Impacts of climate change on extreme precipitation in the upstream of Chushandian Reservoir, China

Rong Gan\textsuperscript{a,b}, Dandan Li\textsuperscript{a,c}, Changzheng Chen\textsuperscript{a,c}, Feng Yang\textsuperscript{d,*} and Xichen Ma\textsuperscript{d}

\textsuperscript{a}School of Water Conservancy Engineering, Zhengzhou University, Zhengzhou 450001, China
\textsuperscript{b}Henan Key Laboratory of Groundwater Pollution Prevention and Rehabilitation, Zhengzhou 450001, China
\textsuperscript{c}Henan International Joint Laboratory of Water Cycle Simulation and Environmental Protection, Zhengzhou 450001, China
\textsuperscript{d}Construction Management Company for Chushandian Reservoir of Project of Henan Province, Xinyang 464000, China

*Corresponding author. E-mail: ktz2022@163.com

ABSTRACT

Analysis of trends in extreme precipitation events within a basin is essential to reliably predict future changes and to inform adaptation strategic planning. Based on daily data from eight stations in the upper basin of Chushandian Reservoir from 1957 to 2017, and Multi-model outputs from four Global Climate Models in CMIP6, we calculated the extreme precipitation index. Mann-Kendall method and linear trend analysis were used to examine the spatial and temporal variability of the extreme precipitation index. The results show that there is a clear downward trend in precipitation and precipitation intensity from 1957 to 2017 (represented by RX1day, RX5day, R10 mm, R20 mm, and SDII), and an upward trend in the annual scales of R95p, R99p, CWD, and CDD. The trend of the extreme precipitation index (represented by PRCPTOT, R20 mm, R95p, and SDII) in future periods is decreasing in 2020–2050 and then increasing in 2060–2100, with a significant increasing trend after the 2060s. These findings indicate that total precipitation, the frequency, and persistence of extreme precipitation are on the increase, and the future situation of extreme precipitation is severe, especially in autumn, followed by summer.

Key words: Chushandian reservoir, climate change, CMIP6, extreme precipitation index

HIGHLIGHTS

- There is a significant downward trend in the total amount and intensity of extreme precipitation in the study area in 1957–2017.
- Global warming tends to increase extreme precipitation in terms of frequency and intensity.
- Extreme precipitation value domains predicted by climate change are noticeably higher than historical levels.
INTRODUCTION

The 4th, 5th, and 6th Assessment Reports of the United Nations Intergovernmental Panel on Climate Change (Alexander et al. 2013) all point to significant changes in land-surface precipitation patterns in the context of global climate change, posing enormous challenges to the ecological environment, human life, and social development (Lu et al. 2021). The frequency and intensity of extreme precipitation events have increased in recent years, and extreme precipitation has become a hot issue in the field of global climate change and its impacts (Ribes et al. 2018). On a global scale, extreme precipitation shows a significant and widespread positive trend in most parts of the world (Lowry et al. 2016). Extreme precipitation variability in China is consistent with global trends (Zhou et al. 2016; Shi et al. 2018). Precipitation is more spatially heterogeneous than temperature and has a direct impact not only on surface river runoff but also on agricultural development and food security (Gao et al. 2017). The extreme precipitation in China exhibits obvious regional characteristics in the global climate context (Cao et al. 2019). From July 17 to July 20, 2021, Zhengzhou City, Henan Province, China, accumulated 617.1 mm of rainfall in 3 days, while the average annual rainfall is 640.8 mm (Shi et al. 2021). The continuous heavy precipitation caused the subway to stop running, traffic paralysis, widespread power outages, casualties, and the emergency evacuation of 100,000 residents.
Global climate models are an effective tool for predicting extreme hydrological events under future climate change. Due to the resolution and associated uncertainty of Global Climate Models (GCMs), it is limited in the reliable response of small watersheds to future climate conditions. However, Multi-model integration results show better simulation performance by reducing spatial ambiguity and inconsistency (Mondal et al. 2021). The results of many studies on Coupled Model Intercomparison Project phase 5 (CMIP5) (Samuels et al. 2018) collectively showed that multi-model ensemble means tend to be more representative of precipitation characteristics than individual models. CMIP6 is organized differently from the five previous ones. These changes mainly take into account the quantification of the radiative forcing caused by nature or by humans. In general, CMIP6 products outperform CMIP5 statistics in terms of performance accuracy (Baaci et al. 2021), especially precipitation, and the climate signal obtained through CMIP6 has been significantly improved. The output of global climate models is used to explore the trends of extreme precipitation changes with future climate change, which is an effective means to avoid extreme disaster events and reduce accident risks.

