ORIGINAL ARTICLE

Spatiotemporal changes of the aridity index in Xinjiang over the past 60 years

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Abstract

The Aridity Index (AI), calculated from 99 homogeneous meteorological stations from 1961 to 2020, was used to analyze the variation of dryness/wetness climate change in Xinjiang in the past 60 years. The results show that the annual AI in Xinjiang has demonstrated a significant decreasing trend over the past 60 years; that is, the climate in Xinjiang, especially southern Xinjiang, has shown a relatively wetting trend. The interdecadal variations from the 1960s to 2010s explained that the total station ratio of arid and extremely arid areas showed a decreasing trend. In contrast, the semi-arid, humid, and semi-humid areas showed increasing trends, especially since the beginning of the twenty-first century. The interdecadal spatial evolution characteristics show that Xinjiang's dryness/wetness climate reversed in the 1990s. An abrupt change in the annual AI occurred in 1986, after which the study region was continuously wetting. The first empirical orthogonal function (EOF) decomposition mode is consistent in Xinjiang; that is, the climate in Xinjiang is generally dry or wet, and the intensity of this change varies among different regions. The second mode reflects the opposite spatial distribution characteristics of the dryness/wetness climate in southern and northern Xinjiang with the Tianshan Mountains. Dryness/wetness climate changes in Xinjiang mainly exhibit 2.5-year and 6-year oscillation periods, between which the 6-year period is even more significant.

Keywords Aridity Index · Temporal and spatial variation · Climate change · Xinjiang

Introduction

Climate change has significantly impacted the global and regional water cycles and the distribution of dryness/wetness climate zones in the past few decades. Central Asia's arid region is the world's largest non-zonal arid region. Its ecological environment is fragile and sensitive to global climate change (Chen et al. 2011; Donat et al. 2019; Ma et al. 2019). The arid region of Central Asia responded significantly to global warming in the twentieth century, and the temperature increased significantly. The precipitation in Central Asia increased (Wang et al. 2008). The precipitation in the arid region of Central Asia is mainly affected by westerly circulation and North Atlantic Oscillation (NAO) (Aizen et al. 2001). Northwest China, adjacent to the five Central Asian countries, is located between Central Asia's arid and monsoon regions. It is a transitional region affected by westerly and monsoon and its complex climate characteristics (Huang et al. 2012). At the beginning of the twenty-first century, some studies concluded a transition from the warm-dry pattern to the warm-wet pattern in northwest China, especially in Xinjiang (Shi et al. 2003). In recent years, the study of 'Climate Warming and Humidification' in this area has attracted more and more attention from academia and governments at all levels (Yao et al. 2022; Kumar et al. 2015). Therefore, in the context of global warming, it is of practical significance to analyze the characteristics of aridity and humidity changes in Xinjiang's climate.

In past research, there was no standard definition of 'dry' or 'wet.' The core of the characterization of dryness/wetness climate change refers to a change in the surface water moisture availability/loss or the balance of moisture income/expenditure (Wang et al. 2014). Under global warming, a single precipitation change analysis cannot reflect a region's

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true dryness/wetness, especially in arid areas where precipitation is much less than evapotranspiration. Drought is generally considered to be the difference between the water supply in terms of water availability and the atmospheric water demand through evapotranspiration (Thornthwaite 1948). In contrast, the aridity index (or humidity index) considers precipitation and evaporation, providing a better picture of dryness/wetness conditions than a single precipitation analysis can provide (Zhang et al. 2016a). Many studies have also suggested that the aridity index can reflect the actual situation of the dryness/wetness climate in an integrated manner (Yuan et al. 2017; Zhang et al. 2022a, b). Yuan et al. (2017) used the annual aridity index to explore the temporal and spatial variabilities in China's terrestrial climate's dryness/wetness conditions from 1961 to 2015. The results showed that the regional differences in the trend and periodicity of dryness/wetness climate changes in China were obvious, and the dryness/wetness climate changes were highly correlated with precipitation in northern China. Li et al. (2015), Zhang et al. (2016a), and Xu et al. (2017) analyzed the spatial and temporal distribution characteristics of the surface humidity index and extreme dryness/wetness events in different regions of China. They identified differences in the dryness/wetness climate change trend among different areas. Ding and Wang (2016) reported that Northwest China has experienced a shift from a warm-dry to a warm-wet climate in recent decades, called the "warming and wetting" climate trend. The causes of localized wetting and precipitation increases in Northwest China are still uncertain, and there is still a great deal of uncertainty about whether the signs of warming and wetting will continue or expand. There is also a lack of clear conclusions about the characteristics of this "warming and wetting" climate trend in the western part of Northwest China at varying temporal scales (Yao et al. 2022; Wang et al. 2020; Zhang et al. 2022a, b). Donat et al. (2019) also pointed out that the aridity index (AI) can be used in arid regions. However, the uncertainty in the results is high due to the poor observed coverage in most arid regions worldwide. As above shows that global climate change's impacts on dryness/wetness climate change in different regions are quite different and complex, and there are still many uncertainties regarding the regional-scale impact mechanisms. It is not clear how the dry and wet climate evolved based on the aridity index in Xinjiang. Therefore, in this study, the temporal and spatial evolution of the dryness/wetness climate in Xinjiang will be analyzed in detail based on AI, which is of great significance for understanding the adaptation to climate change in the region.

