Research Article

Projected Changes in Precipitation Extremes over Shaanxi Province, China, in the 21st Century

Ling Li,1 Ziniu Xiao,2 Shuxiang Luo,1 and Aili Yang3

1Beijing Building Technology Development Co., Ltd., Beijing 100069, China
2State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
3Xiamen University of Technology, Xiamen 361024, China

Correspondence should be addressed to Ling Li; yamdestiny@163.com

Received 26 November 2019; Revised 14 February 2020; Accepted 4 May 2020; Published 26 May 2020

Academic Editor: Marina Baldi

Copyright © 2020 Ling Li et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Extreme precipitation events, which have intensified with global warming, will have a pernicious influence on society. It would be desirable to understand how they will evolve in the future as global warming becomes more serious with time. Thus, the primary objective of this study is to provide a comprehensive understanding of the changing characteristics of the precipitation extremes in the 21st century over Shaanxi Province, a climate-sensitive and environmentally fragile area located in the east of northwestern China, based on a consecutive simulation of the 21st century conducted by the regional climate model RegCM4 forced by the global climate model HadGEM2-ES at high resolution under middle emission scenario of the Representative Concentration Pathway 4.5 (RCP4.5). Basic validation of the model performance was carried out, and six extreme precipitation indices (EPIs) were used to assess the intensity and frequency of the extreme precipitation events over Shaanxi Province. The results show that RegCM4 reproduces the observed characteristics of extreme precipitation events over Shaanxi Province well. Overall for the domain, the EPIs excluding consecutive dry days (CDD) have a growing tendency during 1980–2098 although they exhibit spatial variability over Shaanxi Province. Some areas in the arid northern Shaanxi may have more heavy rainfalls by the middle of the 21st century but less wet extreme events by the end of the 21st century. And the humid central and southern regions would suffer more precipitation-related natural hazards in the future.

1. Introduction

Climate change is becoming an increasingly imminent threat to the world. Due to a large increase in atmospheric moisture, the hydrological cycle will be more active in a warmer climate, which would lead to increases in both the frequency and intensity of climate extremes [1–4]. The Intergovernmental Panel on Climate Change (IPCC) reports pointed out that the frequency and intensity of precipitation extremes would increase significantly in the future [5, 6]. Compared with the average state, the extremes events are more abrupt, unpredictable, and destructive and can be a severe threat to the natural resources and ecology that mankind depends on for existence and development, especially the precipitation extremes which would cause huge losses to social economy and urban construction [7]. Therefore, it might be of primary importance to understand the changes and trends of extreme precipitation under the background of global warming.

For decades, most of the analyses of climate change have focused on changes in mean values. It was not until recently a growing interest in climate extremes is motivated due to their critical impact on human society. Studies reported that temperature and precipitation extremes exhibited a widespread and significant increase in the past decades at a global scale [8, 9]. The occurrence of extreme precipitation events seems to be more common with the increase in total precipitation over many areas of the globe [10, 11], particularly in the high latitudes and tropical regions, and in winter in the northern midlatitudes [12–14]. To better understand the
characteristics of precipitation extremes at present and in the future, many researchers used climate models as primary tools for the simulation and projection of climate change, and valuable findings have been obtained [15–17]. In the simulation of the 21st century climate change scenarios, increasing trends in precipitation extremes have been projected over many regions, including the US and Europe, although with substantial geographical variability [18–21].

Similar to other regions in the world, changes in precipitation extremes have been observed over China in recent decades [22]. However, change patterns of precipitation extremes varied in different geographic regions of China. Analyses on the trends of precipitation extremes in the Yangtze River Basin showed that there was a positive trend for the number of rainstorm days during 1960–2002 [23], and the extreme precipitation events as measured by frequency and intensity were in a significant increasing trend after about 1975–1985, which occurred mainly in the southeast and southwest parts of the Yangtze River Basin and the Yangtze River Delta [24]. Changes in precipitation extremes presented drying trends between 1959 and 2008 in the Yellow River Basin [25]. Besides, historical records of 1951–2012 suggested that southwestern China had generally become drier and experienced enhanced precipitation extremes in the past 60 years [26]. The arid region of Northwest China witnessed an abrupt change in precipitation extremes with a weakening trend from 1961 to 1984 and a strengthening trend from 1985 to 2010 [27]. In addition, scientific projections of future changes in the precipitation extremes over China have also been carried out by simulations from global climate models (GCMs) or regional climate models (RCMs) under different emission scenarios, and the studies implied that there would be an overall increasing trend in extreme precipitation events over most areas of China in the 21st century, particularly in the southeast coastal zone and the middle and lower reaches of the Yangtze River and North China [28–32].

