Revealing Flood Patterns Across Japan at +2℃ and +4℃ Stages Based on the 150-m Rainfall-Runoff-Inundation (RRI) Model

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Introduction

Climate change is expected to increase global flood risks. Currently, most studies on future flood projections are conducted at large scales, using hydrological models with resolutions ranging from tens to hundreds of kilometers. In Japan, previous research has utilized a 1-km resolution model and 25-km resolution climate projection ensemble, d4PDF to estimate future flood frequencies. However, several critical gaps remain: (1) Insufficient attention has been given to river cross-sections beyond downstream outlets. (2) Kilometer-scale simulation results are still too coarse for local disaster prevention decisions and public climate change education. (3) The 25-km d4PDF data struggles to capture mesoscale weather systems, such as senjo-kousuitai, which significantly contribute to localized floods. (4) Existing studies have not accounted for factors like reservoir operation and river-slope water exchanges during inundation, which markedly influence discharge volumes. These gaps hinder a comprehensive understanding of future flood pattern changes in Japan.

To address this, this study uses the latest 5-km d4PDF data and employs the Rainfall-Runoff-Inundation (RRI) model with 150-m grid-resolution to project Flood Frequency Curves (FFCs) across all river cross-sections in Japan under stages of 2°C and 4°C global mean temperature increases.

Method

The hourly precipitation input is derived from the 5-km d4PDF dataset, which includes simulations of the historical stage and projections for the +2°C and +4°C stages. Each stage contains 12 ensemble members, each providing 60 years of data, resulting in 720 years of hourly precipitation data per stage. This extensive dataset enables robust estimation of FFCs.

The RRI model is employed for flood simulation. However, due to the enormous data volume and the complexity of the hydrodynamic model, simulations are extremely time-consuming. To address this, the study applies the Aggregating Grid Events (AGE) method to identify critical precipitation events (return period ≥ 10 years) for constructing FFCs at various river cross-sections, significantly reducing the number of events requiring simulation.

Peaks-Over-Threshold method is used to estimate FFCs by fitting the simulated flood peaks to a Generalized Pareto Distribution.

$$Icrease\ Ratio = \frac{Q_f}{Q_b} \qquad \textbf{Eq. 1}$$

$$F = \frac{\max\left(Q_t - Q_{t-1}, Q_t - Q_{t-2}, \ldots, Q_t - Q_{t-d}\right)}{CA \times d} \qquad \textbf{Eq. 2}$$

Where, Q_b and Q_f represent the Q100 at historical and future stages, respectively; Q_t represents discharge at timestep *t*; d is the duration, i.e., 6 hours in this study; CA denotes the upstream contribution area; and max() is a function that returns the maximum value.

The Mann-Kendall (M-K) test is employed to detect monotonic trends, while the Kolmogorov–Smirnov (KS) test assesses the significance of differences between distributions. A 95% confidence interval is used to reject the null hypothesis. Key metrics in this study include the increase ratio and flashiness (see Eq. 1 and 2). The increase ratio quantifies changes in the 100-year discharge (Q100) between historical stage and future stages. Flashiness measures the speed and intensity of discharge rise during flood events.

