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Spatial and temporal variations of precipitation in Northwest China during 1973-2019

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Abstract

The Shaanxi-Gansu-Ningxia (SGN) region in Northwest China has been challenged by drought and water shortage for decades. Based on the precipitation data from 30 weather stations in the SGN region during 1973–2019, the Empirical Orthogonal Function (EOF) and the Wavelet analysis (WA) were applied to analyze the precipitation spatio-temporal variations at different time scales. The results showed that precipitation at annual scale had decreased significantly ($P < 0.01$) at the rate of 1.46 mm/10a during 1973–2019, and 56.7% of stations showed a decreasing trend, which was mainly concentrated in the Jing River basin. In terms of seasonal precipitation, more than 65% of the stations showed an increasing trend in summer and winter, with increasing at 2.06 mm/10a and 0.56 mm/10a, respectively, but most significantly, 86.7% of the stations showed a decreasing trend in the spring, and only less than 15% of the stations in the Hulu River basin showed an increasing trend. This study will help to further improve understanding of climate change, and provide reference to cope with future climate change and solve the problem of water shortage.

1 Introduction

As a hydrometeorological element, precipitation greatly influences ecological environment and socio-economic development (Wu et al. 2022). First, in the context of climate change and human activities, precipitation-related extreme weather events have occurred more frequently in recent years (Zhang et al. 2021). Second, as a key component of the global water cycle, it directly influences elements of the hydrologic process such as precipitation redistribution, infiltration and runoff, the surface and subsurface water table, which inevitably affects the changes in precipitation patterns (Liu et al. 2021; Xu et al. 2019). Meanwhile, with further changes in precipitation patterns, extreme weather events are likely to occur more frequently (Harris et al. 2018). Moreover, the change in precipitation

patterns directly affects the development and utilization of regional water resources (Lu et al. 2019). Therefore, it is necessary to study the complexity characteristic of precipitation for analyzing the variation law of water cycle under climate change and revealing the influence of climate change on precipitation.

The globe is currently experiencing a change dominated by warming, but the local responses around the world are different. For instance, precipitation had increased over the past 50 years and reported in the high latitudes in the Northern Hemisphere, Central Africa, India and Southeast Asia, while a declining trend in precipitation in the low latitudes such as North Central South America, Southern Africa, Australia, and Indonesia (Gu et al. 2016; Yang et al. 2017). Additionally, many scholars have also investigated the trends of precipitation in a number of different areas and regional scales. For example, Lavender et al. (2013) found that precipitation has significant changes in Australia with decreases in the east and increases in the north-west. The increasing trend of summer precipitation in southern Brazil is consistent with the warming trend in daily maximum and minimum temperatures (Sansigolo et al. 2010). Wang et al.

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(2020) found that the drought severity is slightly increasing in eastern Northwest China, while in the western Northwest China, there is a certain asymmetry in temperature and precipitation increases in recent decades.

In addition, precipitation is likely to be affected by warming, which also has an effect on the global and regional water cycle (Lambert et al. 2008). The increase in temperature leads to an increase in the water holding capacity, and the increase in the surface temperature of land and sea makes its evaporation also enhanced, implying that the actual atmospheric moisture content will increase and the possibility of droughts occurring is exacerbated by the increase in potential evaporation (Findell et al. 2019; Goyal 2004; Trenberth et al. 2003; Xie et al. 2010). Li et al. (2020) found that the increase in precipitation is dependent on the enhanced recirculation rates (combination of the effects of evaporation and water vapor irradiation).

The SGN region, as an important node of "the Belt and Road", is located in the transition zone between monsoonal and continental climates, with a fragile ecological environment, and is one of the most sensitive areas to global climate change (Li et al. 2021a; Shi et al. 2007). Over the past decades, while the spatial and temporal distributions of precipitation have changed significantly, drought has become a serious natural hazard with the increasing demand for water in SGN region (Liu et al. 2016; Yang et al. 2017). Therefore, it is of great significance to study the variation of precipitation over long periods, especially in the arid and semi-arid areas of the northwest. Li et al. (2021a) investigated the variability and spatial distribution of precipitation in different climate zones by the monthly precipitation data

in northwestern China during 1960–2015. Lu et al. (2021) studied the variability and the possible mechanisms of the extreme precipitation in northwest China. Cao et al. (2021) investigated the spatiotemporal characteristics of drought in northwest China by using the Theil-Sen median trend and Mann-Kendall test correlation analysis. Liu et al. (2016) also analyzed the relationships between the dryness/wetness conditions and ENSO in northwest China. Although many researchers have conducted comprehensive analyses regarding precipitation trends, the information on the spatial distribution patterns and temporal trends at different time scales still need to be strengthened.

In general, the main objectives of this study based on hydrometeorological data in SGN region during 1973–2019 are as follows: (1) to analyze the spatio-temporal characteristics of annual and seasonal precipitation; (2) to discern the major spatial patterns of precipitation by revealing nonlinear and non-stationary characteristics; (3) to detect periodic analysis of annual and seasonal precipitation series. This study will help to further improve understanding of climate change, and provide reference to cope with future climate change and solve the problem of water shortage.