Shaanxi Province is located in northwestern China, midlatitude land area of the Northern Hemisphere. This region is particularly vulnerable to climate change. Natural disasters such as floods and droughts are frequent and serious in the area. Therefore, research on the response of the extreme precipitation events to climate change is crucial for developing adaptation strategies to reduce climate risks for Shaanxi Province. According to the daily precipitation observed data over the area, researchers found that the regional climate of Shaanxi Province tended to get drier in the past decades, whereas the changing trend in extreme precipitation events had apparent regional differences. The negative trends were mainly detected in the northern Shaanxi, and the precipitation extremes happened more frequently in southern Shaanxi than in northern and central Shaanxi [33, 34]. However, most of these previous works are limited to characteristics of extreme precipitation events over Shaanxi Province during historical periods. Few analyses were conducted on the prediction for the future. In this paper, we investigated the change patterns of the extreme precipitation events over Shaanxi Province in the 21st century with focus on extreme precipitation indices, by using data from observation and simulation and projection conducted by RegCM4 at high resolution, one of the regional climate models that is capable of describing climate feedback mechanisms acting at the regional scale and providing better representations of regional climate variation [35]. This study on variability of the precipitation extremes would not only provide insights into climate change in the future but also be a scientific basis for the development of risk-reduction measures and early warning systems.

2. Data and Methods

2.1. Study Area. For this work, Shaanxi Province, situated in the east of northwestern China and ranging from 31.7°N to 39.6°N latitude and 105.5°E to 111.2°E longitude, was selected as the study area (see Figure 1). Shaanxi Province comprises three distinct natural regions—the mountainous southern region (Southern Shaanxi, SS), the Wei River valley (Central Shaanxi, CS), and the northern upland plateau (Northern Shaanxi, NS). The Qin Mountains separate Shaanxi into two sharply differentiated climatic regions, which cause the hydrological conditions of Shaanxi Province.
varied from north to south. The annual precipitation total varies with different areas ranging from 320 to 1258 mm, the lesser amount in the north, increasing to the higher total in the south. Most of the annual rainfall occurs between May and September. With climate extremes happening frequently, natural hazards, including winter droughts, floods, and hailstones, are common in Shaanxi Province.

2.2. Model and Data. In this study, the RegCM4 from the Abdus Salam International Center for Theoretical Physics (ICTP) was adopted to capture local climatology over Shaanxi Province at high resolution and generate detailed climate change projections at local scales. The regional climate model system RegCM was originally developed at the National Center for Atmospheric Research (NCAR). Compared to previous versions (RegCM1, RegCM2, and RegCM3), the latest version of the model, RegCM4, includes major upgrades in the structure of the code and its pre- and postprocessors, along with the inclusion of some new physics parameterizations, which enable the model to be flexible, portable, and easy to use. It can be easily applied to any region of the world at different resolutions for a wide range of studies, from process studies to future climate simulation. Being a limited area model, the RegCM4 for this work was driven by initial and lateral boundary conditions from HadGEM2-ES, a coupled Earth System Model that was used by the Met Office Hadley Center for the CMIP5 centennial simulations, under the middle emission scenario RCP4.5. The model was run over CORDEX-EA (East Asia) with China continent included centered at (35°N, 115°E), at a grid spacing of 0.25° × 0.25° (latitude by longitude) for the period 1979–2098. The Community Land Model (CLM) was used to carry out land surface processes, and the Emanuel scheme was adopted as the convective precipitation scheme. The ocean flux parameterization follows Zeng et al. in this study. The model output data over Shaanxi Province were used for the study.

The observational precipitation data employed for model evaluation, provided by the National Meteorological Information Center (NMIC) of China (available at http://data.cma.cn/), were obtained by interpolating the quality-controlled observed daily precipitation data series over China Mainland from 2472 meteorological stations at 0.5° × 0.5° (latitude by longitude) spatial resolution. Because we focused on analyzing the Shaanxi Province domain in the paper, only 82 gridded precipitation data of Shaanxi Province for the period 1980–2009 were selected to validate the model performance.

