Spatiotemporal Variations in Extreme Precipitation and Their Driving Factors in the Water-Wind Erosion Crisscross Region of the Loess Plateau (1970-2020): A Postprint

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Abstract

The water-wind erosion crisscross region of the Loess Plateau, as a typical ecologically fragile area in northern China, experiences more pronounced impacts of extreme rainfall events on its environment and ecosystems due to its unique topography and climatic conditions. Based on data from 28 meteorological stations in the water-wind erosion crisscross region and using the RClimDex model to calculate 11 extreme precipitation indices, this study employs linear correlation analysis, Mann-Kendall trend test, and wavelet cross-analysis to examine the spatiotemporal distribution characteristics of extreme precipitation events in the Loess Plateau' s water-wind erosion crisscross region from 1970 to 2020, and to explore the driving factors of these events. Results show: (1) From 1970 to 2020, consecutive dry days (CDD) in the water-wind erosion crisscross region exhibited a decreasing trend, while the remaining 10 indices showed increasing trends, reflecting a continuous increase in the frequency, magnitude, and intensity of extreme precipitation events in the study area over the past 50 years. The increase in annual precipitation in the crisscross region is closely related to the increase in extreme precipitation events, and the increase in extreme precipitation events is mainly caused by the number of moderate rain days (R10) and heavy rain days (R20). (2) From 1970 to 2020, extreme precipitation events showed an overall increasing trend across the entire region, with significant occurrences in the central and southwestern parts of the crisscross region; the extreme precipitation amount and intensity in the Shaanxi section exhibited a significant increasing trend with more pronounced extremization. (3) The three extreme precipitation indices of wet-day total precipitation (PRCPTOT), rainstorm days (R25), and 5-day maximum precipitation (R5d) exhibit different power levels with influencing factors including El Niño-Southern Oscillation (ENSO), East Asian Summer Monsoon (EASM), and sunspots (SN), with the cross-wavelet transform power with SN being the largest, indicating that SN has the highest correlation with extreme precipitation indices among the influencing factors and exerts the greatest influence on extreme precipitation events.

Full Text

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Temporal and Spatial Variations of Extreme Precipitation and Analysis of Driving Factors in the Water-Wind Erosion Crisscross Region of the Loess Plateau from 1970 to 2020

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Abstract: As a typical ecologically vulnerable area in northern China, the water-wind erosion crisscross region of the Loess Plateau is particularly sensitive to extreme rainfall events due to its unique topography and climatic conditions. This study selected 28 meteorological stations in the crisscross region and calculated 11 extreme precipitation indices using the RClimDex model. Linear correlation analysis, the Mann-Kendall trend test, and cross-wavelet analysis were employed to examine the spatiotemporal distribution characteristics of extreme precipitation events from 1970 to 2020 and to explore their driving factors. The results indicate: (1) The number of consecutive dry days (CDD) in the crisscross region showed a decreasing trend from 1970 to 2020, while the other 10 indices exhibited increasing trends, reflecting increases in the frequency, magnitude, and intensity of extreme precipitation events over the past 50 years. There is a close relationship between increased annual precipitation and increased extreme precipitation events, with the increase in extreme precipitation events primarily caused by increases in the number of moderate and heavy rain days. (2) Extreme precipitation events showed an overall increasing trend across the entire region from 1970 to 2020, with significant increases occurring in the central and southwestern parts of the crisscross region. The Shaanxi section exhibited a particularly significant increasing trend in extreme precipitation amount and intensity, with the degree of extremity being most pronounced there. (3) Among the three large-scale factors examined—El Niño-Southern Oscillation (ENSO), East Asian Summer Monsoon (EASM), and sunspot number (SN)—the cross-wavelet transform power varied across different extreme precipitation indices. The cross-wavelet transform between SN and the indices showed the maximum power, indicating that SN has the highest correlation with extreme precipitation indices and exerts the greatest influence on extreme precipitation events.

Keywords: water-wind erosion crisscross region; extreme precipitation; temporal and spatial characteristics; cross wavelet; Loess Plateau

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) stated in its Sixth Assessment Report that global mean surface temperature has increased by 0.9–1.2°C. As global warming intensifies, the water cycle strengthens, inevitably leading to increased regional precipitation. Since the 21st century, extreme precipitation events have shown an upward trend in many regions and countries worldwide. In 2021, for instance, Zhengzhou City in Henan Province, China, experienced catastrophic heavy rainfall that caused 1.201×10^{9} CNY in economic losses and affected over 1.479×10^{6} people. Extreme precipitation events not only trigger natural disasters such as floods and droughts but also severely impact socioeconomic and cultural development.