As a typical continental arid climate area, Xinjiang has low precipitation, intense evaporation, a dry climate, and a fragile ecological environment. Therefore, dryness/wetness climate change significantly impacts economic and social development, ecological environment restoration, and

people's production and livelihoods in this area (Zhou et al. 2020; Zhao et al. 2019). At the beginning of the twenty-first century, Shi et al. (2003) proposed that the climate in Northwest China, especially in Xinjiang, is "warming and wetting." In recent years, many studies have explored this "warming and wetting" climate trend in Xinjiang. However, Xinjiang's dryness/wetness characteristics differ due to different selection indicators, thus reflecting the complexity of climate humidification in arid areas. It is difficult to completely, objectively, and clearly describe Xinjiang's dryness/wetness evolution characteristics considering only single climate factors such as precipitation or temperature (Yao et al. 2021a, b, c). In this study, the aridity index, which takes into account both precipitation and potential evapotranspiration, is used to analyze the spatial and temporal evolution characteristics of dryness/wetness climate change in Xinjiang over the past 60 years (1961–2020) to discover and summarize the evolution law of the dryness/wetness climate in Xinjiang and better understand the regional climatic conditions and influencing factors.

The rest of this paper is divided into the following sections. The second part is the data and methods, where we describe the observations used in this study and the research methods used in the analysis. In the third part, we present the results of the analysis. The fourth part contains the results and discussion.

# Data and methods

Overview of the study area

Xinjiang is located in the hinterland of the Eurasian continent along the northwestern border of China, far from the geographical location of the sea, and the unique topography of Xinjiang forms its continental, strongly temperate, arid climate. Xinjiang has a vast territory, with a significant difference in climate between the north and the south and a significant disparity in water and heat distribution. Figure 1 shows the Xinjiang region and the locations of the research stations (I: northern Xinjiang, II: Tianshan Mountains, and III: southern Xinjiang).

Data sources and methods

Meteorological data

The National Information Center of the China Meteorological Administration has produced long-time-series ground homogenization observation data (Cao et al. 2016) that have been widely used in research in the climate change field because of their excellent data quality (Dong and Sun 2018; Dong et al. 2022; Li and Chen 2021; Zhang et al. 2022a,

Fig. 1 Schematic diagram of the study area (I: northern Xinjiang, II: Tianshan Mountains, and III: southern Xinjiang)
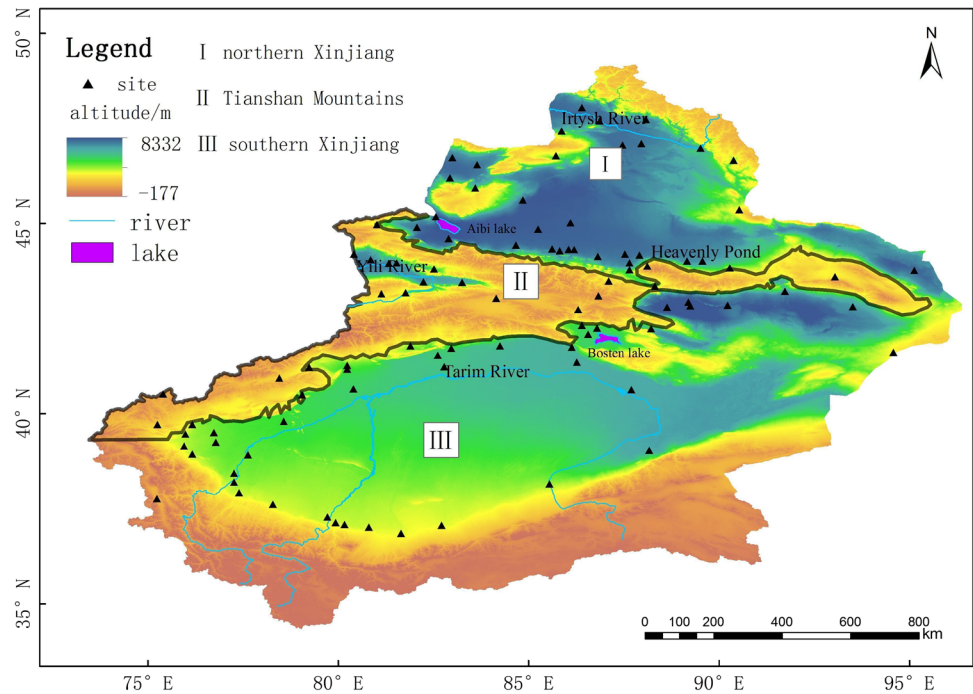
b). From these data, 99 national meteorological stations in Xinjiang at which daily mean temperature, maximum temperature, minimum temperature, mean sunshine hours, mean relative humidity, mean wind speed, and precipitation data were recorded with high data series completeness from 1961 to 2020 were selected. Both temperature and humidity are at the 2-m height. Based on these basic data, the Aridity Index was calculated.