We chose three climatic periods for the analysis and split the model output dataset accordingly. The period 1986–2005 was considered as the reference period and 2046–2065 as the mid-21st century, as suggested by IPCC AR5. Since the model simulation and projection were in a continuous run from 1979 to 2098; the last twenty-year period 2079–2098 was defined as the late 21st century. The RegCM4-simulated precipitation for the reference period was used to validate the performance of RegCM4 by comparing with observations, while the precipitation data for the other two periods were selected to predict the characteristic patterns of precipitation extremes in future over Shaanxi under the RCP4.5 scenario.

2.3. Methods. The extreme precipitation indices (EPIs) recommended by the joint CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (http://etccdi.pacificclimate.org/) are a suite of climate change indices which primarily focus on precipitation extremes and provide some insights into changes in these extremes. They could evaluate many aspects of changes in intensity, frequency, and duration of extreme events and have been widely used in lots of researches [36–39]. In this study, six extreme precipitation indices (EPIs) were applied to reflect different aspects of extreme precipitation events in Shaanxi Province, including Rx1day, Rx5day, R95p, R10 mm, CDD, and SDII. The indices were calculated according to their definitions, as shown in Table 1. All indices except CDD measure the intensity or frequency of precipitation. The CDD is used to express the length of the dry spell. Besides, R10 mm was chosen in consideration of the impact that potential change in rainfall could have on soil erosion, which is commonly concerned in Shaanxi Province.

To facilitate the comparison and analysis, the observational precipitation data were bilinearly interpolated onto the same spatial resolution as that of model outputs. The method of bilinear interpolation is a technique for calculating values of a grid location-based on nearby grid cells. It uses 4 nearest neighbors to generate an output surface. Using the four nearest neighboring cells, bilinear interpolation assigns the output cell value by taking the weighted average. Finally, a total of 329 grids at a spatial resolution of 0.25° × 0.25 cover the study area. The EIPs at each grid point were calculated for the analysis. Correlation analysis was applied to analyze the consistency between RegCM4 output and data from observations. Besides, the method of the linear regression algorithm was used to detect trends in extreme events. Differences between the reference period and the 21st century period were calculated as the climate change.

3. Validation of the Model Simulation

3.1. Annual and Monthly Mean Precipitation Patterns. To validate the performance of the model for precipitation simulation over Shaanxi Province, we firstly compared the average annual and monthly precipitation in the simulation with corresponding observations during the 1986–2005 period. Figure 2 displays the spatial distributions of the annual mean precipitation over Shaanxi Province by observation and simulation, both of which peak at the SS, above 800 mm/year, and decrease toward the NS with values below 400 mm/year. The CS regions are characterized by precipitation amounts around 400–800 mm/year. In general, this precipitation pattern was well captured by the model for the entire domain. Although the RegCM4 overestimated the annual mean precipitation over most regions of Shaanxi Province, the percent deviation is generally within ±15% (see...
Figure 2(c)). In some areas, the percent deviation is within ±5%.

The precipitation of Shaanxi Province also shows an intra-annual variability (see Figure 3). In Shaanxi Province, most of the precipitation concentrates on flood season (May to September), which is up to 75% of the total. Wintertime (January, February, and December) constitutes the driest season, with minimum total precipitation amounts below 23 mm on average. The RegCM4 can reproduce the annual precipitation cycle well although it underestimates most of the rainfall in dry months (January, March, and December) while overestimates the precipitation of wet months. But the difference between the model and observations is relatively small, mostly within ±7%.

### 3.2. Spatial Distribution of Precipitation Extremes

The spatial distribution of six observed and simulated average annual EPIs over Shaanxi Province from 1986 to 2005 and the differences between the simulation and observation are presented in Figure 4. For observed wet extreme indices (all indices except CDD), the spatial pattern is similar to that of annual mean precipitation with high value in the south and low value in the north. The consecutive dry days described by CDD show a reversed distribution. Overall, the RegCM4 could well reproduce the spatial pattern of the EPIs although the simulated values of wet extreme indices were over-estimated in general across the domain. The simulated value