2 Materials and methodology

2.1 Study area and data

The study area, SGN (34º30′-37º50′ N, 105º02′-108º55′ E), covering 31 cities in Shaanxi, Gansu and Ningxia Hui Autonomous Region with an area of 6.9×10^4 km^2 (Fig. 1).
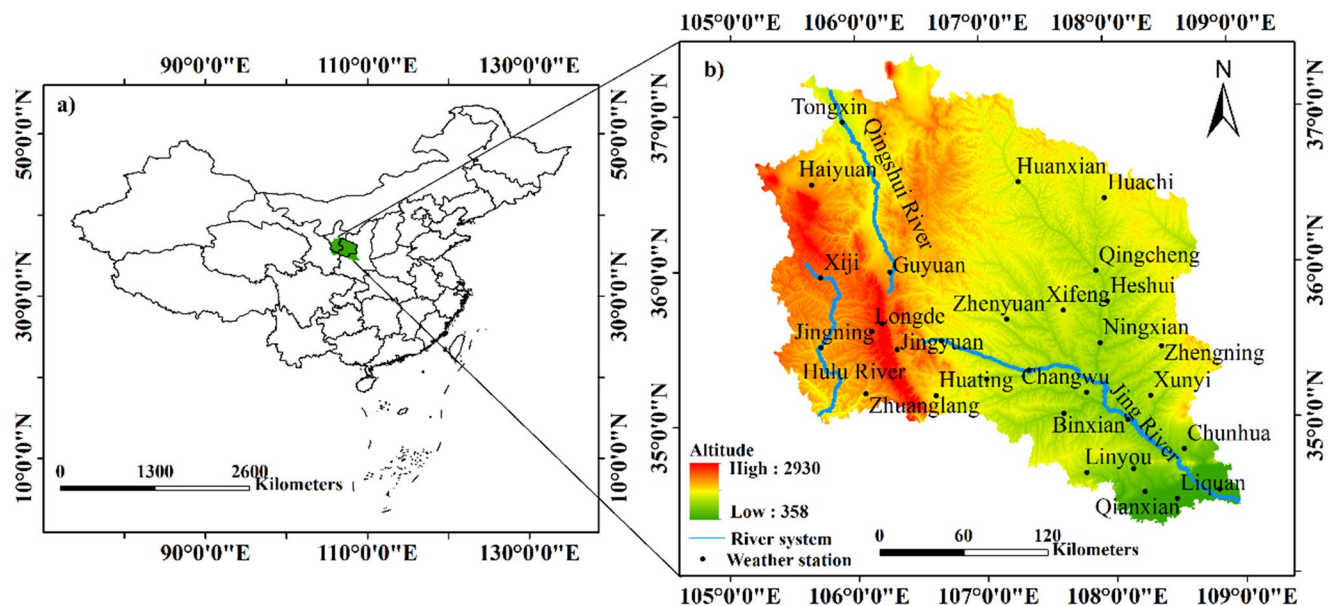

Fig. 1 Geographic location of the study area and distribution of the weather stations: **a** map of China, with study area shown in green; **b** a topographical map of the study area with the distribution of the weather stations (black dots)

Three rivers, Jing River, Hulu River and Qingshui River, originate in the Liupan Mountain region of Ningxia. The terrain is high in the northwest and low in the southeast in Jing River basin; the Qingshui River basin is high in the south and low in the north, with an altitude of 500–2000 m and mainly loess hills; the Hulu River basin is high in the north and low in the south, with an average elevation of 1800 m and ravines in the basin. In terms of different climatic zones in China, study area is connected by Northern Temperate Continental (TC), Southwestern Mountain Plateau (MP), and Eastern Temperature Monsoon (TM) climate zones, which is the special geographical location and complex climate environment (Gui et al. 2021).

The daily meteorological data were downloaded from National Climate Center of China Meteorological Administration (CMA) for the period 1973–2019 (http://data.cma.cn/). The datasets have been processed with strict quality control including consistency checks and extreme inspection, and are available with missing rate of less than 0.1%. A few missing data were interpolated based on nearest stations (Barrios et al. 2018). Based on the length of the original time series, we have considered from the seasonal scale (spring as March–May, summer as June–August, autumn as September–November, and winter as December–February) and the annual scale to assess the spatial distribution patterns and temporal trends of precipitation at different time scales. Furthermore, * and ** indicate that the linear trends are statistically significant at the 95% and 99% confidence levels, respectively.