Calculation of AI and classification of the dryness/wetness climate grade

In this paper, AI was calculated as the ratio of the annual potential evapotranspiration (PET) to annual precipitation. The calculation formula is expressed as follows:

$$AI = \frac{E}{P}. \tag{1}$$

AI is the aridity index, P is the annual precipitation, and E is the annual PET. In this paper, E is calculated by the FAO56 Penman–Monteith method recommended in the "Meteorological Drought Grade standard" revised by Zhang et al. (2017). The calculation method is as Formula 2

$$E_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}, \tag{2}$$

where E_0 stands for daily PET (mm), G is the soil heat flux density (MJm^{-2}d^{-1}), T is the daily mean temperature at

the 2-m height (°C), u_2 is the wind speed at the 2-m height (ms^{-1}), as is the mean saturated water vapor pressure (kPa), ea is the actual water vapor pressure (kPa), Δ is the slope of the saturated water vapor pressure curve (kPa°C^{-1}), γ is the dryness/wetness gauge constant (kPa°C^{-1}), and R_n is the surface net radiation (MJm^{-2}d^{-1}). The surface net radiation (R_n) is calculated from the net surface shortwave radiation R_{ns} and the net surface longwave radiation R_{nl}. The net surface shortwave radiation Rns is calculated according to Formula (3) as follows:

$$R_{ns} = 0.77 \times \left[a_s + b_s\left[\frac{n}{N}\right]\right]R_{so}, \tag{3}$$

where R_{so} is the extraterrestrial radiation (MJm^{-2} day^{-1}), n is the actual sunshine hours (h), N is the maximum possible sunshine hours (h), the coefficient a_s is the transmission coefficient of the extraterrestrial radiation reaching the ground on cloudy days, and $a_s + b_s$ is the transmission rate of the extraterrestrial radiation reaching the ground on sunny days. The monthly a_s and b_s values are calculated according to the national standard of the 'dry−wet' climate grade (Mao et al. 2017).

By calculating the AI and referring to the classification method of the dryness/wetness climate proposed by Zhang et al. (2021), the climate zone was classified into six grades, namely, a superhumid area, humid area, semi-humid area, semi-arid area, arid area, and extremely arid area. The specific classification criteria are shown in Table 1.

Table 1 Grades of dryness/wetness climate division

Grade	1	2	3	4	5	6
Climate zone	Superhumid	Humid	Semi-humid	Semi-arid	Arid	Extremely arid
AI	< 0.5	0.5 ~ 1.0	1.0 ~ 1.5	1.5 ~ 3.5	3.5 ~ 20.0	≥ 20.0

Other research methods

The nonparametric Theil–Sen median estimation and Mann–Kendall test were used to estimate the linear trend. Sen's slope estimation is a nonparametric test method proposed and developed by Sen in 1968 (Sen 1968). Zhang et al. (2000) estimated the trend slope of N to the data in n samples (Jiang et al. 2015). When the calculation result is greater than 0, the time series to be analyzed shows an upward trend. When the calculation result is less than 0, the time series to be analyzed shows a downward trend.

The Mann–Kendall test was used to detect the mutation of Xinjiang's annual average AI value. The Mann–Kendall test is a nonparametric test method. Compared to parametric test methods, the Mann–Kendall test does not require the sample to follow a certain distribution and is unaffected by a few outliers. This test is thus more suitable for sequential variables (Fensholt et al. 2012; Yue et al. 2002).

Morlet wavelet analysis was used to study the periodicity of the dryness/wetness changes. The wavelet transform method has the characteristics of multiresolution analysis and can characterize the local characteristics of a signal in both the temporal and frequency domains. By decomposing a time series into the time–frequency domain, the significant fluctuation pattern of the time series can be obtained; that is, the periodic change dynamics and the time pattern of the periodic change dynamics can be determined (Morlet 1982; Torrence et al. 1998).

