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Greenhouse Gas Forcing and the Changing Persistence of Extreme Rainfall Episodes in East Asia

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Abstract:

This study investigates how greenhouse gas forcing alters the persistence structure of extreme rainfall events in East Asia by combining CMIP6 multi-model ensembles (23 models, daily resolution, 1950–2100, ~2.1 million grid–time samples) with observational datasets (ERA5 and APHRODITE, 1979–2022). Extreme rainfall events are identified using a peaks-over-threshold approach (95th and 99th percentiles), and persistence is quantified through a run-length encoding framework coupled with a generalized extreme value (GEV) distribution for duration modeling. A hierarchical Bayesian model is further introduced to separate thermodynamic and dynamic contributions to persistence changes. Results show that under SSP5-8.5, the frequency of multi-day extreme rainfall events (>3 consecutive days) increases by 26–38%, while mean event duration increases from 2.3 days to 3.1–3.8 days by the end of the century. The tail index of duration distributions shifts significantly ($\Delta\xi \approx +0.12$), indicating heavier persistence tails. Moisture budget diagnostics reveal that column-integrated water vapor increases by 6.8% per °C warming, contributing 57% of the persistence extension, while circulation changes account for the remaining 43%. Model validation against observations yields a correlation of 0.84 for persistence metrics. These results demonstrate that greenhouse gas forcing systematically reorganizes rainfall duration structure rather than merely increasing intensity.

1.INTRODUCTION

Extreme rainfall is a major climate risk in East Asia, where dense population, monsoon rainfall, complex terrain, and rapid urban growth jointly increase flood exposure. Greenhouse gas forcing can intensify the hydrological cycle by increasing atmospheric moisture, altering energy balance, and changing large-scale circulation patterns [1,2]. Recent hydrometeorological research has also shown that analog-ensemble post-processing can improve week 1–2 regional temperature forecasts

and support better prediction of snowmelt, water storage, and streamflow by representing nonlinear atmospheric–hydrologic relationships [3]. This finding suggests that the analysis of rainfall extremes should not focus only on rainfall amount, but should also consider how atmospheric forcing affects the persistence and hydrological consequences of extreme events. In East Asia, these processes are closely linked to the East Asian summer monsoon, the western North Pacific subtropical high, the Meiyu–Baiu rainband, and moisture transport from surrounding oceans [4,5]. These circulation systems can organize rainfall over several days and may produce long-lasting flood hazards when moisture supply and vertical motion remain active. Most previous studies on extreme rainfall in East Asia have focused on rainfall intensity, annual maxima, or percentile-based precipitation indices [6]. These indicators are useful for measuring the magnitude of extreme rainfall, but they do not fully describe the temporal structure of rainfall episodes. Flood risk is strongly affected by rainfall duration because multi-day rainfall can saturate soil, raise river levels, reduce drainage capacity, and increase the probability of compound flooding. Common indices such as Rx5day and consecutive wet days partly describe persistent rainfall, but they often treat duration as a fixed-window or threshold-counting problem rather than as an event-level persistence process [7,8]. As a result, they may miss changes in the full distribution of rainfall-event duration, especially the upper tail of long-lasting extreme rainfall episodes [9,10]. The persistence of extreme rainfall is controlled by both thermodynamic and dynamic factors. Higher temperature increases the water-holding capacity of the atmosphere and can support longer rainfall events when moisture transport remains continuous. At the same time, circulation changes, including monsoon displacement, blocking systems, frontal activity, low-level jets, and vertical motion, strongly affect where rainfall occurs and how long it persists [11,12]. These factors may interact in nonlinear ways. For example, increased water vapor can amplify rainfall intensity, but persistent circulation patterns are often needed to maintain rainfall over multiple days [13]. Therefore, changes in rainfall duration cannot be explained by thermodynamic scaling alone. A more complete analysis should separate the contribution of moisture increase from the contribution of circulation change. Existing studies have not fully tested whether greenhouse gas forcing changes the duration structure of extreme rainfall, rather than only its intensity [14,15]. Some studies rely on short observational records, single datasets, or simple ensemble means, which limits their ability to assess long-term persistence, inter-model uncertainty, and the tail behavior of rainfall duration [16,17]. In addition, many analyses do not directly compare historical observations with future climate projections in a unified event-based framework. This makes it difficult to determine whether future extreme rainfall events in East Asia will simply become stronger, or whether they will also become longer and more clustered in time [18]. This study addresses these gaps by combining CMIP6 multi-model simulations with ERA5 and APHRODITE observations to examine extreme rainfall persistence in East Asia from 1950 to 2100. Extreme rainfall events are identified using the 95th and 99th percentile thresholds, and event duration is measured using run-length encoding to capture the continuous structure of rainfall episodes. A generalized extreme value distribution is used to model the tail behavior of event duration, while a hierarchical Bayesian model is applied to separate thermodynamic and dynamic contributions. This study aims to quantify changes in multi-day extreme rainfall, test whether the duration tail becomes heavier under greenhouse gas forcing, and clarify the relative roles of water vapor increase and circulation change. By shifting the focus from rainfall magnitude alone to event persistence, this work provides a more detailed basis for understanding future flood risk, improving regional climate-risk assessment, and supporting adaptation planning for East Asia.