2.2 Empirical orthogonal function analysis

The spatio-temporal variations of precipitation were analyzed using Empirical Orthogonal Function (EOF). The EOF analysis has proven to be a powerful tool to discern the major spatial patterns from the spatiotemporal pattern of geographic data by revealing nonlinear and non-stationary interactions (Monahan et al. 2009; Yu et al. 2015). It provides a brief method to describe patterns in variations of the target variable anomalies (Wu et al. 2023). If the target variable Y was observed N times in M spatial points, then the anomaly is.

$$\Delta(m, n) = Y(m, n) - \overline{Y}(n) \tag{1}$$

where $m = 1, 2, …, M$, and $n = 1, 2, …, N$, spatial points and times of observations, $\overline{Y}(n)$ is the mean value of the target variable $Y(m, n)$.

$$\Delta(m, n) = \sum_{k=1} EOF_k(m) EC_k(n) \tag{2}$$

where $EOF_k(m)$ is the kth spatial pattern for each of spatial points m, $EC_k(n)$ is the expansion coefficient for each of times n.

2.3 Wavelet analysis

The Wavelet analysis (WA) has certain advantages in identifying periodic oscillations of signals. With the development of multidisciplinary intersection, WA is widely used for multi-time scale feature analysis in hydrometeorological research (Chen et al. 2018; Morlet et al. 1982). This method can fully reveal the change trends of hydrometeorological data in the time series of different timescales. Please see the detail equations of WA described by Hsu and Li (Hermida et al. 2015).

3 Results

3.1 Spatial distribution of precipitation

Due to the specificity of geographical location and the complexity of various climatic factors, the linear trend of precipitation has significant differences in space (Fig. 2). The spatial distribution of precipitation trends over annual and seasonal scales from 1973 to 2019 had distinct regional characteristics. Topography and climate changed from southeast to northwest, the annual precipitation presented a decreasing trend (56.7% of the stations). Among the four seasons, 66.7% of stations in summer and 83.3% of stations in winter showed an increasing trend, while spring and autumn showed a decreasing trend by 86.7% and 46.7% of stations, respectively. The seasonal mean precipitation was sorted as summer (258.86) > autumn (142.23) > spring (96.26) > winter (15.67) (Table 1). Furthermore, Extremum ratio (ER), the ratio of the difference between the maximum and minimum values to the minimum value, is used to determine changing magnitude of variables. In this study, we want to investigate the relative changing magnitude of precipitation. The annual mean precipitation ranged from 264.22 to 631.72 mm, while the ER_annual was 1.39. The seasonal mean precipitation was highly variable, which the order was ER_{winter} (2.83) > ER_{autumn} (2.18) > ER_{spring} (1.53) > ER_{summer} (1.33).

In addition, to further analyze the spatial distribution characteristics of precipitation, Fig. 3 shows the first eigenvector fields (LV1) of annual and seasonal standardized precipitation in SGN region. The annual, spring, summer, autumn, and winter precipitation had similar characteristics, with variance contributions of 61.9%, 75.9%, 46.5%, 79%, and 83.7%, respectively. Except for summer, the variance contribution of LV1 was around 70%. This distribution of

Fig. 2 Precipitation trends in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019. The green (red) dot indicates the increasing (decreasing)
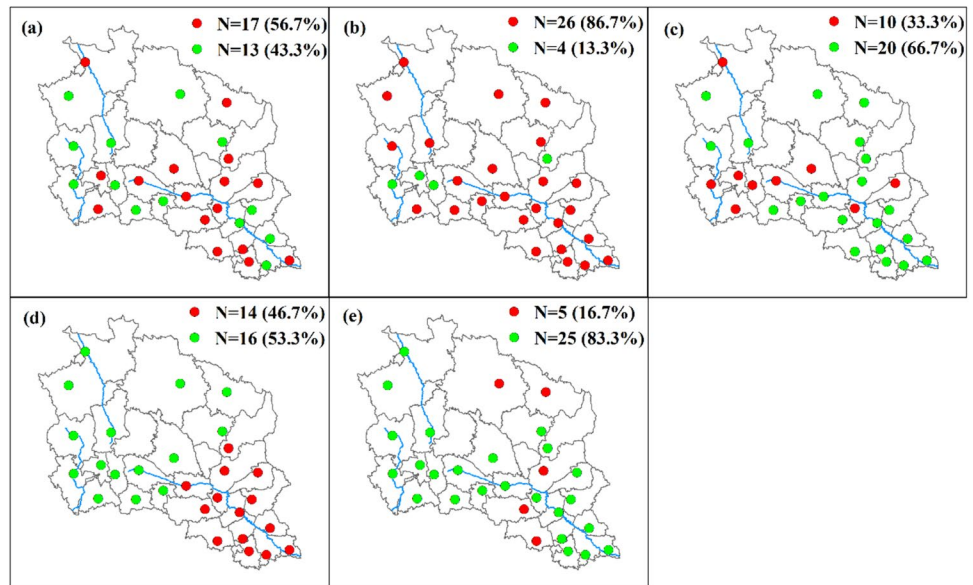

Table 1 Multi-year mean statistic value of precipitation (mm)

	Annual	Spring	Summer	Autumn	Winter
Minimum	264.22	48.89	149.34	59.83	6.16
Maximum	631.72	123.75	348.13	190.07	23.54
Mean	513.02	96.26	258.86	142.23	15.67
ER	1.39	1.53	1.33	2.18	2.83

anomalous variations reflected the most basic characteristics of precipitation space. The interannual variability of annual and seasonal scale precipitation was generally consistent, including the Qingshui River, Hulu River and Jing River basins. In other words, the interannual variation of precipitation in SGN region was characterized by in-phase.