The natural orthogonal function (EOF) decomposition method was used to study the distribution characteristics of Xinjiang's dryness/wetness spatial anomalies. Empirical orthogonal function (EOF) analysis, also known as eigenvector analysis, is used to analyze the structural characteristics of matrix data and extract the main data features. Also called principal component analysis, it is the most commonly used linear dimension reduction method. This analysis method aims to map high-dimensional data into a low-dimensional space through some linear projection while expecting to maximize the amount of information (variance) of the data in the projected dimension to allow fewer data dimensions to be used while retaining as many original data points as possible. The EOF analysis method can decompose a temporally varying variable field into a spatial function component that does not change temporally and a temporal function part that depends only on time and does not change spatially (Pang et al. 2014; Cai et al. 2022).
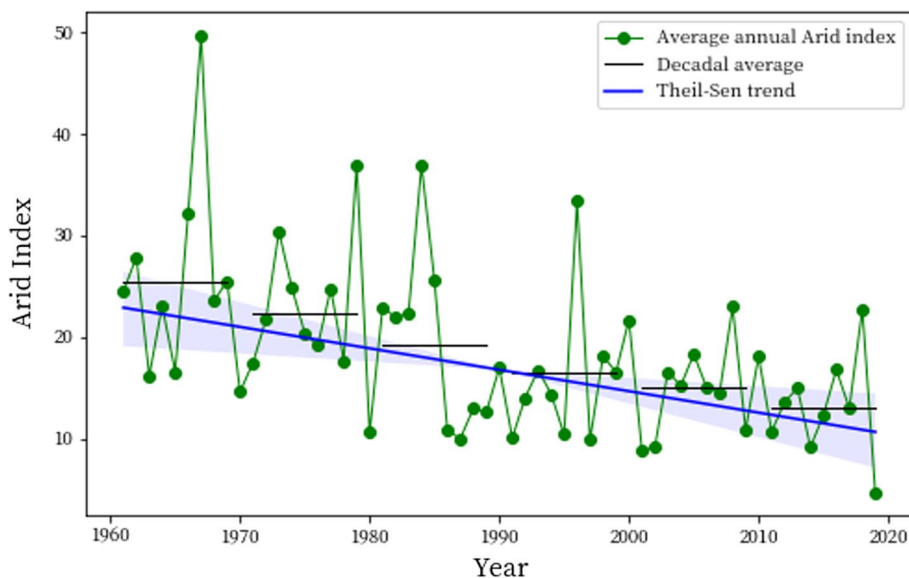
Results

Temporal characteristics of the dryness/wetness climate in Xinjiang in the last 60 years

From 1961 to 2020, the annual AI of Xinjiang showed a significant downward trend, decreasing by 2.1 per decade (passing the 0.05 significance test); this result reflects that the climate in Xinjiang has become more humid over the past 60 years. The aridity index showed a turning point in the late 1980s; the values were high in the early stage and low in the late stage, indicating that the climate in Xinjiang was relatively dry before the late 1980s and relatively wet after this period. 2020 was the wettest year in Xinjiang in the past 60 years, with an annual aridity index of 4.71, while 1968 was the driest year in Xinjiang in the past 60 years, with an annual AI of 49.67. In terms of the annual trend, AI showed a decreasing trend year by year. The AIs of each decade were 26.44 in the 1960s, 22.76 in the 1970s, 18.63 in the 1980s, 16.03 in the 1990s, 15.30 in the 2000s, and 13.59 in the 2010s (Fig. 2).

Xinjiang has a vast territory, and the climate difference between southern and northern Xinjiang is significant. Therefore, the Xinjiang Geographical Division divides Xinjiang into northern Xinjiang, the Tianshan Mountains, and southern Xinjiang. The annual AI trends in northern Xinjiang, Tianshan Mountains, and southern Xinjiang are consistent with those in Xinjiang overall, showing significant downward trends and consistent wetting trends, with decline rates of 0.42, 0.22, and 4.58/10a, respectively. The annual AI values of northern and southern Xinjiang decreased each year, while that of the Tianshan Mountains showed a decreasing trend with interdecadal fluctuations; in the three regions, the AIs decreased by 34%, 33%, and 56%, respectively, in the 2010s compared to the 1960s. Among the three subregions, the tendency to get wet was more obvious in southern Xinjiang, followed by northern Xinjiang, and then the Tianshan Mountains. The wettest year in northern Xinjiang was 2016, with an annual aridity index of 2.64; the driest year was 1962, with an annual aridity index of 8.84. The wettest year in the Tianshan Mountains was 1998, with an annual aridity index of 1.63, and the driest year was 1985, with an annual aridity index of 6.17. The wettest year in southern Xinjiang was 2020 when the annual aridity index was 2.86; the driest year was 1968, when the annual aridity index was 98.41.

**Fig. 2** Sen trend of the annual average AI in Xinjiang

From the perspective of the spatial variation in the annual drought index corresponding to the Sen trend results in Xinjiang, the annual aridity index in Xinjiang has shown a downward trend over the past 60 years; that is, it has shown a wetting trend, especially in the southern Basin and eastern Xinjiang. This wetting trend is most obvious, and the aridity index decreases by more than 5 per decade on average, among which those in the Bayingolin Mongol Autonomous Prefecture and some areas of Turpan City decreased by 8–16. The aridity index values in most areas of northern Xinjiang decreased by $0.05 \sim 5$ per decade. This conclusion is similar to the previous

conclusions obtained from analyses of drought indices such as the meteorological drought composite index (MCI), Palmer drought severity index (PDSI), and precipitation index (Wu et al. 2022; Guo et al. 2022).

The significance test showed that 83% of the stations in Xinjiang recorded significant downward trends in the annual AI, passing the 0.05 significance test. That is, most of Xinjiang became significantly wetter. Only the southern Ili Valley, Tacheng, Turpan, Hotan, and Bayingolin Mongol Autonomous Prefecture did not pass the 0.05 reliability test (Fig. 3).

