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Postprint: Spatiotemporal Characteristics of Extreme Precipitation in the Ili River Basin Based on CMIP6

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Abstract

Under global warming, disaster risks associated with extreme precipitation events are increasingly exacerbated, posing severe threats to regional socioeconomic development and public life and property safety. This study first conducts a spatiotemporal characteristic analysis of eight extreme precipitation indices in the Yili River Basin from 1981 to 2024, and employs the multi-model ensemble mean method and Sen's slope estimator to analyze spatiotemporal variations of extreme precipitation indices under different scenarios from 2025 to 2050, utilizing data from multiple models of the Coupled Model Intercomparison Project Phase 6 (CMIP6) under various scenarios. The results indicate that: (1) Extreme precipitation indices in the Yili River Basin during 1981–2024 predominantly exhibit increasing trends, particularly pronounced in the eastern and southwestern mountainous regions. (2) Under SSP245 and SSP585 scenarios for 2025–2050, extreme precipitation demonstrates considerable variability yet an overall upward trend, with the SSP585 scenario showing more frequent and intense extreme precipitation events. Annual precipitation and heavy precipitation events increase significantly in the eastern and southern mountainous areas of the Yili River Basin, displaying stronger precipitation trends and elevated extreme precipitation risks, whereas the northern and central plain regions experience relatively fewer heavy precipitation events. Such spatial heterogeneity may differentially affect the frequency of regional natural disasters, agricultural production, and livestock husbandry. These findings can provide a scientific basis for local government agencies to develop prevention and control strategies for extreme precipitation events.

Full Text

Abstract

Under the influence of global warming, the disaster risks associated with extreme precipitation events are intensifying, posing serious threats to regional socioeconomic development and public safety. This study analyzes the spatio-temporal characteristics of eight extreme precipitation indices in the Ili River Basin from 1981 to 2024, and projects their changes from 2025 to 2050 under different scenarios using multimodel ensemble data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and Sen's slope estimation method. The results show that: (1) From 1981 to 2024, most extreme precipitation indices exhibited an increasing trend, particularly in the eastern and southwestern mountainous regions. (2) From 2025 to 2050, under the SSP245 and SSP585 scenarios, extreme precipitation is projected to show large fluctuations but an overall upward trend. Specifically, under the high-emission SSP585 scenario, extreme precipitation events are expected to become more frequent and intense, with significant increases in annual precipitation and heavy precipitation events in the eastern and southern mountainous areas of the Ili River Basin, demonstrating a stronger precipitation trend and higher extreme precipitation risk. In contrast, heavy precipitation events are projected to be relatively fewer in the northern and central plains. This spatial heterogeneity may differentially impact the frequency of natural disasters and agricultural and pastoral production across the region. The findings provide a scientific basis for local governments to formulate strategies for preventing and mitigating extreme precipitation hazards.

Keywords: CMIP6; extreme precipitation; spatio-temporal variation characteristics; Ili River Basin

Introduction

Climate change intensifies extreme precipitation events by increasing their frequency, intensity, and duration, causing severe damage to socioeconomic development and ecosystems []. Furthermore, extreme precipitation, particularly when precipitation intensity reaches certain thresholds, can trigger flooding disasters that pose serious threats to lives and property []. Therefore, investigating the spatio-temporal distribution patterns of extreme precipitation and projecting future conditions are crucial for enhancing disaster resilience and formulating adaptation strategies across regions. Climate change has led to divergent trends in extreme precipitation across different regions, triggering disastrous events and attracting widespread societal attention []. Zhang et al. [] employed extreme value distribution and statistical methods to analyze the spatio-temporal evolution of extreme precipitation in the Qinling region across multiple phases, comparing seasonal differences. Zou et al. [] selected precipitation amount, intensity, maximum precipitation, and heavy precipitation indices, applying the Mann-Kendall trend test and wavelet transform to analyze extreme precipitation in the Wei River Basin, further exploring relationships between extreme precipitation indices and atmospheric circulation factors. Zhao et al. [] studied extreme precipitation in Northwest China using the Mann-Kendall test, finding increasing trends in extreme precipitation events in the arid regions of Northwest China, particularly in Northern Xinjiang and the Tianshan Mountains. Yang et al. [] analyzed the spatio-temporal evolution of summer extreme heavy precipitation in Xinjiang using percentile threshold methods, revealing patterns in arid and semi-arid regions. These studies show that increased frequency and intensity of extreme precipitation have led to more rainstorm floods and geological hazards such as landslides and debris flows in Northwest China, including Xinjiang []. Given the growing frequency and intensity of extreme precipitation events and their potential to trigger major floods, investigating their trends and patterns has become particularly urgent and important [].