| Index     | Index name                          | Definitions                                                                 | Units   |
|-----------|-------------------------------------|------------------------------------------------------------------------------|---------|
| Rx1day    | Maximum 1-day precipitation         | Annual maximum 1-day precipitation                                          | mm      |
| Rx5day    | Maximum 5-day precipitation         | Annual maximum consecutive 5-day precipitation                              | mm      |
| R95p      | Very wet day precipitation          | Annual total precipitation when daily precipitation >95th percentile         | mm      |
| R10mm     | Number of heavy precipitation days  | Annual count of days when daily precipitation ≥10 mm                         | days    |
| CDD       | Consecutive dry days                | Annual maximum number of consecutive dry days with daily precipitation<1 mm | days    |
| SDII      | Simple daily intensity index        | Average daily precipitation on wet days (daily precipitation ≥1 mm) in the year | mm/day  |
Figure 4: Continued.
Figure 4: Spatial distribution of six annual mean EPIs over Shaanxi Province from 1986 to 2005. The left panels are for observed EPIs, the middle panels are for simulated EPIs, and the right panels are for the difference between simulation and observation. (a–c) Rx1day; (d–f) Rx5day; (g–i) R95p; (j–l) R10 mm; (m–o) CDD; (p–r) SDII.
of Rx1day showed underestimation mainly in the north of the NS and some southeastern parts of the SS. The maximum overestimation can be found in the Hanzhong area of the SS with a deviation below 40% (see Figure 4(c)). For Rx5day and R95p, the largest positive deviations also occurred in Hanzhong with values greater than 65% and 35%, respectively (see Figures 4(f) and 4(i)). Figure 4(l) indicates that the maximum difference between observed and simulated R10 mm can be found in the SS, with a magnitude of more than 25%. As an indicator of less precipitation, the CDD was underestimated in some northern parts of the NS and the center of the CS with negative bias up to −32%. The SS appears to be drier in the simulation than in the observation (see Figure 4(o)). The simulated SDII is generally higher than that in the observations, with bias up to 21%. The lower SDII was only found in some central parts of the CS, the southern parts of the SS, and the transition zone between the CS and the SS (see Figure 4(r)).

In general, the spatial pattern of the simulated EPIs in Shaanxi Province is closely consistent with the observations, showing obvious differentiation from south to north. The simulated and observational values of almost all EPIs, except CDD, are higher in the SS area and smaller in NS area, meaning that extreme precipitation events in the SS area were the most severe events and the NS area suffered drought events during 1986–2005. Although differences between observation and simulation varied over the domain, the biases are within ±15% in a great measure. Furthermore, the spatial correlation coefficients of the indices between model simulation and observation are generally above 0.79 (see Table 2), indicating that the high-resolution model generally captures the observed spatial pattern and amount of six EPIs well.

### 4. Precipitation Projections in the 21st Century

#### 4.1. Projected Changes in Monthly Mean Precipitation

Projected annual cycles of monthly mean precipitation under the RCP4.5 scenario for the mid-21st century (2046–2065) and the late 21st century (2079–2098) are presented in Figure 5. The projected annual cycles of precipitation in both periods are considerably similar to that of the reference period, with maximum rainfall in July in summer and minimum values in December and January in winter. But compared with the reference period, the annual total precipitation was projected to increase for the two periods in the 21st century. According to Figure 6, an obvious increase in precipitation would happen from May to July for the mid-21st century, particularly in July with a magnitude of more than 20 mm. But the province is expected to experience less rainfall in August during this period. By the end of the 21 century, Shaanxi Province would have more precipitation prolonged from March to July. However, strong reductions in precipitation exceeding 25 mm from August to September can also be detected. The projected changes in monthly mean precipitation during the 21st century indicate that the flood season (normally from May to September) characterized by heavy rainfall would begin early, and the large increase in precipitation would lead to frequent occurrence of floods.

#### 4.2. Projected Trends in Precipitation Extremes

The temporal evolutions of the EPIs from the period 1980–2098 are shown in Figure 7. Most of the EPIs (except for CDD) were detected to have moderate increase in this complete period, which implies that intensity of precipitation (Rx1day, Rx5day, R95p, and SDII) and frequency of heavy precipitation (R10 mm) would increase in the future. The regional average trends for the Rx1day would increase by 0.81 mm/decade, with statistical significance at the 1% level. Rx5day and R95p demonstrated positive trends of 0.27 mm/decade and 1.75 mm/decade, respectively. The trend of R10 mm was detected with a magnitude of 0.12 d/decade. In contrast, the CDD was found to have a negative trend of 0.28 d/decade during the period, implying less extreme drought in the long term. The magnitude of the trend for SDII is very weak, at the rate of 0.03 mm/d/decade. However, except for Rx1day, the trends of other EPIs cannot show statistical significance at the 5% level, which may be caused by the fact that the precipitation does not respond to greenhouse gases well. As for the projected period 2006–2098, the EPIs have similar conclusions with only the Rx1day index showing a statistically significant trend, details of which are not shown here.