The Huaihe River brings abundant hydropower energy, but extreme precipitation events occur frequently in the upper reaches of the Huaihe River, and people living along the river are under serious threat from flood and drought disasters (Yang et al. 2013). The CR plays an important role in controlling floods in the upstream mountainous areas and improving flood control standards in the downstream rivers, while making full use of flood resources to promote local economic development. It is crucial to grasp the spatial and temporal characteristics of extreme precipitation for the safe operation of the reservoir dams and for safeguarding the lives and properties of the surrounding living residents. However, the current research mainly focuses on the analysis of historical hydro-meteorology and lacks the exploration of future extreme precipitation. This study provides useful information for analyzing water resources management, risk control, ecosystem protection as well as climate change impacts.

This study focuses on the following aspects: (1) analyzing the temporal trends and spatial distribution characteristics of the interannual variation of extreme precipitation in the upstream of CR from 1957 to 2017 and (2) exploring the temporal trends and abrupt changes of the interannual variation of the regional extreme precipitation index in the study area from 2021 to 2100.

**STUDY AREA AND DATA**

**Study area**

The Chushandian Reservoir (CR) is located in the central region of China, and the reservoir dam site is situated in the Huaihe River main stream of Xinyang, Henan Province. Above the dam site to the Huaihe River origin river channel length of 100 km, the reservoir control basin area of 2,900 km², the total reservoir capacity of 1.251 billion m³. The basin shape is slightly east-west oval, the east-west length is about 70 km, the average width is 22.3 km, the shape factor is 0.592, the elevation is 80–1,000 m (Figure 1). CR is built with great support from the state, and its main task is flood control, taking into account various functions such as irrigation, water supply, power generation, and tourism. Most of the upstream areas of the reservoir have lush pine forests and good vegetation, and a few hilly areas have sparse grass and forests. The land utilization rate is about 22%, mostly planted with rice and wheat, of which rice fields account for about 70%. Plantation and original forest areas account for about 50% of the watershed area. The soil cover is mostly red-brown powder clay on the slope of the hillock, and heavy loam and sandy loam on the terrace along both banks of the dry tributaries.

The average annual precipitation varies from 842.59 mm in the north to 1,228.69 mm in the south. The precipitation is unevenly distributed within the year, with about 50% of the annual precipitation in summer (June–August), precipitation in winter (December–February) accounting for only 7.85% (Figure 2).

**Data sources**

This study used the long-term observed daily precipitation data from the Chushandian Reservoir Administration of Henan Province. To ensure consistency and completeness of the precipitation data, missing precipitation values on consecutive days were filled by the average precipitation from neighboring stations (Zhang et al. 2011). The precipitation data of eight meteorological stations from 1957 to 2017 were finally selected by excluding stations with shorter data years to guarantee the same time series length.

The CMIP6 (https://esgf-node.llnl.gov/search/cmip6/) released by World Climate Research Programme (WCRP) is the largest number of models involved, the most extensive numerical experiments designed, and the most extensive simulation data provided in the more than 20 years of the CMIP program (Kumar et al. 2013). Four global climate models from the
Scenario Model Comparison Program Scenario Model Intercomparison Project (MIP) (Table 1), all contain historical data from 1850 to present under four combined scenarios (SSP126, SSP245, SSP370, and SSP585). Based on the previous validation of simulation accuracy for different models (Wang et al. 2021), the model with better simulation results is selected.
for Multi-model ensemble averaging. The design of the Scenario (MIP) emission pathway consists of two elements: the determination of the future global average radiative forcing levels and the selection of the socioeconomic scenarios corresponding to each radiative forcing level (Table 2).