In order to reveal the local characteristics of precipitation, Fig. 4 shows the second eigenvector fields (LV2) of annual and seasonal standardized precipitation in SGN region. The

spatial patterns of annual, spring and summer precipitation showed a positive-negative distribution in the northwest-southeast direction with a variance contribution of 17.1%, 6.7% and 23.3% for LV2, respectively. In autumn, the Qingshui River and Hulu River basins were positive, and the center of negative values was near the Jing River basin, with a variance contribution of 10.05% for LV2. The large absolute values in winter were centered in the higher elevation of the Liupan Mountain, which was the watershed of the Qingshui River, Jing River and Hulu rivers. Combined with the positive and negative variations of the time coefficients (PC2) of LV2, it revealed that the LV2 of annual, spring and summer showed a northwest-southeast increasing distribution in the local characteristics. The regions with increased precipitation and increased variability in autumn were in the Qingshui River and Hulu River basins. The winter

Fig. 3 The first eigenvector fields (LV1) of precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019. The values at top right corner indicates the variance contribution rate of LV1
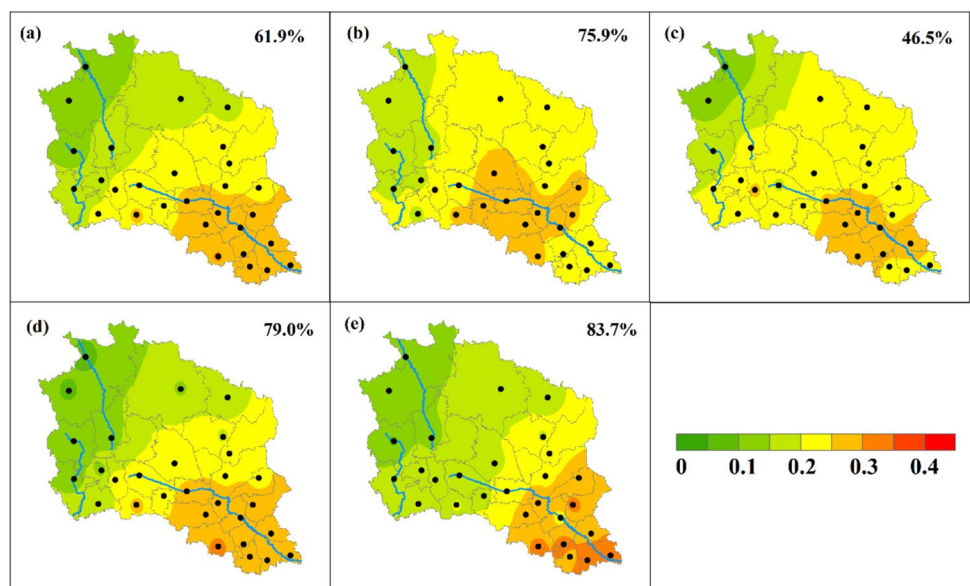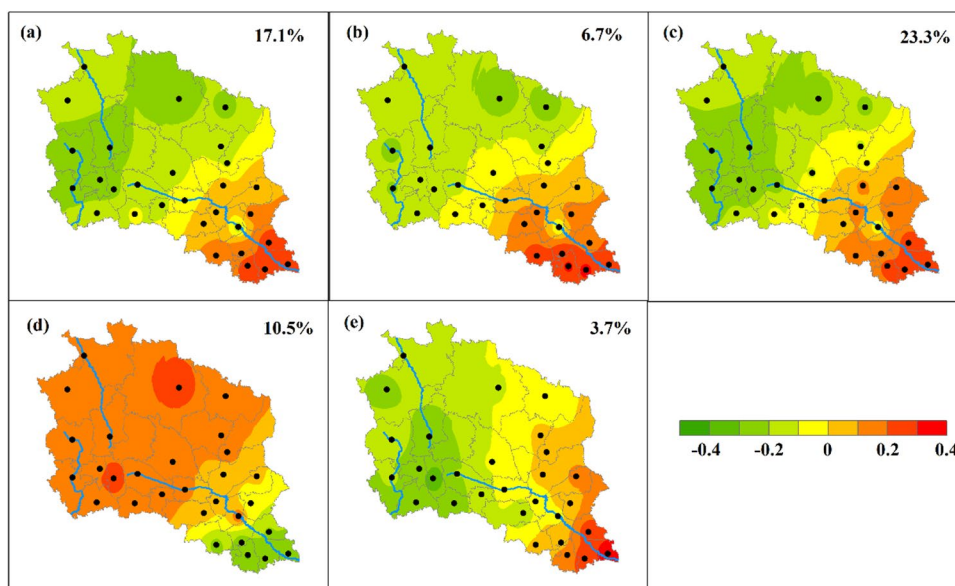
Fig. 4 The second eigenvector fields (LV2) of precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019. The values at top right corner indicates the variance contribution rate of LV2

precipitation was influenced by the topography such as the Liupan Mountain, showing a pattern of northwest-southeast spaced distribution.