Result

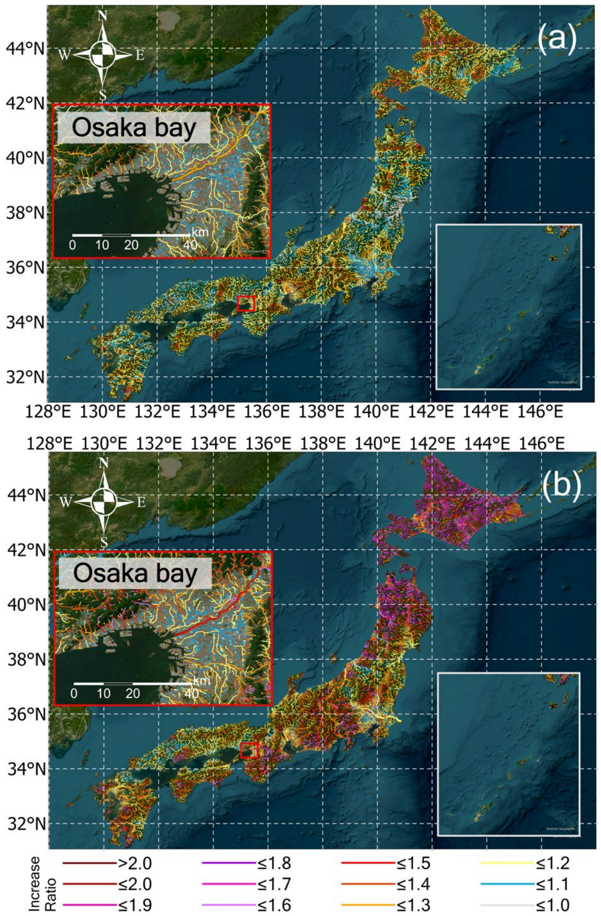

Fig. 1 Spatial distribution of Q100 increase ratios at +2°C (a) and +4°C (b) stages.

According to Fig. 1, Q100s are expected to increase 1.16 (+2°C) and 1.37 (+4°C) times. The northern regions, followed by Chubu, will experience relatively higher increases, with northern regions showing greater climate sensitivity.

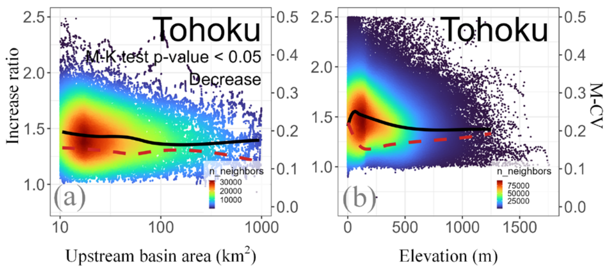

Fig. 2 Q100 increase ratios of Tohoku region vary with basin area and elevation at the +4°C stage

Taking Tokoku region at +4°C stage as an example, Fig. 2 shows the increase ratios in small river basins are comparable to or exceed those of large river basins, underscoring the need for enhanced flood prevention in upstream areas. Additionally, rivers situated in transition zones between mountains and plains show higher increase ratios, necessitating further countermeasures for these vulnerable zones.

Fig. 3 shows that most of the national A-class basins are projected to become more prone to flash floods with flashiness increase by over 10% at the +2°C stage and over 20% at the +4°C stage. Southern Japan, already at high risk of flash floods, is expected to experience further intensification. Northern Japan, particularly under +4°C warming, is poised to face new challenges with a pronounced increase in flashiness, highlighting the urgent need for adaptive flood management strategies.

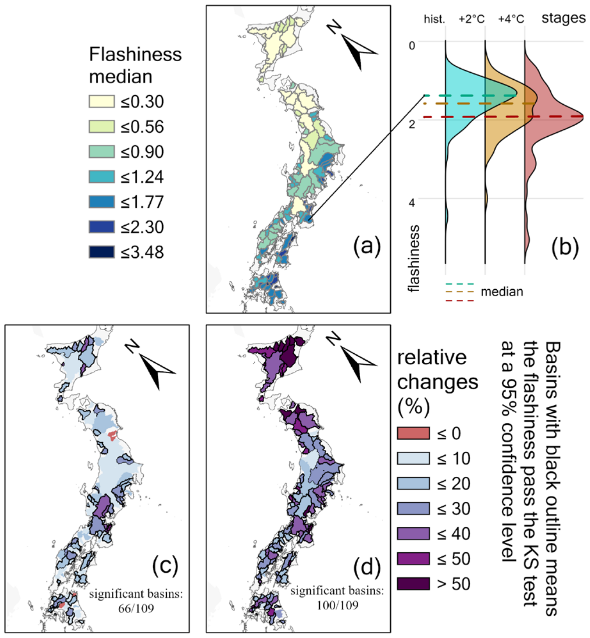

Figure 3 Spatial distribution of flashiness medians and their relative changes at the +2°C and +4°C stages

Conclusion

This study identified critical regions for flood prevention from national and regional perspectives, and revealed an overall elevated flash flood risk across Japan, contributing to informed decision-making and the implement of public-engaged flood mitigation policies.