**METHODS**

**Extreme precipitation indices**

In this study, 11 extreme precipitation indices (Table 3) were selected to discuss the characteristics of extreme precipitation, as recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) ([http://ccma.seos.uvic.ca/ETCCDI](http://ccma.seos.uvic.ca/ETCCDI)). The RClimDex (1.0) package in R version 3.5.3 ([http://etccdi.pacificclimate.org/software.shtml](http://etccdi.pacificclimate.org/software.shtml)) was used to calculate the extreme precipitation index and for data quality control, such as checking internal consistency and extreme values. These extreme precipitation indices were a reflection of changes in precipitation activity in different aspects such as frequency, intensity, and duration.

**Table 1 | Information of four CMIP6 models used in this study**

| No. | Model           | Institution                                      | Resolution   |
|-----|-----------------|--------------------------------------------------|--------------|
| 1   | BCC-CSM2-MR     | Beijing Climate Center, China Meteorological Administration, China | 1.125°×1.125° |
| 2   | CanESM5         | Canadian Centre for Climate Modelling and Analysis, Canada      | 2.8°×2.8°    |
| 3   | MIROC6          | Japan Agency for Marine-Earth Science and Technology, Japan     | 1.4°×1.4°    |
| 4   | MRI-ESM2-0      | Meteorological Research Institute, Japan              | 1.125°×1.125° |

**Table 2 | Scenario MIP experiments design**

| Name of experiment | Experiment Description |
|--------------------|------------------------|
| SSP585             | High forcing scenario with a stable radiative forcing of ~8.5 W/m² in 2100 |
| SSP370             | Moderate to high forcing scenario, with radiative forcing stable at ~7.0 W/m² in 2100 |
| SSP245             | Medium forcing scenario, radiative forcing stabilizes at ~4.5 W/m² in 2100 |
| SSP126             | Low forcing scenario with a stable radiative forcing of ~2.6 W/m² in 2100 |

**Table 3 | Twelve extreme precipitation indices considered in this study**

| Index | Indicator name                | Definition                                      | Units |
|-------|-------------------------------|-------------------------------------------------|-------|
| CDD   | Consecutive dry days          | Maximum number of consecutive days with RR < 1 mm| days  |
| CWD   | Consecutive wet days          | Maximum number of consecutive days with RR ≥ 1 mm| days  |
| R10 mm| Number of wet days            | Annual count of days with RR ≥ 10 mm            | days  |
| R20 mm| Number of heavy precipitation days | Annual count of days with RR ≥ 20 mm            | days  |
| R25 mm| Number of very heavy precipitation days | Annual count of days with RR ≥ 25 mm            | days  |
| PRCPTOT| Annual total wet-day precipitation | Total annual precipitation from days with RR ≥ 1 mm | mm    |
| R95P  | Very wet days                 | Total annual precipitation from days with RR > 95th percentile | mm |
| R99p  | Extreme wet days              | Total annual precipitation from days with RR > 99th percentile | mm |
| RX1day| Max 1-day precipitation amount | Maximum 1-day precipitation amount              | mm    |
| RX5day| Max 5-day precipitation amount | Maximum 5-day precipitation amount              | mm    |
| SDII  | Simple precipitation intensity index | The ratio of annual total wet-day precipitation to the number of wet days | mm/day|
Trend analysis and Mann-Kendall test

Linear fitting equations were used to characterize the trend changes of meteorological elements (Ding et al. 2018). A positive slope indicated an upward trend in the hydrological series over time, while the opposite indicated a decline. The Mann-Kendall non-parametric test (M-K test) (Mann 1945) was commonly used for testing time series trends in meteorology, hydrology, and climatology. The M-K trend significance test was represented by statistical parameter $Z$.