The Loess Plateau constitutes an important ecological barrier in China. With its complex landform types, increased extreme precipitation intensity exacerbates shallow landslides and other gravitational erosion processes while also causing soil erosion and destruction of check dams and small reservoirs, thereby increasing disaster risk and affecting the sustainability of ecological construction on the Loess Plateau. Numerous scholars have analyzed spatiotemporal variation characteristics of extreme precipitation on the Loess Plateau using extreme precipitation indices. Chen Xiaoqiu et al. found that extreme precipitation in the source region of the Yellow River Basin showed a significant increasing trend, while the central and eastern regions exhibited significant decreasing trends. Yang Weitao et al. studied extreme precipitation on the Loess Plateau and found that total annual precipitation, precipitation intensity, and heavy precipitation events all showed upward trends, though these trends were not significant and remained close to average values. The spatial differences among various extreme precipitation indices were evident, showing certain spatial heterogeneity, which provides guidance for extreme precipitation research in the complex climatic conditions of the Loess Plateau' s water-wind erosion crisscross region.

Against a background of continuous warming, precipitation in arid and semi-arid regions tends to increase. The water-wind erosion crisscross region along the Great Wall in northern Loess Plateau represents a transitional zone from the loess hilly-gully region to the Mu Us Desert. This area is an extremely typical climate-sensitive region and ecologically vulnerable zone where water erosion and wind erosion occur alternately throughout the year. Precipitation not only causes intense water erosion but also intensifies subsequent wind erosion. Therefore, research on the spatiotemporal variation characteristics of extreme precipitation events in the water-wind erosion crisscross region is urgently needed. Current research on this region has primarily focused on the processes and mechanisms of wind-water interactive erosion and the dynamic changes in vegetation cover and their relationships with water and sediment, while insufficient attention has been paid to the evolution of climate factors.

This study selected 28 meteorological stations in the water-wind erosion crisscross region and utilized daily precipitation data from 1970 to 2020. Using the RClimDex model to calculate 11 extreme precipitation indices, we employed linear correlation analysis, the Mann-Kendall trend test, and cross-wavelet methods to investigate the spatiotemporal variations and driving factors of extreme precipitation in the Loess Plateau' s water-wind erosion crisscross region. The findings can enable government agencies and relevant departments to respond rapidly to extreme precipitation events and reduce losses, while also playing an important role in preventing severe soil erosion, reducing sediment input into the Yellow River, and promoting regional sustainable development.

2 Study Area and Methods

2.1 Study Area

The water-wind erosion crisscross region of the Loess Plateau (103°33 -113°53 E, 35°20 -40°10 N) is an important natural geographical unit in northwestern China, belonging to the semi-arid steppe zone. This transitional area from gully region to desert receives annual precipitation of 250–450 mm and represents one of the most geomorphologically fragile regions on the Loess Plateau. The region extends from the Great Wall in the north to Shenchi, Lingwu, Xingxian, Suide, Wuqi, Huanxian, Guyuan, Anding, and Dongzhi in the south, covering parts of Shaanxi, Shanxi, Gansu, Qinghai, Inner Mongolia, and Ningxia provinces. Areas north of the Great Wall are dominated by wind erosion, while areas to the south are dominated by water erosion. The complex climatic conditions and geological structure, combined with intense wind-water composite erosion, make this region particularly sensitive to extreme precipitation events.

[Figure 1: see original paper]

2.2 Data Sources

Meteorological data were obtained from the China Surface Climate Data Daily Dataset provided by the National Meteorological Information Center. Based on principles of data completeness and continuity, daily precipitation data from 28 meteorological stations within the study area from 1970 to 2020 were extracted. The RClimDex software was used for data quality control, missing value imputation, and outlier processing.

El Niño-Southern Oscillation (ENSO) data were characterized using NINO3.4 sea surface temperature data (5°S–5°N, 150°–90°W) obtained from the NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/data/climateindices/list/). East Asian Summer Monsoon (EASM) data were sourced from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn). Sunspot data were obtained from the Solar Influences Data Analysis Center of the Royal Observatory of Belgium (http://www.sidc.be/silso/datafiles).