3.2 Temporal evolution of precipitation

Figure 5 shows the time series of annual and seasonal mean precipitation in SGN region from 1973 to 2019. The annual, spring and autumn ($P < 0.01$) mean precipitations showed a significantly decreasing trend in SGN region from 1973 to 2019, with decreasing at 1.46 mm/10a, 3.74 mm/10a, and 0.34 mm/10a, respectively (Table 2). And precipitation in summer and winter, on the contrary, increasing at the tendency rate of 2.06 mm/10a and 0.56 mm/10a. Based on the annual and seasonal mean precipitation changes analysis, we calculated the percentage of seasonal precipitation to annual precipitation during 1973–2019. During this period, spring, summer, autumn and winter accounted for 18.8%, 50.5%, 27.7%, 3.1% of the annual precipitation, respectively. These results indicate that precipitation is mainly concentrated in summer, and winter is the season with the least precipitation.

Figure 6 shows the evolutionary characteristics of the time coefficients (PC1) of the first eigenvector field of annual and seasonal precipitation. The larger absolute value of the time coefficient indicates a more typical spatial type of precipitation at that moment. In general, PC1 shows a slight declining trend, with a turning point in 1996. Combined with the positive value areas of LV1, reflecting a slight decrease in precipitation in SGN region from 1973 to 2019. Among the four seasons, the PC1 of LV1 in spring and autumn were mostly positive values before 1996, and considering that the spatial distribution of LV1 was mostly positive values, which indicated that the precipitation was high in spring

and autumn. After 1996, the changes of PC1 were mostly positive values in summer and winter, and combined with the positive value areas of LV1, it could be seen that the summer and winter precipitation in SGN region increased after 1996. These results are generally consistent with the analysis results in Fig. 5.

The evolutionary characteristics of the time coefficients (PC2) of the second eigenvector field of annual and seasonal precipitation in SGN region are presented in Fig. 7. The results showed that the modal variation characteristics reflected by PC2 was generally consistent with the level of typical precipitation fields responded by LV2 (Fig. 4), suggesting that the precipitation in the northwestern part of SGN region showed an increasing trend, while the southeastern part showed a decreasing trend. In addition, the interannual variation of PC2 on the regional scale was roughly the similar to the first mode, with a turnaround in 1996, after which precipitation began to decline. Regardless of whether the annual or seasonal evolution characteristics were considered, the precipitation increased slightly before the beginning of the 1996, whereas it began to decline afterward.

Figure 8 shows the results of the period analysis of annual and seasonal precipitation in SGN region from 1973 to 2019. The annual precipitation had a long period of 29-year and a short period of 11-year over the time domain, of which 29-year was the most important. Among the four seasons, the period of precipitation in summer was similar to that of the precipitation in autumn, both of which had a period of 29-year. The main period of precipitation for spring and winter were 20-year and 23-year, respectively.

Fig. 5 Temporal evolution of the precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019
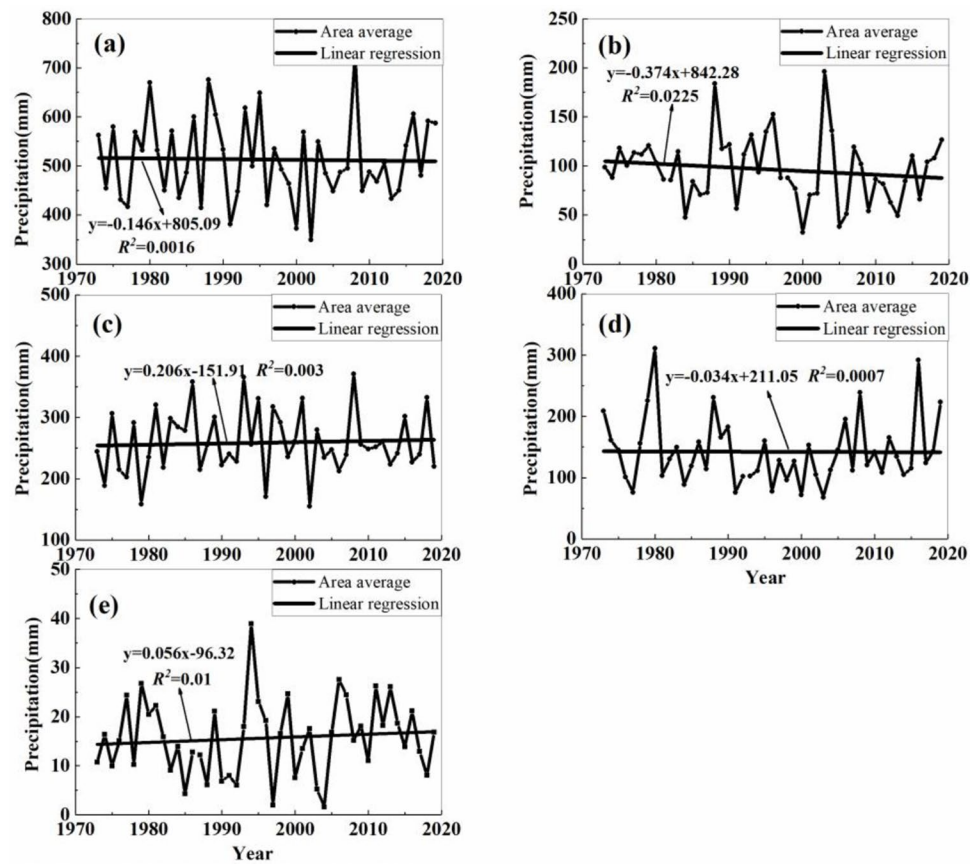