Fig. 3 Sen linear trend results of the annual AI (/10a) in Xinjiang from 1961 to 2020. (Solid circles pass the 0.05 reliability test; hollow circles fail the 0.05 reliability test)
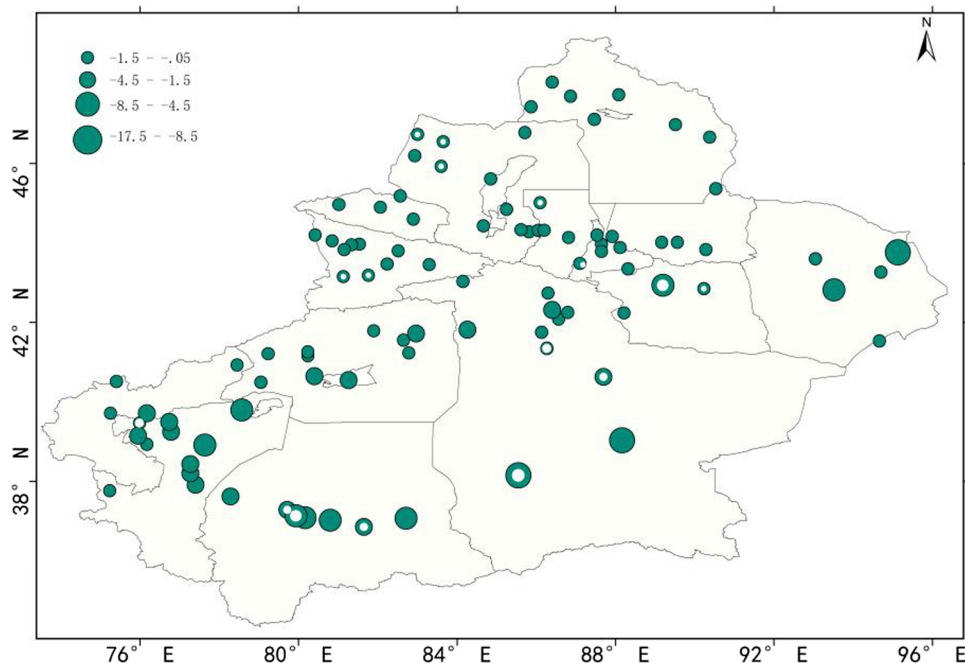
## Spatial distribution characteristics of AI climate zones in Xinjiang

From the distributions of the average AI and average precipitation from 1961 to 2020, the climate zone divisions obtained from the aridity index results in Xinjiang are consistent with the regional boundaries divided by precipitation (Fig. 4). Most of northern Xinjiang and the western part of southern Xinjiang receive precipitation totals between 100 and 200 mm, and the average annual aridity index in these regions is less than 20. Most of these areas are arid and semi-arid. Among them, the average annual precipitation totals in some areas of the Ili River Valley and the southern mountainous areas of Urumqi, Celestial Pond, and other Tianshan Mountains are greater than 300 mm, and the average annual aridity index is less than 3.5, corresponding to semi-arid and semi-humid areas. The average annual precipitation totals in the southern Xinjiang basin and the eastern Xinjiang region are mostly less than 100 mm and, in some areas, even less than 50 mm, indicating perennially arid areas. The average annual aridity index values here are greater than 20, suggesting extremely arid areas.

Interdecadal variability characteristics of dryness/wetness climate zones in Xinjiang

Taking the mean value of the aridity index from 1961 to 1990 as the base period, the AI anomalies in the Tacheng area, northern Altay, Tianshan Mountain, the west of southern Xinjiang, Bayingolin Mongol Autonomous Prefecture, and eastern Xinjiang region in the 1960s were

positive, indicating drier conditions than those in the base period, especially in the southern part of Bayingolin Mongol Autonomous Prefecture and the local area of Hami City. In the 1970s, most of Xinjiang still had positive anomalies, with drier conditions than the base period. Compared to the 1960s, the driest area began to move to the Hotan area in the southern Tarim Basin, and most of the Tianshan Mountains and eastern Xinjiang had negative anomalies, with wetter conditions than the base period. Since the 1980s, most areas of Xinjiang have become wetter, with significantly increased wet conditions compared to the previous 2 years. That is, the western part of southern and northern Xinjiang and the eastern part of the Tarim Basin had negative anomalies, while the eastern part of Changji Prefecture, the western part of Hotan, and most of Kashgar were dry areas. In the 1990s, the aridity index values in most areas of Xinjiang exhibited negative anomalies, with significantly wetter conditions than those in the base period, especially in the southern Xinjiang Basin and most parts of eastern Xinjiang. In the 2000s and 2010s, most of northern Xinjiang, the Tianshan Mountains, Hami City in eastern Xinjiang, Kashgar, Kizilsu Kirghiz Autonomous Prefecture, and Hotan in western, southern Xinjiang were wet, especially in southern Xinjiang and eastern Xinjiang. With further wetting, only the eastern part of Changji Prefecture was a dry area. In general, Xinjiang's dryness/wetness changes reversed between the 1980s and the 1990s. Before this period, most of Xinjiang showed a drying trend. Since the 1980s, Xinjiang has tended to be wet, and this trend is more pronounced in the southern Xinjiang region (Fig. 5).