2.3 Methods

2.3.1 Extreme Precipitation Indices The Expert Team on Climate Change Detection and Indices (ETCCDMI) has defined 27 extreme temperature indices and 11 extreme precipitation indices for quantitative study of spatiotemporal variation characteristics of extreme climate. This study adopted 11 extreme precipitation indices (Table 1) to analyze extreme precipitation events in the water-wind erosion crisscross region.

2.3.2 Linear Correlation Analysis Correlation analysis can be used to examine consistency in variation trends between two or more datasets. This study used Pearson correlation analysis to investigate relationships between extreme climate events and influencing factors. The correlation coefficient (r) is expressed as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where n is the sample size; X_i is the observed value of X at time i; $\bar{X}$ is the sample mean of X; Y_i is the observed value of Y at time i; $\bar{Y}$ is the sample mean of Y. When |r| > 0, the variables are correlated; when |r| = 0, they are independent. The closer the absolute value is to 1, the stronger the correlation. When r > 0, the relationship is positive; when r < 0, it is negative.

2.3.3 Cross-Wavelet Transform The cross-wavelet transform for two time series X and Y is defined as:

$$W_{XY}(n) = W_X(n) \cdot W_Y^*(n)$$

where $W_{XY}(n)$ is the cross-wavelet coefficient matrix of time series X_n and Y_n; $W_X(n)$ is the wavelet coefficient matrix of time series X_n; $W_Y(n)$ is the wavelet coefficient matrix of time series Y_n; and $W_Y^*(n)$ is the complex conjugate matrix. The cross-wavelet transform power is $|W_{XY}(n)|$, where greater power indicates stronger correlation between the two time series.

2.3.4 Mann-Kendall Trend Test For a time series variable X = {X_1, X_2, ···, X } where n is the series length, the trend test statistic S and the normally distributed statistic Z are defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(X_j - X_i)$$

where sgn is the sign function:

$$\operatorname{sgn}(X_j - X_i) = \begin{cases} +1 & \text{if } X_j - X_i > 0 \\ 0 & \text{if } X_j - X_i = 0 \\ -1 & \text{if } X_j - X_i < 0 \end{cases}$$

The variance of S is:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

The standardized test statistic Z is:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\operatorname{Var}(S)}} & \text{if } S < 0 \end{cases}$$

In the trend test, if the null hypothesis is rejected at confidence level α, it indicates a significant trend in the time series data.

3 Results

3.1 Temporal Variation Characteristics of Extreme Precipitation

Trend analysis of extreme precipitation indices revealed that consecutive dry days (CDD) showed a decreasing trend at a rate of 0.8 $d \cdot (10a)^{-1}$ (P > 0.05). The other 10 extreme precipitation indices exhibited increasing trends to varying degrees: consecutive wet days (CWD) increased at 0.02 $d \cdot (10a)^{-1}$ (P > 0.05); total precipitation on wet days (PRCPTOT) increased at 12.7 $mm \cdot (10a)^{-1}$ (P < 0.05); moderate rain days (R10mm) increased at 0.3 $d \cdot (10a)^{-1}$ (P < 0.05); heavy rain days (R20mm) increased at 0.15 $d \cdot (10a)^{-1}$ (P > 0.05); torrential rain days (R25mm) increased at 0.1 $d \cdot (10a)^{-1}$ (P > 0.05); very wet day precipitation (R95p) increased at 2.9 $mm \cdot (10a)^{-1}$ (P > 0.05); extremely wet day precipitation (R99p) increased at 2.1 $mm \cdot (10a)^{-1}$ (P > 0.05); maximum 1-day precipitation (RX1day) increased at 1.3 $mm \cdot (10a)^{-1}$ (P < 0.05); maximum 5-day precipitation (RX5day) increased at 2.4 $mm \cdot (10a)^{-1}$ (P < 0.05); and simple daily intensity index (SDII) increased at 0.1 $mm \cdot d^{-1} \cdot (10a)^{-1}$ (P < 0.05).