2.Materials and Methods

2.1 Study Area and Sample Description

The study area covered East Asia, including eastern China, the Korean Peninsula, Japan, and nearby monsoon regions. This region was selected because it is strongly affected by the East Asian summer monsoon, western North Pacific moisture transport, and frequent multi-day rainfall. Daily precipitation data from 23 CMIP6 models were used for 1950–2100 under historical and future forcing conditions. The dataset included about 2.1 million grid–time samples after spatial and temporal matching. ERA5 and APHRODITE daily precipitation data from 1979 to 2022 were used as observation-based references. Grid cells with many missing values, weak rainfall seasonality, or poor overlap between model and observation periods were removed. The final samples covered both coastal and inland rainfall regimes.

2.2 Experimental Design and Control Tests

The experiment tested whether greenhouse gas forcing changes the duration of extreme rainfall events. Historical simulations were used as the reference period, and SSP5-8.5 simulations were used as the high-forcing experiment. Extreme rainfall events were defined by the 95th and 99th percentile thresholds for each grid cell. This setting considered regional differences in rainfall amount. One control test used the historical period to check whether the models could reproduce rainfall duration in ERA5 and APHRODITE. Another control test used intensity-based indices, such as extreme rainfall frequency and annual maximum daily rainfall. This comparison tested whether greenhouse gas forcing changes rainfall duration beyond rainfall intensity.

2.3 Measurement Methods and Quality Control

Daily precipitation data from CMIP6, ERA5, and APHRODITE were converted to the same unit and regridded to a common spatial resolution. Calendar differences among CMIP6 models were corrected before event identification. Missing values, negative precipitation values, and abnormal spikes were checked and removed. For each grid cell, percentile thresholds were calculated from the baseline period and then applied to the historical and future periods. Extreme rainfall events were defined as consecutive days with precipitation above the selected threshold. Short gaps from missing records were not filled, because this could falsely extend rainfall events. Model outputs were checked against ERA5 and APHRODITE using event frequency, mean duration, and persistence correlation.

2.4 Data Processing and Model Formulation

Extreme rainfall duration was measured using run-length encoding. For each grid cell, a binary rainfall sequence was built from the selected threshold. Consecutive extreme-rainfall days were counted as one event, and the number of days was taken as event duration. The binary sequence was written as:

$$I_t=\begin{cases}1, & P_t \geq P_q \\ 0, & P_t < P_q\end{cases}$$

where P_t is daily precipitation on day t, and P_q is the local 95th or 99th percentile threshold. Event duration was the length of consecutive $I_t=1$ days. The tail behavior of rainfall duration was fitted with a generalized extreme value distribution:

$$G(z)=\exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\xi}\right\}$$

where z is event duration, μ\muμ is the location parameter, σ is the scale parameter, and ξ is the tail-shape parameter. A higher ξ means a heavier duration tail and a higher chance of long-lasting extreme rainfall.

