainfall events and (b) top 36 rainfall events; (c) percentage difference between the selected historical and future events
Table SI. Parameter value settings in the IFAS model
Table SII. Performance of the IFAS model in the IRB
Table SIII. Top 20 rainfall events in the IRB and IM-SBs
Table SIV. Top 36 rainfall events in the IRB and IM-SBs
Table SV. Peak discharge results for the top 20 rainfall events in the IRB and IM-SBs
Table SVI. Peak discharge results for the top 36 rainfall events in the IRB and IM-SBs

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