Fig. 4 Distribution diagram of the annual AI (color-filled areas) and annual precipitation (isoline) in Xinjiang from 1961 to 2020
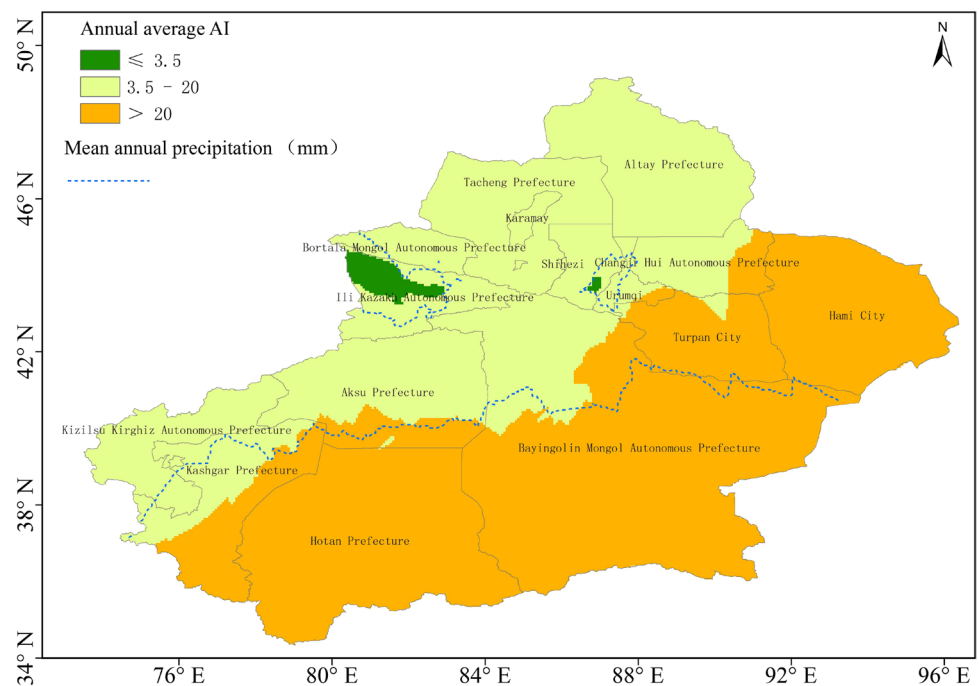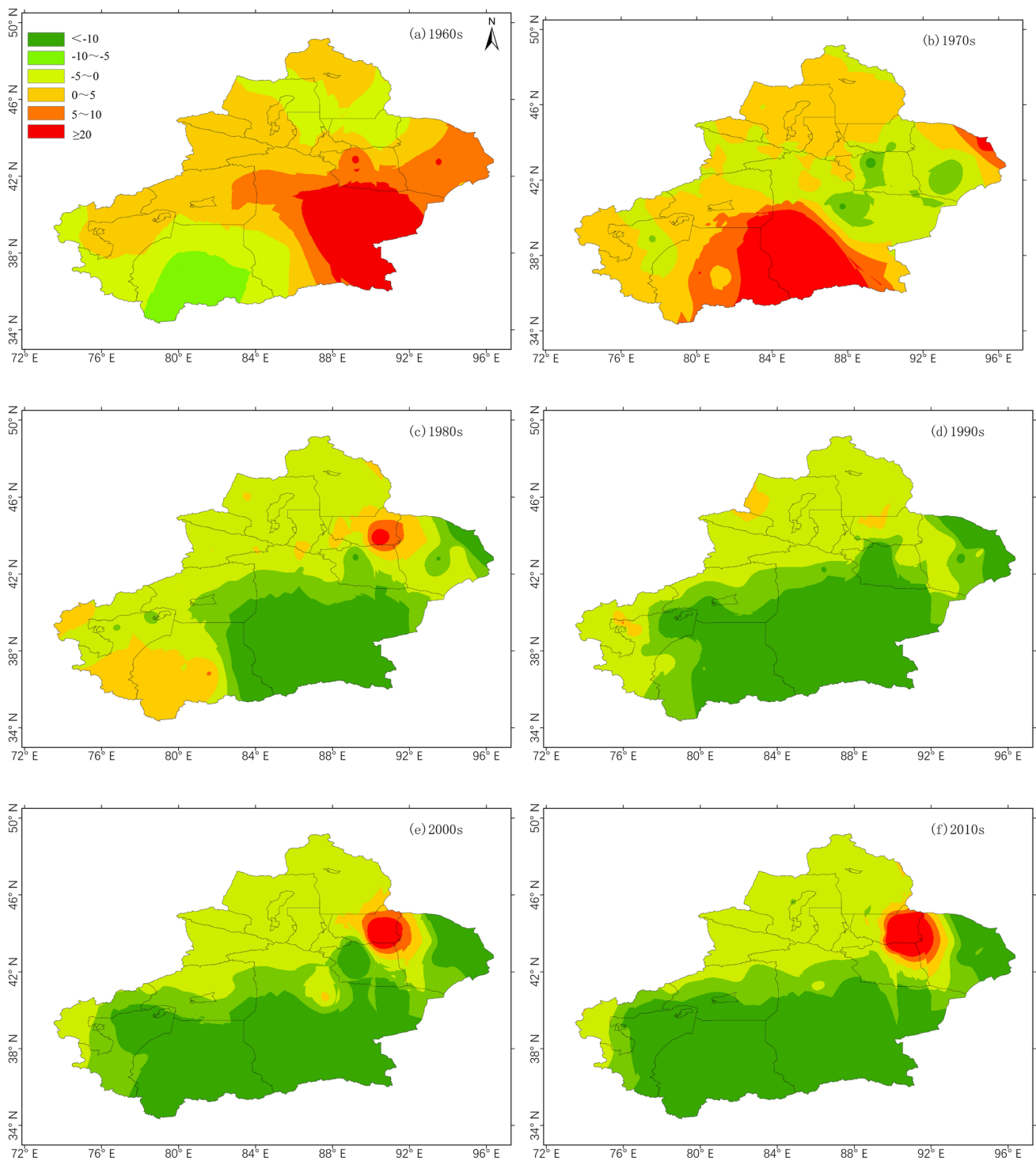
Fig. 5 Distribution of AI anomaly values in Xinjiang from the 1960s to the 2010s (**a**–**f**)