Analyzing potential future climate change impacts represents a major goal of global climate research, and the Coupled Model Intercomparison Project Phase 6 (CMIP6), led by the World Climate Research Programme, serves as the primary means to achieve this objective []. Multimodel ensemble analysis not only enhances understanding of climate system complexity but also provides scientific foundations for predicting and responding to future climate change. Previous studies have selected various CMIP6 models for different research purposes. For example, Wang et al. [] evaluated 20 CMIP6 models for simulating diurnal temperature range in China; Hu et al. [] assessed high-resolution models for precipitation characteristics; Yang [] and Xiang et al. [] analyzed climate state distributions and extreme temperature and precipitation features; Zhang et al. [] selected optimal models to analyze precipitation and temperature variations in Xinjiang. While some studies have examined precipitation spatio-temporal evolution in the Ili River Basin, in-depth analysis of extreme precipitation and future projections remains limited []. Therefore, this study focuses on the Ili River Basin, analyzing spatio-temporal distribution characteristics of eight extreme precipitation indices from 1981 to 2024, and systematically examining their evolution under different climate scenarios using CMIP6 multimodel ensemble data to provide scientific support for regional extreme precipitation projections.

1 Study Area Overview

The Ili River Basin is located in Xinjiang Uygur Autonomous Region, China, situated between the northern branch of the Borokhoro Mountains and the southern branch of the Kharkh Mountains, with geographical coordinates ranging from 80°09 ~84°56 E and 42°14 ~44°50 N. It serves as an important corridor connecting China with Central Asia, West Asia, and Europe []. The study area features diverse landform types, with an overall terrain pattern of "higher in the east and lower in the west, narrower in the east and wider in the west" []. Due to its location in the hinterland of the Eurasian continent, surrounded by mountains on three sides, warm and moist airflows from the west can directly converge into the Ili Valley plain, significantly increasing the probability of extreme precipitation events []. Additionally, the basin's large topographic relief causes most precipitation to converge into the Ili River, exposing residents along the river to severe threats from mountain floods []. These unique geographical and climatic conditions make the Ili River Basin a high-incidence area for extreme precipitation events, significantly impacting the regional ecological environment, residents' lives, and interregional economic and cultural exchanges.

2 Data Sources and Model Selection

The meteorological data used in this study are divided into two categories: historical observations and future simulations. Historical precipitation data consist of daily precipitation datasets from national meteorological stations in the Ili River Basin for the period 1981-2024 (http://data.cma.cn), which have undergone quality control. Drawing upon previous experience in model selection for China and Xinjiang, and considering research requirements and data availability, we ultimately selected 20 climate models from CMIP6 (https://node.llnl.gov/search/cmip6/). These models were bilinearly interpolated to a 0.25°$×$0.25° resolution and downscaled to each meteorological station, followed by bias correction using the Delta method to obtain corrected data for each model .

To screen for climate models suitable for the Ili River Basin, we compared the bias-corrected data from 20 models with observed daily precipitation data from 1981-2024 using Taylor diagrams (Figure 2). The Taylor diagram comprises three metrics: standard deviation, correlation coefficient, and root mean square error (RMSE). Model accuracy is evaluated based on: standard deviation approaching 1 indicates optimal simulation; polar angle represents correlation strength, with larger values indicating better fit; and concentric arcs reflect RMSE, where smaller radius indicates higher accuracy. The analysis revealed that ACCESS and WACCM showed negative correlations with observations, while CESM2 exhibited relatively low correlation. Consequently, these three models were excluded. The final selection retained 17 models, including CanESM5, CESM2-WACCM, Earth3, FGOALS, NESM3, NorESM2, and UKESM1, all showing correlation coefficients greater than 0.6 with minimal inter-model differences. To eliminate confounding factors, these 17 climate models were retained for further analysis.