In the trend test, the original hypothesis $H_0$ is that the time series data $(X_1, ..., X_n)$, which is $n$ independent samples with identically distributed random variables; the alternative hypothesis $H_1$ is a bilateral test that the distributions of $X_k$ and $X_j$ are not identical for all $k, j \leq n$, and $k \neq j$. Given a confidence level, the original hypothesis is rejected if $|Z| > Z_{1-\alpha/2}$. For example, given a confidence level $\alpha = 0.05$, $|Z| > 1.96$ indicates that the significance test with the 95% confidence level is passed. And there is a significant upward or downward trend in the time series data. For the statistic $Z$, it is an upward trend when $Z > 0$; and a downward trend when $Z < 0$ (Ma et al. 2021).

Inverse distance weighted interpolation method

In this paper, the spatial distribution was based on the inverse distance weight method (IDW) (Wang & Huang 2020). IDW used a combination of linear weights of the sampled points to determine the image element values (Equations (1) and (2)). The sum of the weight magnitude of the role of each sampling point value on the interpolation result is 1 (Equation (3)).

$$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i)$$

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{N} d_{i0}^{-p}}$$

$$\sum_{i=1}^{N} \lambda_i = 1$$

where $\hat{Z}(S_0)$ is the interpolation result at $S_0$, $Z(S_i)$ is the monitoring value obtained at $S_i$, $N$ is the number of circumscribed sampling points involved in interpolation, $\lambda_i$ is the weight of each sampling point according to which the interpolation is calculated, and $d_{i0}$ is the distance between the known sampling point $S_i$ and the interpolation point.

RESULTS AND DISCUSSION

Spatio-temporal variation of extreme precipitation indices from 1957 to 2017

Interannual variation

The results of linear tendencies and spatial distribution patterns of the decade rate for 11 precipitation indices during 1957–2017 in the study area are shown in Table 4 and Figure 3.

As shown in Table 4, the spatial distribution of the two indices, RX1day and RX5day, was similar, with most stations showing a non-significant decreasing trend and scattered over most of the study basin (Figure 3(a) and 3(b)). The two indices have a regional average range of $-2.31$ to $4.75$ mm/decade and $-8.35$ to $8.32$ mm/decade, respectively (Table 4). For RX5day, stations with decreasing trend were located in the central part of the study basin. Whereas the stations with increasing trend of RX1day and RX5day were only distributed in the western and northern parts of the basin. It indicated that both persistent heavy precipitation and short duration precipitation in the study area showed decreasing trends.

The regional average of CDD was 0.42 days/decade, showing a slight upward trend, with six stations showing an upward trend and two stations showing a downward trend (Table 4). Similar to CDD, CWD increased at a rate of 0.17 days/decade, with seven stations (a total of eight stations) showing a positive trend (Table 4). All the trends of the stations involved in the CDD and CWD indices did not pass the significance test. These upward trend stations in CDD were mainly distributed in the central and eastern parts of the region, and the stations with higher growth rates were found in the northwest corner of the study area (Figure 3(c)). The stations with decreasing trends were distributed more scattered and with minimal decreasing trends. As shown in Figure 3(d), stations with the increasing trend of CWD covered almost the whole study area, and the higher increasing trend of CWD also occurred in the northwestern part of the study area. The spatial pattern of the indices...
indicated that there were more and more long consecutive dry and wet days, especially in the northwestern part of the study area.

PRCPTOT in the study area showed a fluctuating decreasing trend at a rate of \(-5.07\) mm/decade from 1957 to 2017, and the linear tendencies range from \(-14.19\) to \(21.65\) mm/decade (Table 4). In terms of spatial distribution, stations with increasing trends were only found in the northeastern part of the study area, and the watershed as a whole showed a decreasing trend (Figure 3(k)). The long-term trend of SDII decreased at a rate of \(0.04\) mm/day/decade. There were six stations showing a