The AI sequence of the Xinjiang region was calculated according to the classification standard of six dryness/wetness grades adopted in this paper. There are five kinds of climate zones in Xinjiang, including the extremely arid, arid, semi-arid, semi-humid, and humid regions. From the average value during the 1961–2020 period, the station ratio of the arid climate zone (including extremely arid, arid, and semi-arid areas) in Xinjiang was 93%, while that of the humid climate zone (including semi-humid and humid areas) was only 7% and was distributed mainly in the Tianshan Mountains.

In the 1961–2020 period, the total station ratio of extremely arid and arid areas decreased annually; overall, the number of stations in the extremely arid area decreased from 38% in the 1960s to 14% in the 2010s. The ratio of stations in arid areas fluctuated, with the lowest observed in the 1960s (45%) and the highest observed in the 2000s (52%). The total station ratio of semi-arid, humid, and semi-humid areas increased from 12% in the 1960s to 32% in the 2010s. The ratio of humid and semi-humid areas increased from 4% in the 1960s to 7% in the 2010s. The semi-arid, humid, and semi-humid areas showed significant increasing trends, the extremely arid area showed a significant decreasing trend and the arid area showed fluctuating changes. It can also be seen that the Xinjiang region as a whole showed a wetting trend (Fig. 6).

By analyzing the station ratios of different climate zones in each subregion, it can be seen that the climate zones included in northern Xinjiang are mainly arid and semi-arid regions. The station ratio of arid climate zones identified in each decade decreased annually, while that of semi-arid regions increased annually. The station ratio of arid regions decreased from 32% in the 1960s to 14% in the 2010s, while that of semi-arid regions increased from

8% in the 1960s to 26% in the 2010s. The climate zones in the Tianshan Mountains mainly include arid, semi-arid, humid, and semi-humid areas. From the perspective of decadal changes, the humid, semi-humid, and semi-arid areas in the Tianshan Mountains showed increasing trends, increasing by 4% and 1%, respectively, from the 1960s to the 2010s.

In contrast, the arid area showed a decreasing trend, decreasing by 4% from the 1960s to the 2010s. The southern Xinjiang region contains only extremely arid and arid climate zones. Since the 1960s, the extremely arid climate zone area in this region has shown a significant decreasing trend, while the arid climate zone area has a significant increasing trend. From the 1960s to the 2010s, the station ratio in the arid zone increased by two times (16%), while that in the extremely arid climate zone decreased by 70% (24%). In general, from the perspective of the decadal changes from 1960 to 2020, the station ratios of the humid climate zones in the three subregions of Xinjiang increased, while the proportion of the arid climate zone decreased. It can also be seen from Table 1 that each subregion showed a significant wetting trend, especially since the twenty-first century (Table 2).

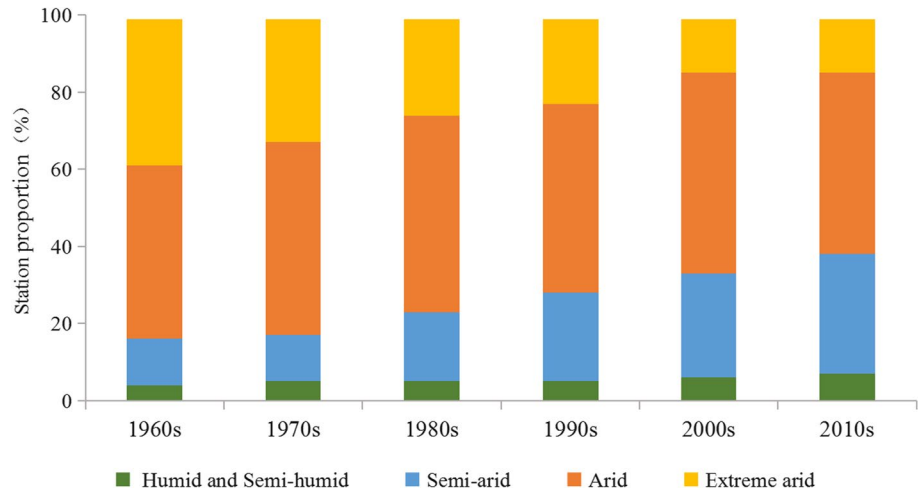**Fig. 6** Interdecadal variations in station ratios in different climate zones