3 Methods

3.1 Extreme Precipitation Indices

This study selected eight extreme precipitation indices from the 27 core indices defined by the World Meteorological Organization's Commission for Climatology and Climate Variability and Predictability Programme . The established extreme precipitation index system categorizes these eight characteristic indices into intensity, relative, and absolute indices. All indices were calculated using the RClimDex 1.0 software.

3.2 Delta Method

The Delta method is a commonly used bias correction approach that calculates biases between model and observational data and applies these biases to adjust future model data, thereby achieving bias correction for future projections []. By implementing the Delta bias correction method, we first calculated the bias between model data and observations during the reference period (1981-2024), i.e., the Delta value. Subsequently, we used the established Delta relationship to adjust future CMIP6 model precipitation data, obtaining more refined and realistic projections.

3.3 Multimodel Ensemble Mean Method

The multimodel ensemble mean method (Multi Model Ensemble) serves as an important approach in climate simulation research [], primarily including equal-weight and unequal-weight ensemble methods. This study employs the equal-weight ensemble average method, calculated as:

$$EE = \frac{1}{N}\sum_{i=1}^{N} F_i$$

where EE represents the equal-weight ensemble average, N is the number of models, and F_i is the simulation result from the i-th model.

3.4 Mann-Kendall (M-K) Trend Test

The Mann-Kendall trend test is commonly used to detect upward or downward trends in time series data. A key advantage is its independence from specific data distributions and its ability to handle data containing outliers and non-normal distributions, making it highly suitable for analyzing time series in climatology, hydrology, and environmental science []. Specifically, when the Z-value exceeds 1.96, it indicates a significant upward trend at the 95% confidence level.

3.5 Sen's Slope Estimation Method

Sen's slope estimation is a nonparametric statistical method that estimates trend slopes by calculating the median of all possible pairwise slopes in the data. This method is insensitive to outliers and can handle non-normally distributed data, making it widely applicable for trend analysis, anomaly detection, and forecasting tasks []. By calculating the slope β of the time series, if $\beta > 0$, it indicates an upward trend; if $\beta < 0$, it indicates a downward trend; and if $\beta = 0$, it indicates no significant change.

4 Results

4.1 Bias Correction Results

Using the Delta bias correction method, we adjusted daily precipitation from 17 climate models. The comparison shows that before bias correction, simulated values exhibited large deviations from observations with unclear seasonal trends. After Delta bias correction at the daily scale, these biases were significantly reduced, bringing simulated daily precipitation much closer to observations. Notably, summer precipitation (especially June-August) is relatively larger, while winter precipitation (December-February) is smaller, consistent with actual seasonal precipitation patterns. This seasonal precipitation difference is well captured in the bias-corrected data [Figure 3: see original paper].

4.2 Evaluation of CMIP6 Climate Model Performance

We employed Taylor diagrams to compare simulation performance between 17 individual climate models and the multimodel ensemble mean (MME) dataset against observations (Figure 4). The MME demonstrated optimal performance with the lowest standard deviation (0.98) and highest correlation coefficient (0.85) relative to observations, along with lower RMSE, outperforming all individual models. In contrast, single models showed varying performance. For instance, Earth3 exhibited good correlation (0.78) but relatively high standard error and RMSE (1.043, 0.133). CanESM5 showed moderate correlation (0.71) but high standard error and RMSE (1.164, 0.174), indicating substantial predictive uncertainty. FGOALS performed poorly across all metrics with high standard error and RMSE (1.126, 0.141) and low correlation (0.65), showing weak linear relationships with observations. NESM3 showed moderate performance with standard error and RMSE of 1.110 and 0.125, respectively, but correlation coefficient of only 0.68. NorESM2 performed well in standard error and RMSE (1.115, 0.128) but had correlation of only 0.66. Overall, MME outperformed individual models and was therefore adopted to analyze spatio-temporal characteristics of extreme precipitation indices under SSP245 and SSP585 scenarios.