These trends reflect that over the past 50 years, the water-wind erosion crisscross region has experienced increasing precipitation duration, with extreme precipitation days becoming more frequent and the intensity of extreme precipitation events continuously strengthening. The upward trend in PRCPTOT reflects gradually increasing extreme precipitation amounts, while the upward trend in SDII reflects continuously strengthening extreme precipitation intensity. Overall, extreme precipitation in the crisscross region has increased in terms of duration, intensity, and frequency.

Correlation analysis between the 11 extreme precipitation indices and annual precipitation (Table 2) showed that except for CDD, which was negatively correlated with annual precipitation, all other indices were significantly positively correlated with annual precipitation. The correlation coefficients between PRCPTOT and annual precipitation, R10mm, and R95p were 0.97, 0.82, and 0.80, respectively—much larger than those between annual precipitation and other extreme indices—indicating that the increase in annual precipitation in the crisscross region is mainly derived from extreme precipitation events.

3.2 Spatial Variation Characteristics of Extreme Precipitation

Kriging interpolation was applied to the annual values of the 11 extreme indices at each station to obtain the spatial distribution of extreme precipitation indices. The Mann-Kendall trend test was used to analyze the significance of spatial changes (Figure 3). The results revealed that extreme precipitation events primarily occurred in the central and southwestern parts of the crisscross region, with the Shaanxi section showing a particularly significant increasing trend ($Z > 2.58$).

The entire crisscross region showed an overall increasing trend, with significant increases concentrated in the central and southwestern areas. The Shaanxi section exhibited significant increases ($1.96 < Z < 2.58$), while the Jin-Shan-Mongolia border area showed non-significant decreasing trends. R10mm showed significant increasing trends in the Ningxia, Gansu, and Shaanxi sections. R20mm showed significant increasing trends in the Ningxia, Gansu, and Shaanxi sections, while showing significant decreasing trends in the western part of Shanxi. R95p showed significant increasing trends in the Ningxia, Qinghai, Gansu, and Shaanxi sections, while showing significant decreasing trends in the western part of Shanxi.

Extreme precipitation events occurred frequently in the central and southwestern parts of the crisscross region, with the Shaanxi section showing particularly significant increases in extreme precipitation amount and intensity, indicating a trend toward more extreme precipitation.

[Figure 3: see original paper]

3.3 Analysis of Driving Factors for Extreme Precipitation

This study selected three large-scale factors—El Niño-Southern Oscillation (ENSO), East Asian Summer Monsoon (EASM), and sunspot number (SN)—and the most representative indices from duration, absolute, and intensity indices to create cross-wavelet power spectrum diagrams (Figure 4) for analyzing the influence of driving factors on extreme climate events in the water-wind erosion crisscross region.

Significant resonance periods of 4–8 years were found between ENSO and PRCPTOT. Significant resonance periods of 2–4 years and 4–7 years were identified between EASM and PRCPTOT. Significant resonance periods of 7–13 years were found between SN and PRCPTOT. Significant resonance periods of 8–12 years were identified between ENSO and R95p. Significant resonance periods of 8–13 years were found between EASM and R95p. Significant resonance periods of 3–4 years were identified between SN and R95p. Significant resonance periods of 2–4 years and 5–7 years were found between ENSO and RX5day. Significant resonance periods of 2–4 years and 5–7 years were identified between EASM and RX5day. Significant resonance periods of 1–3 years were found between SN and RX5day.

The three extreme precipitation indices (PRCPTOT, R95p, and RX5day) showed different power levels with ENSO, EASM, and SN, with the cross-wavelet transform power being greatest with SN. This indicates that extreme precipitation indices have varying degrees of correlation with driving factors, with SN showing the highest correlation with extreme precipitation indices and thus having the greatest influence on extreme precipitation events.

[Figure 4: see original paper]

4 Discussion

This study' s findings on the spatiotemporal variation characteristics of extreme precipitation events in the Loess Plateau' s water-wind erosion crisscross region from 1970 to 2020 show that except for the decrease in consecutive dry days, the other 10 indices exhibited upward trends. Zhu Biao' s research on Northwest China climate found increases in torrential precipitation and extreme precipitation intensity. Shen Lulu et al.' s analysis of extreme temperature and precipitation patterns in the Yellow River Basin is consistent with our results, and similar conclusions have been reported in other studies on extreme precipitation changes in the Loess Plateau region. However, these studies were based on larger geographical divisions such as Northwest China or the entire Loess Plateau, with the crisscross region analyzed only as a component of these larger regions. Research specifically focusing on the crisscross region as a whole is scarce, and existing studies on the region have emphasized wind-water composite erosion mechanisms while giving insufficient attention to climate factors, particularly extreme precipitation.