2.5 Bayesian Attribution and Model Evaluation

A hierarchical Bayesian model was used to separate thermodynamic and dynamic contributions to rainfall-duration changes. Column water vapor represented the thermodynamic factor. Low-level wind, vertical velocity, and moisture convergence represented the dynamic factors. The model estimated how much each factor contributed to changes in rainfall duration across models, regions, and periods. Posterior distributions were obtained for multi-day event frequency, mean duration, and the GEV tail parameter. Model performance was evaluated by comparing CMIP6-based duration metrics with ERA5 and APHRODITE during 1979–2022. Ensemble uncertainty was reported with credible intervals. Robustness was tested using both the 95th and 99th percentile thresholds.

3.Results and Discussion

3.1 Changes in Multi-Day Extreme Rainfall Events

The CMIP6 ensemble showed a clear rise in persistent extreme rainfall under SSP5-8.5. By the late twenty-first century, the frequency of extreme rainfall events lasting more than three consecutive days increased by 26–38%. Mean event duration also increased from 2.3 days to 3.1–3.8 days. This result shows that greenhouse gas forcing changes both rainfall amount and rainfall duration [19]. The increase was stronger in coastal and river-basin regions affected by the monsoon, where moisture supply and frontal rainfall are more active. This pattern agrees with recent CMIP6 studies that reported stronger East Asian summer monsoon rainfall and larger rainfall variability under warming. The spatial pattern of persistence change is shown in Fig. 1.

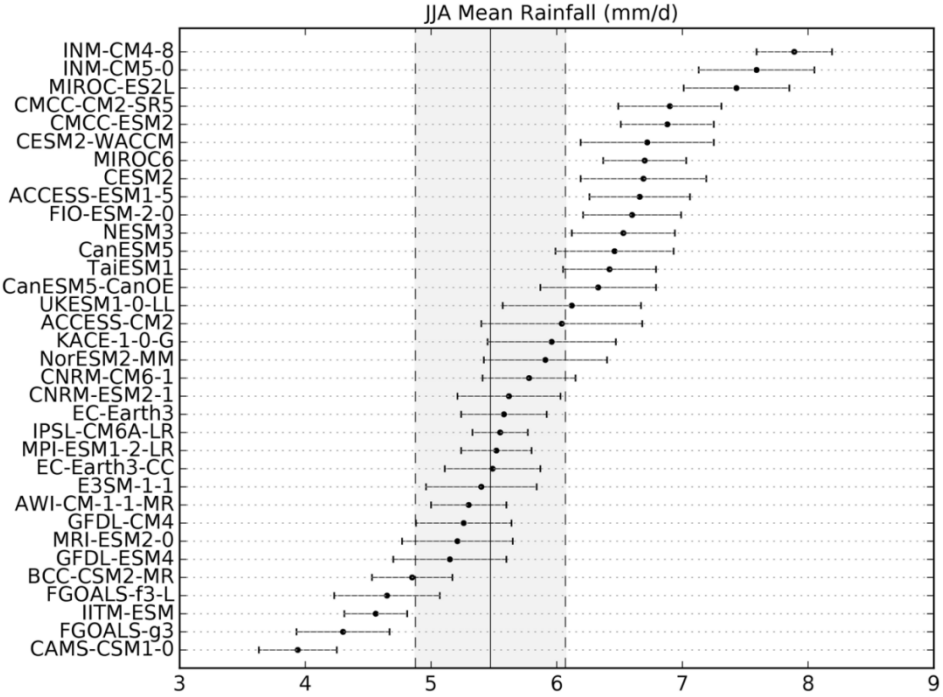


Fig. 1. Changes in multi-day extreme rainfall duration over East Asia under SSP5-8.5.

3.2 Duration Tail Changes and Long Rainfall Risk

The GEV results showed a positive shift in the duration tail index, with $\Delta\xi$ close to +0.12. This means that long-lasting extreme rainfall became more likely under strong greenhouse gas forcing. Compared with rainfall intensity indices, the duration-tail metric gives more information on flood risk. Longer rainfall events can increase soil wetness, river storage, and delayed runoff. Many previous studies used percentile thresholds, annual maxima, or seasonal rainfall indices to study extreme precipitation. These indices are useful, but they do not fully show whether extreme rainfall

lasts longer. The present study adds this missing part by focusing on event duration and heavier persistence tails rather than daily rainfall intensity alone [20,21].