4.3 Historical Spatio-Temporal Distribution of Extreme Precipitation Indices (1981-2024)

The temporal characteristics of extreme precipitation indices in the Ili River Basin from 1981-2024 reveal significant interannual variability. The total precipitation index (PRCPTOT) showed a slow overall upward trend, with higher precipitation in 1998-1999 (818.5 mm) and the lowest value of 514.5 mm in 1985, demonstrating substantial annual variation. Heavy precipitation (R95p) and very heavy precipitation (R99p) fluctuated considerably but exhibited overall upward trends, particularly with large increases in 1998-1999. Maximum 1-day precipitation (RX1day) and maximum 5-day precipitation (RX5day) showed strong interannual variability with slow upward trends, reaching high values in 1998-1999 that indicate severe extreme precipitation events. Precipitation intensity (SDII), as a measure of precipitation intensity, remained relatively stable in most years but increased slowly in high-precipitation years like 1998-1999, suggesting more concentrated and intense rainfall. The longest dry spell (CDD) showed an overall decreasing trend, peaking at 54.1 days in 1985 and reaching its lowest value of 22.9 days in 2010, indicating significant interannual differences in dry period duration. The longest wet spell (CWD) remained relatively stable, fluctuating between 3-6 days, but reached 6.01 days in 1998, showing extended continuous precipitation periods.

The spatial distribution of four extreme precipitation indices (PRCPTOT, RX1day, RX5day, and CDD) shows higher values in eastern and southwestern mountainous areas and lower values in northwestern mountainous and central plain regions. Specifically, PRCPTOT is highest in Xinyuan County (502.95 mm) and Zhaosu County (482.3 mm), indicating these areas receive the most abundant annual precipitation. Notably, Xinyuan County shows high RX1day and RX5day values, particularly its SDII of 6.24 mm $\cdot$ d^{-1}, far exceeding other counties and demonstrating both high precipitation amount and intensity. The longest dry spell (CDD) shows a west-high-east-low pattern, with Horgos City (34.28 days) and Qapqal Xibe Autonomous County (33.5 days) experiencing longer drought cycles, while Nileke County (25.75 days) receives more abundant precipitation. The longest wet spell (CWD) varies significantly, with higher values in eastern and southwestern mountainous areas and lower values in northwestern to central plains. Zhaosu County reaches 6.01 days, significantly higher than other regions, indicating more sustained precipitation periods [Figure 5: see original paper].

4.4 Future Temporal Distribution of Extreme Precipitation Indices (2025-2050)

Under SSP245 and SSP585 scenarios, extreme precipitation indices show significant differences and fluctuations from 2025-2050. Indices such as PRCPTOT, RX1day, and RX5day exhibit upward trends, indicating increasing extreme precipitation events in the Ili River Basin. While both scenarios show upward trends, SSP585 demonstrates larger increases and stronger fluctuations.

Under SSP245, PRCPTOT remains relatively stable, fluctuating between 384.5-404.5 mm. Under SSP585, it shows significant increases, reaching a peak of 435.5 mm, though with lowest values of 314.9 mm and 385.9 mm in certain years, indicating greater uncertainty. Both R95p and R99p fluctuate markedly, with higher intensity and variability under SSP585. SDII fluctuates between 1.74-1.91 mm $\cdot$ d^{-1} under SSP245 and 1.65-1.98 mm $\cdot$ d^{-1} under SSP585, with peaks in 2035 and 2045, suggesting increased probability of extreme precipitation events.

CDD fluctuates between 13.28-55.08 days under SSP245 and 6.17-55.29 days under SSP585, with extreme low values appearing in 2035. CWD shows no clear long-term trend but fluctuates more dramatically under SSP585, with peaks of 55.29 days in 2035 and 21.9 days in 2048, indicating more prominent extreme precipitation characteristics [Figure 6: see original paper].