Table 2 Linear trends of annual and seasonal mean precipitation in SGN region during the entire period (E:1973–2019) (mm/10a)

	Annual	Spring	Summer	Autumn	Winter
E (1973–2019)	-1.46**	-3.74**	2.06**	-0.34**	0.56

4 Discussion

4.1 Comparison with relevant studies

Located in the transition zone between monsoonal and continental climates, the SGN region has various climate conditions and fragile ecological environment, and is one of the most sensitive areas to global climate change (Li et al. 2021b). Therefore, it is of great significance to identify the variation trend of precipitation at different time scales and reveal the spatio-temporal distribution of precipitation patterns based on daily precipitation data.

The globe is experiencing a change dominated by climate warming, but the response in local regions is different. In this study, 56.7% of stations in SGN region showed a decreasing trend, and the annual precipitation had decreased at the rate of 1.46 mm/10a, which is higher than that estimated in China (Li et al. 2016). Our results are consistent with those of Yang et al. (2017) and Wang et al. (2012), who identified a decreasing trend in annual precipitation in the

northwest China over the last decades. Meanwhile, as the climate gradually warms, the decrease in precipitation will lead to an intensification of the drought trend in the region, causing negative effects on soil moisture and surface cover, thereby increasing the occurrence of sandstorms, especially in spring and autumn (Fig. 5), which will have adverse effects on regional water resources and ecological environment. However, owing to the differences in the study area, number of observational stations and time periods, it has been noted that northwest China is also undergoing a warm-dry to warm-wet transition. Deng et al. (2014) found that precipitation in the arid region of northwest China showed a significant increasing trend over the past 50 years, which is different from our results. Furthermore, the temporal variation of annual precipitation existed in the change periods of 11-year and 29-year based on wavelet analysis (Fig. 8), which is consistent with the results of Tian et al. (2012).

4.2 Limitations and future prospects of the study

Changes in precipitation are induced not only by natural climate factors but also by human activities (Cubasch et al. 2000; Gao et al. 2018). Therefore, precipitation changes may be related to climatic variation induced by human activity. Climate change is mainly related to emissions of