Our study treats the crisscross region as an integrated research object, analyzing its temporal and spatial variation characteristics and introducing driving factor analysis. We found that extreme precipitation events significantly occurred in the central and southwestern parts of the crisscross region. Xu Jie et al. analyzed southern Ningxia mountainous areas and found high positive change rates in extreme precipitation indices across most areas. Liu Xinwei et al. found that southeastern Gansu is prone to extreme rainstorms, while Zhang Jing et al. identified increases in extreme precipitation intensity and heavy precipitation days in the Three-River Source region of Shaanxi-Gansu-Ningxia. Some studies have reported inconsistent results, such as Zhu Biao' s finding that the standardized precipitation index in the Loess Plateau' s water-wind erosion crisscross region showed a decreasing trend with potential for continued drought intensification. This discrepancy may be attributed to the quasi-periodic oscillations of precipitation in China at interannual scales, with the Loess Plateau becoming progressively wetter in recent decades and entering its wettest period in 250 years.

Our study found that extreme precipitation events significantly occurred in the central and southwestern parts of the crisscross region, with the Shaanxi section showing particularly significant increases in extreme precipitation amount and intensity, trending toward greater extremity. These findings are similar to those of Li Shuangshuang et al. and Shi Weiliang et al. for Shaanxi Province, where rainstorm floods have become the second most destructive natural disaster, highlighting the need for particular attention to extreme precipitation events in Shaanxi. The central and southwestern parts of the crisscross region have special geographical locations, with the eastern slope of the Tibetan Plateau to the west and the western extension of the Qinling Mountains to the southeast, which favors the formation and maintenance of low-level jets and enhances upward motion, leading to heavy precipitation.

Atmospheric circulation is a crucial factor affecting weather and climate variations. ENSO often triggers global climate anomalies, while variations in the EASM significantly influence climate disasters in China. Research indicates that both sunspot activity and ENSO directly or indirectly affect precipitation, thereby influencing hydrological cycling processes in the study area. Studies have shown that the weakening of the EASM over recent decades, accompanied by abnormal westward extension of the Western Pacific Subtropical High, has continuously transported moisture from the Indian Ocean and Pacific to the arid regions of Northwest China, transforming these regions from warm-dry to warm-wet conditions. Building on previous research, this study further analyzed driving factors for extreme climate, particularly extreme precipitation, in the crisscross region. The results demonstrate that extreme precipitation indices and driving factors exhibit varying degrees of correlation, with sunspot activity showing the greatest influence on extreme precipitation events. Therefore, attention should be paid to monitoring and early warning of extreme precipitation under conditions of active sunspot numbers.

5 Conclusions

Based on daily precipitation data from 28 meteorological stations and 11 extreme precipitation indices calculated using the RClimDex model, this study analyzed the spatiotemporal distribution characteristics of extreme precipitation events in the water-wind erosion crisscross region of the Loess Plateau from 1970 to 2020 and explored their driving factors. The main conclusions are as follows:

1. Consecutive dry days (CDD) in the water-wind erosion crisscross region

showed a decreasing trend from 1970 to 2020, while the other 10 indices exhibited increasing trends. The intensity, frequency, and magnitude of extreme precipitation events in the crisscross region have continuously increased. There is a close relationship between increased annual precipitation and increased extreme precipitation events, with the increase in extreme precipitation events mainly caused by increases in the number of moderate and heavy rain days.

2. Extreme precipitation events showed an overall increasing trend across the entire region from 1970 to 2020, with significant increases occurring in the central and southwestern parts of the crisscross region. The Shaanxi section exhibited a particularly significant increasing trend in extreme precipitation amount and intensity, with the degree of extremity being most pronounced there.

3. Regarding driving factors, the cross-wavelet transform power between extreme precipitation indices and influencing factors was greatest for sunspot number (SN), indicating that SN has the highest correlation with extreme precipitation indices and exerts the greatest influence on extreme precipitation events.

References

[1] Legg S. IPCC, 2021: Climate change 2021 the physical science basis[J]. Interaction, 2021, 49(4): 44-45.

