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Detecting Historical Climate Change Impact on Extreme Rainfall and Flood Discharge Based on Dynamical Downscaling of ERA5: a Case Study in Kuma River Basin, Japan

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Compared with climate change impact assessments based on General Circulation Models (GCMs), the detection of historical climate change signals in extreme rainfall and flood events remain relatively under-examined, especially at the catchment scale in steep, mountainous basins such as Japan. A consistent meteorological–hydrological analysis linking atmospheric drivers to extreme precipitation and resulting river discharge over historical periods is essential for establishing confidence in future flood risk projections. This study investigates the historical evolution of extreme hydroclimatic conditions in Kuma River Basin, Japan, using WRF dynamical downscaling of ERA5 reanalysis (hereafter WRF–ERA5) for the period 1980–2024. Two classes of extreme rainfall are examined: (1) the annual frequency of 12-hour rainfall events exceeding 50 mm (R50mm) and (2) annual maximum 12-hour rainfall accumulation (M12hr).

Key atmospheric variables from the WRF-ERA5 simulation, air temperature (TEMP), specific humidity (SHUM), relative humidity (RH), cloud water content (QCLOUD), and precipitation water content (QRAIN), were extracted for each R50mm and M12hr event. Long-term trends in the vertical atmospheric structure over the basin were evaluated using the non-parametric Mann–Kendall test and the Theil–Sen slope estimator. To quantify hydrological responses to extreme precipitation, a distributed hydrological model 1K-DHM was employed to simulate peak river discharge associated with annual M12hr events.

A heavy rainfall event in Kuma River basin is defined as a 12-hour period with accumulated precipitation exceeding 50 mm (R50mm). The duration of 12 hour is determined according to flood travel time in Kuma River Basin (Ministry of Land, Infrastructure, Transport and Tourism, 2021). Since R50mm events occur intermittently throughout the year, minimizing seasonal bias is critical for robust trend detection. Analysis of event timing reveals a strong seasonal concentration and increasing frequency during June and July; accordingly, atmospheric variables were extracted only for June–July R50mm events over 1980–2024 (**Fig. 1**).

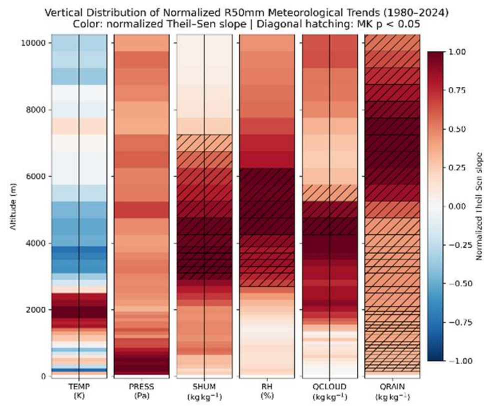

Fig. 1 Long-term (1980–2024) normalized R50mm trends of hydroclimatic variables. Diagonal hatching denotes statistically significant trends ($p < 0.05$).

For each year from 1980 to 2024, the single 12-hour period with the highest accumulated precipitation (M12hr) was identified. The 1K-DHM model was used to simulate peak discharge (DIS) associated with each M12hr event. Vertical trend patterns of meteorological variables during M12hr events are broadly consistent with those identified for R50mm events, indicating similar atmospheric evolution during both frequent and peak rainfall extremes (**Fig. 2**).

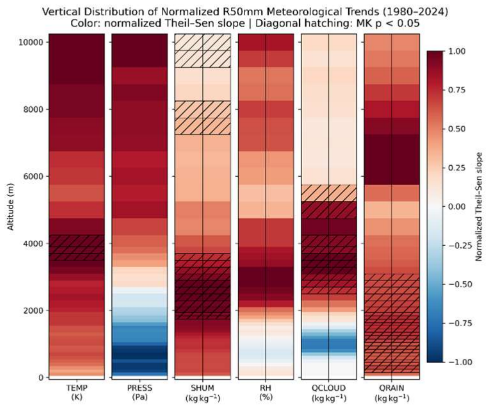

Fig. 2 Long-term (1980–2024) normalized M12hr trends of hydroclimatic variables. Diagonal hatching denotes statistically significant trends based on the Mann–Kendall test ($p < 0.05$).

A key finding of this study is the divergence between rainfall and runoff responses (**Fig. 3**). While the frequency of heavy rainfall events (R50mm) increases significantly (approximately 0.8% yr^{-1}), the magnitude of M12hr rainfall remains statistically stationary (approximately 0.83 mm yr^{-1}). In contrast, simulated peak discharge exhibits a pronounced and statistically significant increasing trend (approximately 39 m^3 s^{-1} yr^{-1}). This divergence indicates a fundamental shift in basin hydrological behavior, whereby flood magnitudes increase even in the absence of non-significant extreme rainfall increases. Such a response implies a rising sensitivity of runoff generation to rainfall inputs. Several interacting mechanisms likely contribute to this non-linear hydrological response. Vertical trend analyses during M12hr events show increasing lower- to mid-tropospheric humidity and localized mid-tropospheric warming, conditions that favor longer-lasting precipitation and reduced evaporative losses rather than sharper rainfall peaks. Consistent with this interpretation, rainfall duration and cumulative rainfall prior to peak intensity exhibit positive, though not statistically significant, trends (approximately 0.21 hr yr^{-1} and 1.48 mm yr^{-1}, respectively).

In summary, all components tested (short-term rainfall intensity, prior rainfall duration and amount, maximum 12-hour rainfall) showed an increasing trend, supported by statistically significant increase in atmospheric moisture, substantially contributed to the increase of antecedent soil moisture, particularly in steep mountainous basins with shallow soils such as Kuma River Basin, and produced disproportionately larger discharge during storm events over years. This rainfall–runoff divergence is consistent with hydrological responses governed by Darcy's law and kinematic wave processes typical of humid mountainous basins in Japan.

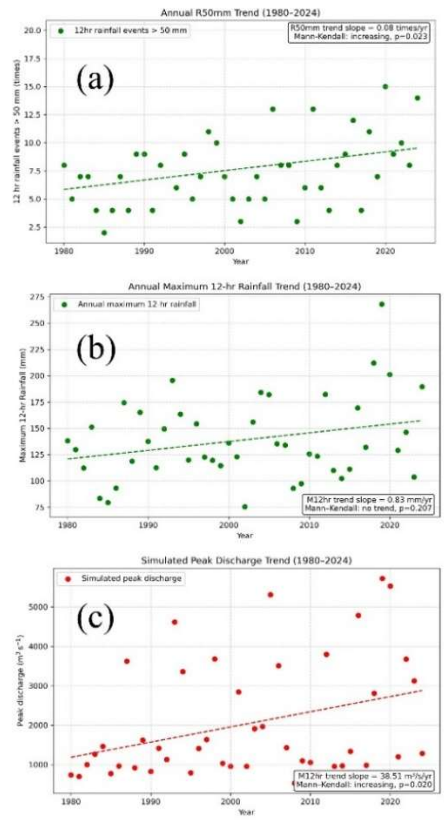

Fig. 3 Long-term (1980–2024) trends in (a) R50mm, (b) M12hr, and (c) DIS in the Kuma River Basin.

Reference

1. Ministry of Land, Infrastructure, Transport and Tourism. (2021). *Kuma River system river improvement basic policy: Materials concerning basic high-water discharge, etc.* (in Japanese). https://www.mlit.go.jp/river/basic_info/jigyo_keikaku/gaiyou/seibi/pdf/kuma/05_kuma_takamizu_R312.pdf