Fig. 6 The time coefficients (PC1) of the first eigenvector field of precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019. The values at top right corner indicates the variance contribution rate of LV1
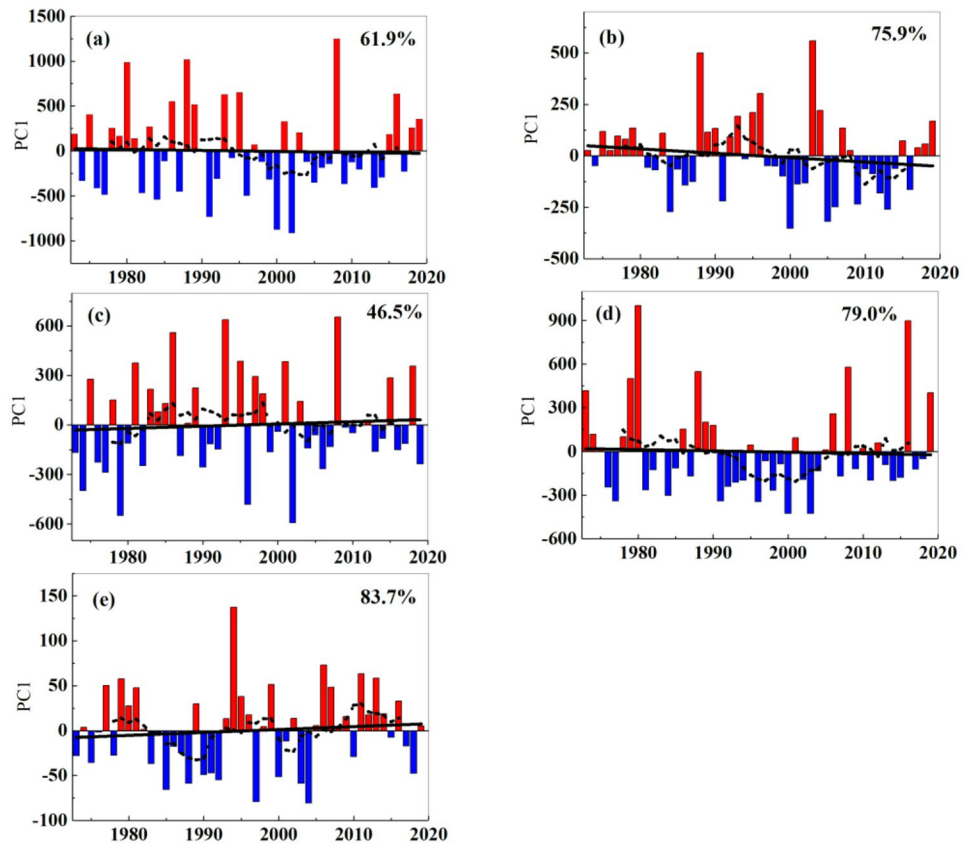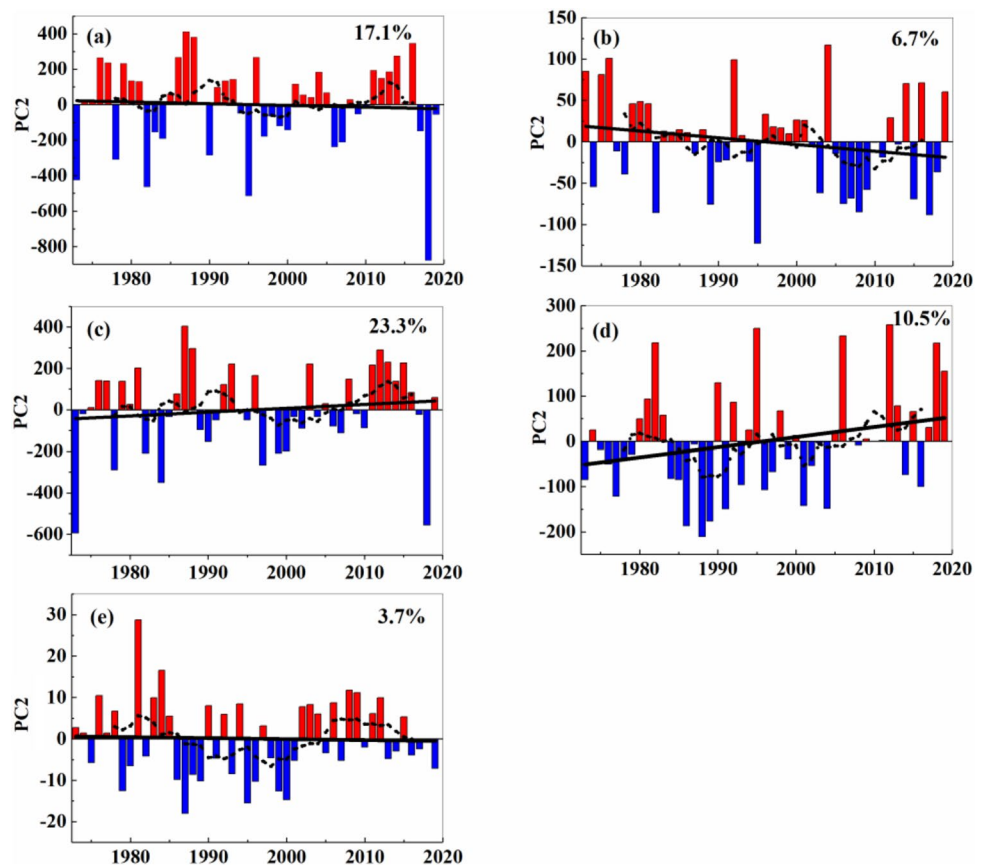
Fig. 7 The time coefficients (PC2) of the second eigenvector field of precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019. The values at top right corner indicates the variance contribution rate of LV2