![Figure 5: Projected annual cycles of monthly mean precipitation for the mid-21st century (2046–2065) and the late 21st century (2079–2098) in Shaanxi Province.](image-url)
Figure 6: Monthly precipitation anomalies projected by RegCM4 (relative to 1986–2005) under RCP4.5 during (a) 2046–2065 and (b) 2079–2098.

Figure 7: Continued.
Figure 7: Temporal evolution of the EPIs from 1980 to 2098 in Shaanxi Province as simulated and projected by the RegCM4: (a) Rx1 day; (b) Rx5 day; (c) R95p; (d) R10 mm; (e) CDD; (f) SDII. The dashed line represents a linear trend.

Figure 8: Spatial changes of six EPIs over Shaanxi Province for the mid-21st century (relative to 1986–2005 period): (a) Rx1 day; (b) Rx5 day; (c) R95p; (d) R10 mm; (e) CDD; (f) SDII.
4.3. Projected Spatial Changes in Precipitation Extremes.

The spatial changes in the six EPIs in the mid-21st century (2046–2065) compared with the reference period are shown in Figure 8. A significant increasing change in the Rx1day was observed across Shaanxi Province, particularly in the northern part of the NS with values larger than 35% and can be more than 40% over portions of the area (see Figure 8(a)). An obvious increase in the Rx5day can be found in the NS, while a moderate decrease of this index up to 16% was projected mainly in the NS (see Figure 8(b)). Similar to the Rx1day, the northern part of the NS could be affected by a great increase in the R95p, with maximum values exceeding 35% (see Figure 8(c)). A relatively minor increase in the R10mm dominates the central part of the CS and the northern part of the NS with the value up to 16%, referring to more heavy precipitation days in this area (see Figure 8(d)). As a drought indicator, the CDD shows a scattered negative change of −5% to −15% over Shaanxi Province, indicating more rainfall in these areas (see Figure 8(e)). An increasing change in the SDII could be mainly found in the northern part of the NS and the transition zone between the CS and the SS, ranging from about 5%–15% (see Figure 8(f)).

For the end of the 21st century (2079–2098), the changing patterns of the EPIs over the whole domain are shown in Figure 9. The Rx1day still shows a spatial pattern of widespread positive change around 5%–25% in most areas of the province. A remarkable increase in the index exceeding 55% was found in the southeastern part of the SS (see Figure 9(a)). More areas in the western part of Shaanxi Province would be affected by a negative change in the Rx5day between −5% and −25%, especially in the boundary zones between Yan’an and Yulin (see Figure 9(b)).

Figure 9: Spatial changes of six EPIs over Shaanxi Province for the end of the 21st century (relative to 1986–2005): (a) Rx1day; (b) Rx5day; (c) R95p; (d) R10mm; (e) CDD; (f) SDII.
Meanwhile, the R95p shows a positive change over most areas of the Shaanxi Province, particularly in the Ankang area of the SS with an obvious increase above 30% (see Figure 9(c)). The R10 mm would have a moderate increase from 5% to 15% in the southeastern part of the SS although an obvious decrease up to −18% was found in the boundary zones between Yan’an and Yulin (see Figure 9(d)). The index of CDD still shows minor changes across the region (see Figure 9(e)). According to Figure 9(f), a decrease in the SDII dominates the boundary zones between Yan’an and Yulin, while the southeastern part of the SS would experience an increasing change in the SDII.

5. Conclusions

By using the gridded observational data provided by the National Meteorological Information Center (NMIC) of China and the results from the high-resolution climate change simulation and projection over China conducted by RegCM4, the future precipitation extremes over Shaanxi Province were investigated. The extreme precipitation indices used to quantify the precipitation extremes include Rx1day, Rx5day, R95p, R10 mm, CDD, and SDII. The period 1986–2005 serves as a reference for future changes. Validation of the performances of the model was conducted by comparing the model results with the observations. Spatial patterns of the future changes and the temporal evolutions of the extreme indices in two periods 2046–2065 and 2079–2098 were analyzed under the RCP4.5 scenario. From the analysis, we have summarized a few primary findings as follows:

1. Based on the validation of the model above, the simulated annual and some monthly precipitations were generally overestimated by the RegCM4, probably due to the uncertainty of the regional climate models and forcing scenarios. Regarding the distribution patterns for the annual precipitation and the EPIs, the model reproduces the characteristics of a decreasing gradient directed from the south to the north during the reference period (except for the CDD, which shows a reverse distribution). This finding is consistent with previous studies as discussed by Liu et al. and Jiang et al. [33, 34], which revealed that the extreme precipitation events have a high consistency with the annual precipitation and happen more frequently in the southern Shaanxi than in the northern and the central Shaanxi. Although discrepancies can be detected between the simulation and the observation, the RegCM4 reasonably captures the annual precipitation cycle and the spatial patterns of all EPIs under present-day climate over Shaanxi Province.