4.5 Mann-Kendall Trend Characteristics of Future Extreme Precipitation Indices

Mann-Kendall trend test analysis reveals that under the SSP585 scenario, all extreme precipitation indices except CWD show Z-values greater than 1.96, indicating significant upward trends. Under SSP245, Z-values range 0.64-1.67, showing slow increases. PRCPTOT under SSP585 shows Z-values higher than SSP245, with more significant increases in eastern and southern mountainous areas, potentially triggering rainstorm floods and landslides. Central plains show smaller increases under SSP245. RX1day and RX5day show significant upward trends under both scenarios, with more pronounced increases under SSP585. Eastern and southern mountainous areas exhibit the largest increases under both scenarios, likely related to topography and climate sensitivity [Figure 7: see original paper].

4.6 Spatial Distribution of Future Extreme Precipitation Trends

Analyzing spatial distribution of multi-year average daily precipitation under future scenarios reveals that high-precipitation areas under SSP245 concentrate in southern regions of the Ili River Basin, with values of 0.00-19.84 mm. Under SSP585, high-precipitation areas expand to include both southern and eastern regions, with values of 2.02-20.76 mm, showing more extensive high-value zones. The SSP585 scenario projects slightly higher precipitation than SSP245, with significant peaks in 2035 and 2045.

To analyze spatial trends from 2025-2050, we divided the Ili River Basin into four subregions: northern (Horgos City, Huocheng County), southern (Zhaosu County, Tekes County), central (Yining City, Yining County, Gongliu County, Qapqal Xibe Autonomous County), and eastern (Nileke County, Xinyuan County). Calculating Sen's slope values for 10 meteorological stations under SSP245 and SSP585 scenarios reveals distinct spatial patterns.

Under SSP245, Sen's slope values range 0.11-0.21, indicating weak increases. Under SSP585, values increase more significantly, with Zhaosu County reaching 0.97. In terms of PRCPTOT, stations in Nileke, Xinyuan, and Gongliu counties show the strongest increases, while Horgos and Tekes stations show weaker increases with slope values of 0.11 and 0.13, respectively. Under SSP245, eastern and southern mountainous areas show increased annual precipitation and heavy precipitation events (R95p), particularly in northeastern and southwestern mountainous regions, elevating rainstorm flood risks. Central plains experience fewer heavy precipitation events. Under SSP585, RX1day increases significantly, with slope values of 0.21 in Yining City and 0.19 in Nileke County, indicating increased frequency of extreme precipitation events. RX5day shows minimal difference between scenarios, fluctuating 13.0-21.9 mm under SSP245 and 14.5-21.8 mm under SSP585, with no long-term trend but larger fluctuations under SSP585 [Figure 8: see original paper] [Figure 9: see original paper].

5 Conclusions

This study analyzed spatio-temporal distribution characteristics of extreme precipitation events in the Ili River Basin from 1981-2024 and revealed evolution patterns of extreme precipitation indices under different scenarios from 2025-2050 using CMIP6 data. The main conclusions are:

(1) From 1981-2024, extreme precipitation indices in the Ili River Basin showed clear upward trends, particularly PRCPTOT, R1Xday, and R5Xday, with more pronounced increases in eastern and southwestern mountainous areas. The northwestern to central plains received relatively less precipitation.

(2) From 2025-2050, under SSP245 and SSP585 scenarios, extreme precipitation indices show upward trends with large fluctuations. Under high-emission SSP585, extreme precipitation becomes more frequent and intense, with remarkable increases in annual precipitation and heavy precipitation events in eastern and southern mountainous regions, indicating stronger precipitation trends and higher risks. In contrast, northern and central plains are projected to experience relatively fewer heavy precipitation events. This spatial heterogeneity may differentially impact natural disaster frequency and agricultural/pastoral production.

(3) With increasing carbon emissions, extreme precipitation events in the Ili River Basin show upward trends, primarily reflected in intensity indices PRCPTOT and R99p. Statistical Z-values increase with emission levels, indicating strengthening trends. Under high-emission SSP585, the Ili River Basin may face more extreme precipitation events, leading to increased annual precipitation and precipitation intensity. Spatially, eastern and southern mountainous areas show the most significant increases, while central plains show smaller increases. Under SSP585, heavy precipitation events increase in eastern and southern mountainous areas, raising risks of rainstorm floods and geological disasters. Central plains experience fewer heavy precipitation events, where precipitation changes will differentially impact regional social life and agricultural production.

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