Fig. 8 Wavelet analysis of the precipitation in SGN region for the **a** annual, **b** spring, **c** summer, **d** autumn and **e** winter during 1973–2019
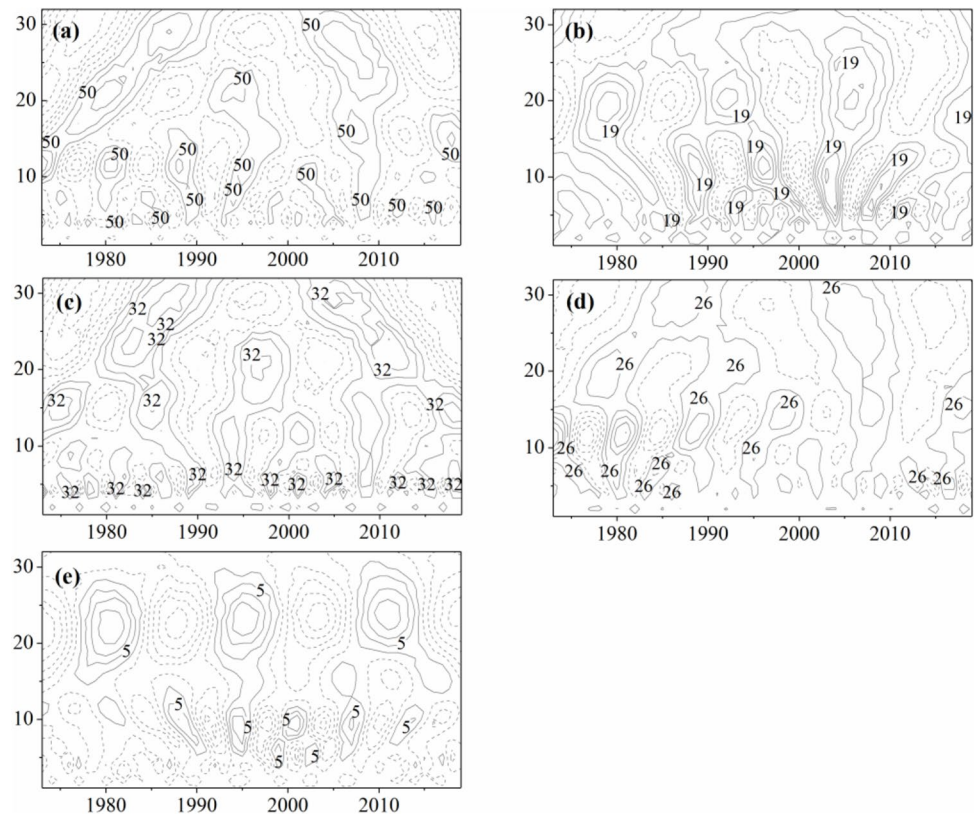
anthropogenic greenhouse gases (Grimm 2011). Furthermore, changes in local climate factors are caused by agricultural activities, especially irrigation (Malek et al. 2018). Agricultural irrigation affects regional climate through artificial change of surface water processes. Changes in regional climate and decreased soil moisture reduce evaporation and transpiration, which decreases air humidity in irrigation areas (Purdy et al. 2018). Previous research suggests that precipitation variation is affected by changes in relative humidity due to vegetation cover and land use change, including water conservation and urbanization (Pielke Sr et al. 2007; Wang et al. 2021). Furthermore, the spatial difference changes were affected by complex topography and geomorphology in precipitation analysis, such as mountains and basins glaciers, which influence water vapor transport and lead to spatial variation in precipitation (Cheng et al. 2015; Li et al. 2017). Therefore, the effect of the various complex conditions on precipitation characteristics in the region need to be further investigated in future studies.

Based on meteorological station data, this study analysed the spatio-temporal characteristics of precipitation in SGN region during 1973–2019. However, the unevenly distributed meteorological stations affect the accuracy of the spatial interpolation results. In addition, the limited number of stations cannot identify the relationship between precipitation variations and elevation and other geographical factors. Thus, high-density meteorological stations with long-term

observations will provide a better understanding of precipitation changes. Meanwhile, whether the decreasing trend of precipitation will continue, how hydrological processes respond to changes in precipitation, and the influence of decreasing precipitation on ecological environment and its mechanisms need to be further studied.

5 Conclusions

The research presented a full picture of the spatial distribution patterns and temporal trends of precipitation in SGN region at different time scales. Some insights are summarized as following:

(1) Precipitation at annual scale in SGN region have decreased significantly ($P < 0.01$) at the rate of 1.46 mm/10a during 1973–2019, and 56.7% of stations showed a decreasing trend, which was mainly concentrated in the Jing River basin.

(2) For the seasonal precipitation, more than 65% of the stations showed an increasing trend in summer and winter, with increasing at 2.06 mm/10a and 0.56 mm/10a, respectively, but most significantly, 86.7% of the stations showed a decreasing trend in the spring, and only less than 15% of the stations in the Hulu River basin showed an increasing trend.

(3) The period analysis showed that the annual precipitation had a long period of 29-year and a short period of 11-year over the time domain. Among the four seasons, the period of precipitation in summer was similar to that of the precipitation in autumn, both of which had a period of 29-year. The main period of precipitation for spring and winter were 20-year and 23-year, respectively.

The results of this study will help to further improve understanding of climate change, and provide reference to cope with future climate change and solve the problem of local water shortage. Limited to space and technical research, the potential causes of precipitation variations in SGN region need to be further studied in future researches.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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