[2] Chen Xiaoqiu, Liu Li, Yu Yangping, et al. Variation trend of extreme climate events of the Yellow River Basin in 1961–2005 period[J]. Yellow River, 2011, 33(5): 3-5.

[3] Yang Weitao, Sun Jianguo, Kang Yongtai, et al. Temporal and spatial changes of extreme weather indices in the Loess Plateau[J]. Arid Land Geography, 2020, 43(6): 1456-1466.

[4] Sun Yanping. Dynamic changes of vegetation cover and the relationship with climatic factors of the water wind erosion crisscross region in the Loess Plateau[D]. Yangling: Northwest A & F University, 2012.

[5] Zhuo Jing, Hu Hao, He Huijuan, et al. Spatiotemporal variation and driving factors of ecological vulnerability in the Loess Plateau of northern Shaanxi[J]. Arid Land Geography, 2023, 46(11): 1768-1777.

[6] Yin Minfeng, Di Mingting, Deng Xinxin, et al. Wind erosion characteristics on windward slopes affected by water erosion in water erosion crisscross region of the Loess Plateau[J]. Science of Soil and Water Conservation, 2022, 20(5): 39-46.

[7] Li Qiuyan, Cai Qiangguo, Fang Haiyan. Advances in complex erosion of wind and water and ecological restoration[J]. Progress in Geography, 2010, 29(1): 165-172.

[8] Wang Jinhua. Impact of vegetation cover change on water and sediment procession in water erosion crisscross region[D]. Xi' an: Xi' an University of Technology, 2017.

[9] Sun Yanping, Zhang Xiaoping, Liu Jianxiang, et al. Dynamic change of vegetation coverage in water wind erosion ecotone in the Loess Plateau[J]. Arid Zone Research, 2013, 30(6): 1036-1043.

[10] Tang Keli, Hou Qingchun, Wang Binke, et al. The environment background and administration way of wind water erosion crisscross region and Shenmu experimental area on the Loess Plateau[J]. Research of Soil and Water Conservation, 1993(2): 2-15.

[11] Yang Can, Wei Tianxing, Li Yiran, et al. Spatiotemporal variations of NDVI before and after implementation of grain for green project in wind water erosion crisscross region of the Loess Plateau[J]. Journal of Beijing Forestry University, 2021, 43(6): 83-91.

[12] Zhao Guoyong, Han Yan, Liu Minghua, et al. Spatial-temporal variation of extreme precipitation events in Henan Province from 1961 to 2013[J]. Research of Soil and Water Conservation, 2018, 25(6): 115-120.

[13] Xu Jie, Bi Yuzhu, Lei Qiuliang, et al. Analysis of extreme climate change trends and influencing factors from 1961 to 2020 in Ningxia Hui Autonomous Region, China[J]. Chinese Journal of Agricultural Resources and Regional Planning, 2022, 43(12): 159-171.

[14] Liu Xinwei, Wang Chenghai, Guo Runxia, et al. Climate and circulation characteristics of extreme rainstorm processes in Gansu[J]. Plateau Meteorology, 2021, 39(5): 750-758.

[15] Zhang Jing, Zhang Ke, Wang Sheng, et al. Spatiotemporal variation analysis of extreme precipitation in the Three River Source Area of the Shaanxi-Gansu-Ningxia contiguous region from 1971 to 2017[J]. Journal of Hohai University (Natural Sciences Edition), 2021, 49(3): 288-294.

[16] Zhu Biao. Variation characteristics of vapor, potential evapotranspiration and extreme temperature and precipitation under the background of warming wetting in northwest China[D]. Lanzhou: Lanzhou University, 2022.

[17] Shi Weiliang, Che Luyang, Li Tao. Probability distribution and comprehensive risk assessment of extreme precipitation in flood season in Shaanxi Province[J]. Arid Land Geography, 2023, 46(9): 1407-1417.

[18] Shen Lulu, Yang Yanfen, Wu Jing, et al. Spatial and temporal variation characteristics of extreme climate events in the Yellow River Basin[J]. Research of Soil and Water Conservation, 2022, 29(2): 231-242.

[19] Zhao Qingyun, Fu Chao, Liu Xinwei, et al. Characteristics of mesoscale system evolution of torrential rain in warm sector over northwest China[J]. Plateau Meteorology, 2017, 36(3): 697-704.