| Table 4 | Trend analysis of extreme precipitation indices in the CR from 1957 to 2017 |
|---------|---------------------------------------------------------------------------------|
| Indices | Units | Extent of basin trends (mean) (decades \(^{-1}\)) | Number of stations (↑)(↓) |
| RX1day | mm | \(-2.31\) to \(4.75\) (0.86) | 3/5 |
| RX5day | mm | \(-8.35\) to \(3.82\) (\(-2.33\)) | 2/6 |
| CDD | days | \(-0.07\) to \(0.77\) (0.43) | 6/2 |
| CWD | days | \(-0.01\) to \(0.33\) (0.17) | 7/1 |
| SDII | mm/day | \(-0.15\) to \(0.16\) (\(-0.04\)) | 2/6 |
| R10 mm | Days | \(-1.02\) to \(-0.07\) (\(-0.62\)) | 0/8 |
| R20 mm | Days | \(-0.28\) to \(0.44\) (\(-0.07\)) | 2/6 |
| R25 mm | Days | \(-0.29\) to \(0.42\) (\(-0.02\)) | 4/4 |
| R95P | mm | \(-3.94\) to \(22.95\) (5.96) | 6/2 |
| R99P | mm | \(-8.31\) to \(14.08\) (1.36) | 5/3 |
| PRCPTOT | mm | \(-14.19\) to \(21.65\) (\(-5.07\)) | 1/7 |

**Figure 3** | Spatial distribution of the long-term (1957–2017) trends in extreme precipitation indices.
decreasing trend, but no one station’s trend change passed the M-K significance test at the 95% confidence interval. It can be seen from the watershed distribution map that the SDII in the study area had a completely opposite trend to the CWD stations, with almost all stations showing a positive trend. These results suggested that the duration of extreme hydrological events in the northwest area upstream of CR was increasing, but the decreasing trend of precipitation intensity was obvious in the whole basin.

It can be seen from the data in Table 4 that the regional long-term trends of R20 mm and R25 mm were showing a slightly decreasing trend with large fluctuations. The two indices had a regional average rate of −0.07 days/decade and −0.02 days/decade, respectively. Simultaneously, the regional average rate of change for R10 mm was −0.62 days/decade, which can be observed to be significantly larger than the decreasing trend of the other two indices. Based on the distribution patterns in Figure 3(f)–3(h), six stations showed a negative trend for R20 mm which scattered almost the whole study area, while two stations showed positive trends, with the northernmost stations showing a significant positive trend (p < 0.05).

Stations with decreasing trends for R10 mm and R20 mm were distributed in almost the entire watershed of the study area. The stations showed increasing trends at R20 mm and R25 mm were mainly located in the northern part of the study area. As for R25 mm, four stations showed a decreasing trend and the others showed an increasing trend, but none of the stations passed the significant test. In addition, the distribution of stations trend changes was more scattered, without obvious regional characteristics.

The regional long-term trend of R95p showed an increase at a rate of 5.96 mm/decade, with linear trends ranging from −3.94 to 22.95 mm/decade, and none of the stations changes passed the significance test (Table 4). In terms of the spatial distributions, Figure 3(i) shows an increasing trend in the study area as a whole, except for several stations in the northwestern and southeastern regions, which showed a decreasing trend. The spatial distribution of R99p shows that the sites with increasing trend are mainly concentrated in the central and southeastern part of the study area, while the sites with decreasing trend are located in the northwestern part of the study area.

In general, most of the extreme precipitation indices at the upstream stations of CR failed the significance test, and the trends were all insignificant. The annual trends of the six indices, RX1day, RX5day, R10, R20, SDII, and PRCPTOT, were all decreasing, indicating that the continuous heavy precipitation and short ephemeral precipitation were all decreasing in the upstream of CR. The decreasing trends of precipitation and precipitation intensity were clearly visible in the whole basin. In addition, the annual scale changes of R95p, R99p, CWD, and CDD indices exhibited a positive trend, reflecting that the tendency of precipitation and drought events to be more polarized.