2. For the two periods of the 21st century, both the intraannual distributions of monthly rainfall are similar to that of the reference period, with the most rainfall in the flood season and minimum in wintertime, implying that precipitation amount due to heavy rainfall events in the flood season occupies a large proportion of the total. The general increase in precipitation was found from May to July during the mid-21st century, while prolonged from March to July during the late 21st century, indicating flood season in Shaanxi Province would come early in the future.

3. In the precipitation extremes projection for the mid-21st century and late 21st century under the RCP4.5 scenario, the examination of the temporal evolution of EPIs from 1980–2098 reveals that the wet extreme indices, including Rx1day, Rx5day, R95p, R10 mm, and SDII, showed an increasing tendency. Meanwhile, the consecutive dry days (CDD) took on a downtrend. These results indicate that Shaanxi Province may confront severe extreme precipitation events with stronger intensity and frequency. However, since the precipitation is sensitive to many factors and cannot respond to greenhouse gases consistently, only the trend of Rx1day shows statistical significance at the 1% level.

4. The spatial changes in wet extreme indices including Rx1day and R95p are mainly positive change dominated during the mid-21st and late 21st century. The other indices exhibited spatial variability over Shaanxi Province. The northern part of NS, known as an arid district but with a pronounced increase of indices by the middle of the 21st century, is expected to undergo more intense downpours, which may alleviate the risk of drying in the arid NS. However, the situation would change as the Rx5day, R10 mm, and SDII show obvious decreasing changes in the boundary zones between Yan’an and Yulin in the NS by the end of the 21st century. The results also imply that the happening of precipitation extremes in the humid SS would be aggravated in the future, particularly during the late 21st century. Although there are few studies on the projection of precipitation extremes over Shaanxi Province, the overall projected changes in the EPIs are generally similar to those for the neighborhood or some wider regions, such as the Loess Plateau, the arid region of northwestern China, and the Yellow River Basin [40–42].

In conclusion, the results have improved our understanding of extreme precipitation events over Shaanxi Province in the 21st century to a degree. However, precipitation patterns are very complex, influenced by diverse topography and large-scale circulation. Our analysis is only based on the simulation and the projection by the RegCM4 under the RCP4.5 scenario. Thus, an analysis of uncertainty in the simulation and prediction of precipitation extremes is necessary for further study. Besides, for a more complete understanding of how precipitation extremes are likely to change in the future, additional model simulations and emission scenarios are needed to develop a more robust set of conclusions and provide more information for evaluating the impacts of climate change on hydrologic processes, water resources, and ecological systems.
Data Availability

The observational precipitation data used to support the findings of this study have been deposited in the repository of the National Meteorological Information Center of China (http://data.cma.cn/). The model output data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors thank the LASG in the Institute of Atmospheric Physics, the Chinese Academy of Sciences, for providing model output data of RegCM4 used in this study. This research was funded by 2018 Open Research Program of LASG in the Institute of Atmospheric Physics, the Chinese Academy of Sciences, and Research Program of Beijing Construction Engineering Group (SGGA14270000000002016002).