[20] Dong X, Zhang S, Zhou J, et al. Magnitude and frequency of temperature and precipitation extremes and the associated atmospheric circulation patterns in the Yellow River Basin (1960–2017), China[J]. Water, 2019, 11(11): 2334.

[21] Ren Yuling. Evaluation and projection of extreme climate changes and its impacts on river runoff and sediment load on the Loess Plateau[D]. Yangling: Northwest A & F University, 2022.

[22] Zhao X, Li Z, Zhu Q, et al. Change of precipitation characteristics in the water wind erosion crisscross region on the Loess Plateau, China, from 1958 to 2015[J]. Scientific Reports, 2017, 7(1): 8048.

[23] Schär C, Lüti D, Beyrle U, et al. The soil precipitation feedback: A process study with a regional climate model[J]. Journal of Climate, 1999, 12(3): 722-741.

[24] Cai Q F, Liu Y, Fang C X, et al. Insight into spatial temporal patterns of hydroclimate change on the Chinese Loess Plateau over the past 250 years, using new evidence from tree rings[J]. Science of the Total Environment, 2022, 850: 157960.

[25] Brown P J, Bradley R S, Keimig F T. Changes in extreme climate indices for the northeastern United States, 1870–2005[J]. Journal of Climate, 2010, 23(24): 6555-6572.

[26] New M, Hewitson B, Stephenson D B, et al. Evidence of trends in daily climate extremes over southern and west Africa[J]. Journal of Geophysical Research: Atmospheres, 2006, 111(D14): D14102.

[27] Regoto P, Dereczynski C, Chou S C, et al. Observed changes in air temperature and precipitation extremes over Brazil[J]. International Journal of Climatology, 2021, 41(11): 5125-5142.

[28] Shi Wenru, Li Xin, Zeng Mingjian, et al. Multi-model comparison and high resolution regional model forecast analysis for Zhengzhou severe heavy rain[J]. Transactions of Atmospheric Sciences, 2021, 44(5): 688-702.

[29] Meehl G A, Tebaldi C. More intense, more frequent, and longer lasting heat waves in the 21st century[J]. Science, 2004, 305(5686): 994-997.

[30] Perkins S, Alexander L, Nairn J. Increasing frequency, intensity and duration of observed global heatwaves and warm spells[J]. Geophysical Research Letters, 2012, 39(20): 20714.

[31] Li G K, Moon S. Topographic stress control on bedrock landslide size[J]. Nature Geoscience, 2021, 14(5): 307-313.

[32] Stocker T F, Qin D, Plattner G K, et al. Climate change 2013: The physical science basis. Contribution of working group I to the Fifth Assessment Report of IPCC the Intergovernmental Panel on Climate Change[M]. Cambridge: Cambridge University Press, 2014.

[33] Jia Yanqing, Zhang Bo, Zhang Yaozong, et al. Correlation analysis of variation of extreme temperature events and ENSO in Yangtze River Delta region during 1960–2014[J]. Acta Ecologica Sinica, 2017, 37(19): 6402-6414.

[34] Huang Jianping, Chen Wen, Wen Zhiping, et al. Review of Chinese atmospheric science research over the past 70 years: Climate and climate change[J]. Scientia Sinica Terrae, 2019, 49(10): 1607-1640.

[35] Zhou T, Wu B, Dong L. Advances in research of ENSO changes and the associated impacts on Asian Pacific climate[J]. Asia Pacific Journal of Atmospheric Sciences, 2014, 50: 405-422.

[36] Chen Wen. Correlation analysis between sunspot activity and sea surface temperature[D]. Shanghai: Shanghai Normal University, 2022.

[37] Chen F, Chen J, Huang W, et al. Westerlies Asia and monsoonal Asia: Spatiotemporal differences in climate change and possible mechanisms on decadal to sub-orbital timescales[J]. Earth Science Reviews, 2019, 192: 337-354.

[38] Dong Linyao, Zhang Pingcang, Liu Jigen, et al. Combined influence of solar activity and ENSO on hydrological processes in Yoshino River Basin, Japan[J]. Advances in Water Science, 2017, 28(5): 671-680.

Note: Figure translations are in progress. See original paper for figures.