**Seasonal changes**

Based on the monthly values of RX1day and RX5day provided by RClimDex software, we explored the seasonal variation of these two indices (Figure 4). RX1day showed the largest increasing trend at a rate of 2.52 mm/decade in autumn. Spring,
winter, and summer also showed an increasing trend with rates of 0.21, 0.19, and 0.05 mm/decade, respectively. As shown in Figure 4, the seasonal variation of RX5day showed a decreasing trend in almost all seasons except autumn. The changes of RX5day in spring and winter showed a decreasing trend of 1.22 and 0.02 mm/decade, respectively, and the greatest decreasing trend was observed in summer with a rate of 3.15 mm/decade. None of the trends passed the significance test of 0.05 in each season, which indicated that the changes in the extreme precipitation index were not significant on the seasonal scale. It should be noted that the seasonal variation of extreme precipitation events in autumn and summer showed the same increasing trend on RX1day and RX5day, while in the other seasons, both indices showed the exact opposite trend. The uneven pattern of seasonal precipitation led to decreased heavy precipitation in summer, rainy autumn, and drought in other seasons in the study area, resulting in decreased risk of flooding in summer and increased risk of flooding in autumn.

**Changes in the extreme precipitation index for 2021–2100**

**Interannual variation**

Since the influence of the large spatial scale of the GCM and the small area of the study basin, it is difficult to analyze the evolution pattern on the spatial scale when analyzing the extreme precipitation changes in the future period (2021–2100). Therefore, the main focus of the extreme precipitation index changes in the future period is on the time scale.

The expected changes in the extreme precipitation indices for the future time periods upstream of CR are shown in Figures 5 and 6. Among the selected 11 extreme precipitation indices, only CDD and CWD show no trend change. It is also found that CDD fluctuates more in the 2080s compared to the 2040s, indicating that the duration of drought days at the end of the century is closely related to different SSPs. Here, the 2040s stands for 2021–2060 and the 2080s for 2061–2100.

![Figure 5](http://iwaponline.com/hr/article-pdf/doi/10.2166/nh.2022.135/1015597/nh2022135.pdf)

**Figure 5** | Box plot of annual changes in the extreme precipitation index for the future (2021–2100) compared to the historical period (1957–2017) under four scenario models (SSP126, SSP245, SSP370, and SSP585).
implementation of certain climate mitigation and response policies could effectively mitigate the drought evolution trend at the end of this century. The value domains of CWD and CDD are closer, indicating that the drought situation will moderate while the trend is not clear. Comparing and analyzing the future trends of R10 mm, R20 mm, and R25 mm indices, we can get that the three indices show a positive trend in the future period ($p < 0.05$). Compared with the historical period (1957–2017), R10 mm is significantly higher than the historical level, R20 mm is higher than the historical level, and R25 mm is taken at the same level as the historical data. This indicates a significant increase in short-term precipitation in the coming period. All indices show an increasing trend with the time series, except for the CDD, which displays a negative trend in the future. R95p and R99p are significantly higher than the range of values taken with the historical period, while RX1day and RX5day are not significantly different from the levels of the historical period. In contrast, there is a clear trend of increasing precipitation in the future period, but a significant trend of decreasing in ordinary daily precipitation intensity. In terms of different SSPs, the trends of future indices under the four SSPs are consistent, whereas the values of index under the SSP585 fetch larger and more concentrated (whether the extreme precipitation indices show an increase or decrease compared to the historical period). For example, the PRCTOT shows an increasing trend compared to the historical period, and the box line plot under SSP585 is higher than the other three SSPs. The future performance of SDII is significantly lower than the historical level, and the range of SDII variation under SSP585 is still higher than the other scenarios.

In general, under climate change conditions, the future precipitation and precipitation intensity in the upper reaches of CR show a positive trend. Total and sustained heavy precipitation increased significantly, and single-day precipitation and precipitation intensity were at the same level as in the historical period. In future periods, CDD decreases while CWD increases, which indicates the mitigation of drought conditions in the study area. This may be related to its geographical
location and climatic conditions. CR is located within Xinyang City, Henan Province, China. Henan is a major agricultural province and wheat-producing area in China, Xinyang City is located on the geographical boundary between the subtropical and warm temperate zones of China (Qinling-Huaihe River), making the area wet and rainy with unique climatic conditions.

Seasonal changes
RX1day and RX5day were selected to explore the seasonal variation characteristics of the upstream of CR in the future period. The annual-scale extreme precipitation indices show that most of the indices in the future increase over time.