References

[1] S. Emori and S. J. Brown, “Dynamic and thermodynamic changes in mean and extreme precipitation under changed climate,” Geophysical Research Letters, vol. 32, no. 17, Article ID L17706, 2005.
[2] P. A. O’Gorman and T. Schneider, “The physical basis for increases in precipitation extremes in simulations of 21st-century climate change,” Proceedings of the National Academy of Sciences, vol. 106, no. 35, pp. 14773–14777, 2009.
[3] K. E. Trenberth, A. Dai, R. M. Rasmussen, and D. B. Parsons, “The changing character of precipitation,” Bulletin American Meteorological Society, vol. 84, no. 9, pp. 1205–1217, 2010.
[4] J. Bao, S. C. Sherwood, L. V. Alexander, and J. P. Evans, “Future increases in extreme precipitation exceed observed scaling rates,” Nature Climate Change, vol. 7, no. 2, pp. 128–132, 2017.
[5] G. A. Meehl, T. F. Stocker, W. D. Collins et al., “Global climate projections,” Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 782–784, Cambridge University Press, Cambridge, UK, 2007.
[6] IPCC, Climate Change 2014: Synthesis report. Contribution of Working Groups I,II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 2014.
[7] S. Piao, P. Ciais, Y. Huang et al., “The impacts of climate change on water resources and agriculture in China,” Nature, vol. 467, no. 7311, pp. 43–51, 2010.
[8] L. V. Alexander, X. Zhang, T. C. Peterson et al., “Global observed changes in daily climate extremes of temperature and precipitation,” Journal of Geophysical Research, vol. 111, Article ID D05109, 2006.
[9] E. M. Fischer and R. Knutti, “Detection of spatially aggregated changes in temperature and precipitation extremes,” Geophysical Research Letters, vol. 41, no. 2, pp. 547–554, 2014.
[10] P. Frich, L. Alexander, P. Della-Marta et al., “Observed coherent changes in climatic extremes during the second half of the twentieth century,” Climate Research, vol. 19, no. 3, pp. 193–212, 2002.
[11] L. Zandonadi, F. Acquaotta, S. Fratianni, and J. A. Zavattini, “Changes in precipitation extremes in Brazil (parana River Basin),” Theoretical and Applied Climatology, vol. 123, no. 3-4, pp. 741–756, 2016.
[12] J. Caesar, L. V. Alexander, B. Trewin et al., “Changes in temperature and precipitation extremes over the Indo-Pacific region from 1971 to 2005,” International Journal of Climatology, vol. 31, no. 6, pp. 791–801, 2011.
[13] E. J. M. van den Besselaar, A. M. G. Klein Tank, and T. A. Buishand, “Trends in European precipitation extremes over 1951–2010,” International Journal of Climatology, vol. 33, no. 12, pp. 2682–2689, 2013.
[14] E. J. Powell and B. D. Keim, “Trends in daily temperature and precipitation extremes for the southeastern United States:1948–2012,” Journal of Climate, vol. 28, no. 4, pp. 1592–1612, 2015.
[15] C. Tebaldi, K. Hayhoe, J. M. Arblaster, and G. A. Meehl, “Going to the extremes,” Climatic Change, vol. 79, no. 3-4, pp. 185–211, 2006.
[16] V. V. Kharin, F. W. Zwiers, X. Zhang, and G. C. Hegerl, “Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations,” Journal of Climate, vol. 20, no. 8, pp. 1419–1444, 2007.
[17] A. Toreti, P. Naveau, M. Zampieri et al., “Projections of global changes in precipitation extremes from coupled model intercomparison project phase 5 models,” Geophysical Research Letters, vol. 40, no. 18, pp. 4887–4892, 2013.
[18] F. Dominguez, E. Rivera, D. P. Lettenmaier, and C. L. Castro, “Changes in winter precipitation extremes for the western United States under a warmer climate as simulated by regional climate models,” Geophysical Research Letters, vol. 39, no. 5, Article ID L05803, 2012.
[19] H. J. Fowler, M. Ekström, S. Blenkinsop, and A. P. Smith, “Estimating change in extreme European precipitation using a multimodel ensemble,” Journal of Geophysical Research, vol. 112, no. D18, Article ID D18104, 2007.
[20] D. Singh, M. Tsiang, B. Rajaratnam, and N. S. Diffenbaugh, “Precipitation extremes over the continental United States in a transient, high-resolution, ensemble climate model experiment,” Journal of Geophysical Research: Atmospheres, vol. 118, no. 13, pp. 7063–7086, 2013.
[21] T. M. Hu, and A. Hall, “Increased interannual precipitation extremes over California under climate change,” Journal of Climate, vol. 28, no. 16, pp. 6324–6334, 2015.
[22] Q. Zhang, J. Li, V. P. Singh, and C.-Y. Xu, “Copula-based spatio-temporal patterns of precipitation extremes in China,” International Journal of Climatology, vol. 33, no. 5, pp. 1140–1152, 2013.