3.3 Thermodynamic and Dynamic Contributions

The Bayesian attribution results showed that thermodynamic forcing explained 57% of the persistence increase, while dynamic changes explained 43%. Column water vapor increased by about 6.8% per °C warming. This added moisture helped rainfall continue for several days when uplift and convergence were present [22]. Circulation changes also had a clear role. Low-level wind, vertical motion, and moisture convergence affected where rainfall persisted and how long it lasted. These results show that persistent extreme rainfall is not caused by moisture increase alone. It is also affected by circulation patterns that keep moisture and upward motion over the same region. The related circulation response is shown in Fig. 2.

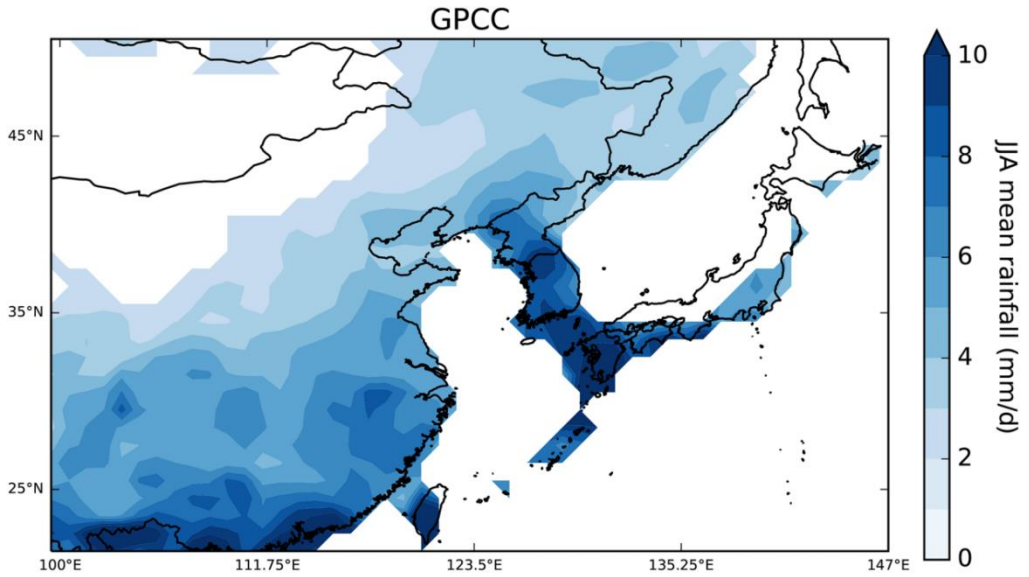


Fig. 2. Moisture and circulation contributions to longer extreme rainfall events.

3.4 Model Validation and Scientific Meaning

Validation against ERA5 and APHRODITE showed a correlation of 0.84 for persistence metrics. This result suggests that the selected CMIP6 models captured the main observed duration features. However, model spread remained large in complex terrain and coastal transition zones. This uncertainty may come from coarse model resolution, smoothed terrain, and weak representation of mesoscale rainfall systems. The main scientific value of this study is that it treats extreme rainfall as a sequence of events rather than isolated daily extremes. The results show that greenhouse gas forcing changes the persistence structure of rainfall episodes. This finding is important for flood control, drainage design, reservoir operation, and climate risk assessment in East Asia.

4.Conclusion

This study examined how greenhouse gas forcing affects the duration of extreme rainfall events in East Asia. By using CMIP6 simulations with ERA5 and APHRODITE observations, the study showed that multi-day extreme rainfall becomes more frequent and lasts longer under SSP5-8.5. Events lasting more than three consecutive days increased by 26–38%, and mean duration rose from 2.3 days to 3.1–3.8 days by the late twenty-first century. The positive change in the GEV tail index shows a higher chance of long rainfall events. Bayesian attribution showed that water vapor increase explained 57% of the duration change, while circulation changes explained 43%. These results indicate that greenhouse gas forcing changes rainfall duration, not only rainfall intensity.

The main value of this study is its event-based method, which links extreme rainfall identification, duration calculation, tail modeling, and physical attribution. This method can support flood-risk assessment, drainage design, reservoir operation, and climate adaptation planning in East Asia. However, uncertainty remains because CMIP6 models have limited resolution and may not fully describe terrain effects, mesoscale convection, and local circulation. Future work should use higher-resolution regional models and longer observation records to improve the assessment of long-lasting extreme rainfall risk.

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