Changes of the extreme precipitation index in future periods relative to historical periods and future evolution patterns are set out in Figures 7 and 8. On an annual scale, RX1day and RX5day for the future period exhibit an increasing trend with the time series. Analyzed from a multi-year perspective, both indices in the 2040s show a positive trend in each season. RX1day shows a significant increasing trend in the spring (passing the confidence test at the 0.05 level). The rate of increase of RX5day index is greater in all seasons, with 7.73 mm/decade in summer. In the 2080s, RX1day and RX5day display a significant increasing trend in autumn, with rates of 4.05 and 8.14 mm/decade, respectively. There is a decreasing trend in RX5day only in winter with a rate of 0.46 mm/decade, and an increasing trend in all other seasons. Nevertheless, the trend failed the significance test of 0.05 in all seasons. It is important to note that with future climate change, the increasing trend of RX1day in all seasons is determined, especially in autumn, showing a significant increasing trend. The performance of RX5day in the 2040 and 2080s is different from that of RX1day. RX1day has a clear upward trend in the spring and autumn of the 2040s, while RX5day has a clear upward trend in the summer and autumn of the 2040s. In the 2080s, both indices show a clear upward trend in autumn, indicating an increasing risk of flooding.

This result suggests that there will be a clear trend of increasing precipitation in the upcoming 2040s, especially during summer and fall. In the study area, the uneven pattern of seasonal precipitation will lead to an increase in continuous heavy summer precipitation, which puts pressure on the coordination and scheduling of water storage in CR. This situation will be mitigated in the second half of the 21st century, with a substantial reduction in the risk of flooding in summer and a doubling of flood control pressure in autumn.

Temporal trends
As Figure 6 shows, the future trends of the 11 extreme precipitation indices can be observed as obvious peaks. Among the indices characterizing the same type of precipitation, only those with more significant trends are selected for the abrupt change analysis. For example, R10 mm, R20 mm, and R25 mm all indicate the characteristics of precipitation persistence, and only R20 mm is selected to analyze the abrupt change information. Therefore, R20 mm, PRCPTOT, SDII, R95p and RX5day indices, and CDD, which characterize drought indicators, were selected for the Mann-Kendall mutation test. Identifying the years with sudden changes in extreme precipitation indices during future periods will help to respond to hydrological extremes such as floods in a timely manner. SSP585 corresponds to the most severe precipitation change. Therefore, this paper mainly analyzed the information of the extreme precipitation index mutation under SSP585.

![Figure 7](http://iwaponline.com/hr/article-pdf/doi/10.2166/nh.2022.135/1015597/nh2022135.pdf) | Box plot of seasonal changes in the extreme precipitation index for the future (2021–2100) compared to the historical period (1957–2017) under four scenario models (SSP126, SSP245, SSP370, and SSP585).
Figure 9 shows the results of the abrupt change characteristics for the extreme precipitation index upstream of CR by the Mann-Kendall non-parametric test. From 2020 to 2023, the UF of CDD shows a fluctuating trend of increasing and then decreasing, with negative values in the following years. This indicates that the CDD mainly shows a decreasing trend in the future period without significant sudden changes. The UF value of PRCPTOT is positive overall. It shows a decreasing trend only at the beginning of the future time (2020–2022), with 2046 being the year of increasing abrupt changes, and breaks the confidence level in 2057, showing a significant increasing trend \((p < 0.05)\). The M-K tests and cumulative distance plots for R20 mm and SDII show excellent agreement. With a fluctuating trend at the beginning of the future time period, 2052 and 2054 are the mutation years in which the two indices increase, respectively, and break through the confidence level in 2057 and 2058 before maintaining a significant increasing trend \((p < 0.05)\). R95p shows a decreasing and then increasing trend until the 2050s, mainly a decreasing trend. The mutation years of both R95p and RX5day appear in the mid-2050s. The difference is that the RX5day, similar to the R20 mm and SDII, shows a fluctuating trend in the early future. R95p and RX5day are above the confidence level in 2063 and 2072, respectively, and present a significant upward trend since then. The study also found that the indices, except CDD, showed an overall trend of decreasing and then increasing. The year of abrupt change from decreasing to increasing trend occurs around the 2050s, while the increasing trend is more pronounced after 2060s.