[23] B. D. Su, T. Jiang, and W. B. Jin, “Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China,” Theoretical and Applied Climatology, vol. 83, no. 1-4, pp. 139–151, 2006.
[24] Q. Zhang, C. Xu, Z. Zhang et al., “Spatial and temporal variability of precipitation maxima during 1960–2005 in the Yangtze River basin and possible association with large-scale circulation,” Journal of Hydrology, vol. 353, no. 3-4, pp. 215–227, 2008.
[25] W. Wang, Q. Shao, T. Yang et al., “Changes in daily temperature and precipitation extremes in the Yellow River Basin, China,” Stochastic Environmental Research and Risk Assessment, vol. 27, no. 2, pp. 401–421, 2013.
[26] M. Liu, X. Xu, A. Y. Sun et al., "Is southwestern China experiencing more frequent precipitation extremes?" Environmental Research Letters, vol. 9, no. 6, Article ID 064002, 2014.
[27] Y. Chen, H. Deng, B. Li, Z. Li, and C. Xu, "Abrupt change of temperature and precipitation extremes in the arid region of Northwest China," Quaternary International, vol. 336, pp. 35–43, 2014.
[28] Y. Zhang, Y. Xu, W. Dong, L. Cao, and M. Sparrow, "A future climate scenario of regional changes in extreme climate events over China using the PRECIS climate model," Geophysical Research Letters, vol. 33, no. 24, Article ID L24702, 2006.
[29] X. Gao, Y. Shi, D. Zhang, and F. Giorgi, "Climate change in China in the 21st century as simulated by a high resolution regional climate model," Chinese Science Bulletin, vol. 57, no. 10, pp. 1188–1195, 2012.
[30] J. Xu, Y. Shi, X. Gao, and F. Giorgi, "Projected changes in climate extremes over China in the 21st century from a high resolution regional climate model (RegCM3)," Chinese Science Bulletin, vol. 58, no. 12, pp. 1443–1452, 2013.
[31] B. Zhou, Q. H. Wen, Y. Xu, L. Song, and X. Zhang, "Projected changes in temperature and precipitation extremes in China by the CMIP5 multimodel ensembles," Journal of Climate, vol. 27, no. 17, pp. 6591–6611, 2014.
[32] Y. Peng, X. Zhao, D. Wu et al., "Spatiotemporal variability in extreme precipitation in China from observations and projections," Water, vol. 10, no. 8, Article ID 1089, 2018.
[33] W. Liu, M. Zhang, S. Wang, B. Wang, F. Li, and Y. Che, "Changes in precipitation extremes over Shaanxi Province, northwestern China, during 1960–2011," Quaternary International, vol. 313-314, pp. 118–129, 2013.
[34] R. Jiang, J. Xie, Y. Zhao, H. He, and G. He, "Spatiotemporal variability of extreme precipitation in Shaanxi province under climate change," Theoretical and Applied Climatology, vol. 130, no. 3-4, pp. 831–845, 2016.
[35] F. Giorgi, B. Hewitson, J. Christensen et al., "Regional climate information-evaluation and projections," Climate Change 2001: The Scientific Basis. Contribution of Working Group to the Third Assessment Report of the Intergovernmental Panel on Climate Change, vol. 881, pp. 585–636, Cambridge University Press, Cambridge, UK, 2001.
[36] E. Lupikasza, "Spatial and temporal variability of extreme precipitation in Poland in the period 1951–2006," International Journal of Climatology, vol. 30, no. 7, pp. 991–1007, 2010.
[37] L. A. Vincent, E. Aguilar, M. Saindou et al., "Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008," Journal of Geophysical Research Atmospheres, vol. 116, no. D10, Article ID D10108, 2011.
[38] M. Santos and M. Fragoso, "Precipitation variability in Northern Portugal: data homogeneity assessment and trends in extreme precipitation indices," Atmospheric Research, vol. 131, pp. 34–45, 2013.
[39] B. Zhou, C. Liang, P. Zhao, and Q. Dai, "Analysis of precipitation extremes in the source region of the Yangtze River during 1960–2016," Water, vol. 10, no. 11, Article ID 1691, 2018.
[40] Z. Li, F.-L. Zheng, W.-Z. Liu, and D.-J. Jiang, "Spatially downscaling GCMs outputs to project changes in extreme precipitation and temperature events on the Loess Plateau of China during the 21st Century," Global and Planetary Change, vol. 82-83, pp. 65–73, 2012.
[41] P. Qin and Z. Xie, "Detecting changes in future precipitation extremes over eight river basins in China using RegCM4 downscaling," Journal of Geophysical Research: Atmospheres, vol. 121, no. 12, pp. 6802–6821, 2016.
[42] Y. Wang, B. Zhou, D. Qin, J. Wu, R. Gao, and L. Song, "Changes in mean and extreme temperature and precipitation over the arid region of Northwestern China: observation and projection," Advances in Atmospheric Sciences, vol. 34, no. 3, pp. 289–305, 2017.