**DISCUSSION**

This paper synthesizes the trends of extreme precipitation indices recommended by the ETCCDI in the upper reaches of the CR from 1957 to 2017. It also explores the extreme precipitation evolution within the study area in the future (2021–2100) under climate change by using the four latest climate model outputs from four SSP scenarios of CMIP6. The purpose of this study is to investigate the historical precipitation evolution patterns and future extreme precipitation trends in the upstream of CR in changing environments.
Gao et al. (2017) suggested that the use of long-term observations from multiple weather stations for analysis is very necessary. There is an overall decreasing trend in precipitation upstream of the CR and a spatial consistency in the trend changes at the regional level. Previous studies (Liang et al. 2011) have reported that precipitation tends to increase over most of the Northern Hemisphere between 30 and 85°N over the course of the twentieth century, which contrasts with our finding that the upper of CR tends to be drier over the past half-century (1957–2017). This vividly illustrates the spatial heterogeneity of temporal trends in precipitation at low and mid-latitudes of the world (Pingale et al. 2014). Wang & Zhou (2005) found that while annual precipitation in China showed a significant upward trend in the southwest, northwest, and east, it also undergone a significant downward trend in the central, northern, and northeastern parts of the country, consistent with our findings. The results of the study indicate that annual mean and extreme precipitation intensities have decreased significantly on an annual scale over the last 60 years, accompanied by decreases in precipitation frequency. In contrast, the longest dry season duration (CDD), the longest rainy season duration (CWD), and the frequency of extreme heavy precipitation (R95p and R99p) increased during the study period. This indicates that both precipitation activity and extreme precipitation events are decreasing in the upper of CR from 1957 to 2017, while the frequency of extreme precipitation events with shorter durations and higher intensities is increasing. The enhanced frequency of extreme precipitation leads to a concentration of precipitation in the study area, the dry period is drier and the rainy season has more precipitation. The seasonal distribution shows the greatest variation of precipitation in summer, with an increase in short precipitation and a decrease in heavy precipitation, so the risk of flooding decreases in summer, while the risk of drought in spring and the risk of flood control increases significantly in autumn.

Global warming determines the intensification of global climate change and associated risks. Global climate models have been widely used to understand past and future changes in global and regional climate events (Wainwright et al. 2019). Multi-model integration results show better representativeness by reducing spatial ambiguity and inconsistency (Su et al. 2020).
Therefore, this paper obtains Multi-model integration results by simple weighted averaging of four GCMs to explore the characteristics of extreme precipitation index changes in future periods.

CONCLUSION

Based on the measured data of eight meteorological stations and the multi-mode output results of CMIP6, we discussed the temporal and spatial changes of extreme precipitation index in the upper reaches of Chushandian Reservoir (CR) under global climate change. The major conclusion can be summarized as follows:

(1) Annual mean precipitation and extreme precipitation intensity (represented by R10 mm, R20 mm, R25 mm, and SDII) decreased significantly from 1957 to 2017, accompanied by a decrease in precipitation frequency (RX1day and RX5day). The stations with decreasing trends are widely scattered in the basin, and the few stations with increasing trends are distributed at the basin edges.

(2) From 2021 to 2100, the upstream area of Chushandian Reservoir will become wetter, the drought events will ease, and the seasonal distribution will be more consistent. The risk of flood disaster in summer will be greatly reduced, and the pressure of flood control in autumn will be doubled.

(3) The precipitation, precipitation intensity, and precipitation frequency in the future period of the study area show an increasing trend, among which the increasing trend of PRCPOTOT and R95p is exceptionally significant ($p < 0.05$).

(4) The extreme precipitation index (represented by PRCPOTOT, R20 mm, R95p, and SDII) tends to decrease (2020–2050) and then increase (2060–2100) in the future period, with a sudden change in the extreme precipitation index between 2050 and 2060, and a significant increase after 2060. The results of the study provide a basis for CR managers to better respond to extreme hydrological events.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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