Table 2 Ratios of stations in different climate zones of Xinjiang in each decadal period (%)

		1960s	1970s	1980s	1990s	2000s	2010s
Northern Xinjiang	Semi-arid	8	9	14	17	22	26
	Arid	32	31	26	23	18	14
Tianshan Mountains	Humid and semi-humid	4	5	6	6	8	8
	Semi-arid	4	3	4	6	5	5
	Arid	5	5	4	2	2	1
Southern Xinjiang	Arid	8	14	22	24	32	32
	Extremely arid	37	31	23	21	13	13

Analysis of the dryness/wetness climate cycle and mutation detection in Xinjiang

From the AI wavelet analysis results in Xinjiang shown in Fig. 7a, the original AI curve changed disorganizedly, and no evident periodicity can be seen. Through Morlet wavelet analysis, it can be seen from Fig. 7b and c that the periodicity of the dryness/wetness changes in Xinjiang is significant, mainly with 2.5-year and 6-year periodic changes, and the confidence of both periods exceeds 95%.

According to the abrupt AI change detection results obtained in Xinjiang over the past 60 years in Fig. 8, the UB and UF curves intersected in 1986, and the UF curve passed the critical line of the 0.05 level in 1992; that is, the abrupt change in the wetting trend in Xinjiang reached significance in this year, and then, the AI maintained a decreasing trend
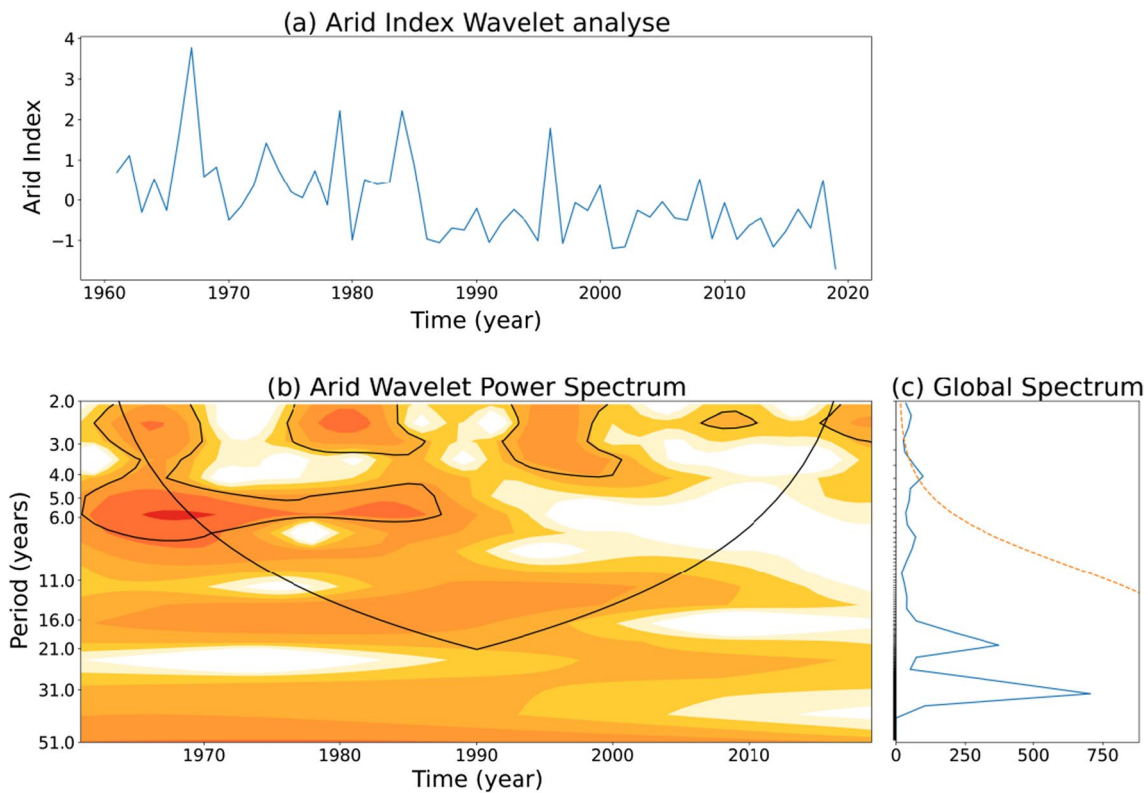
Fig. 7 Wavelet analysis results of the annual AI: **a** AI source data series, **b** Morlet wavelet analysis power spectrum, and **c** significant periodic spectrum (red dashed line is the 95% confidence interval)
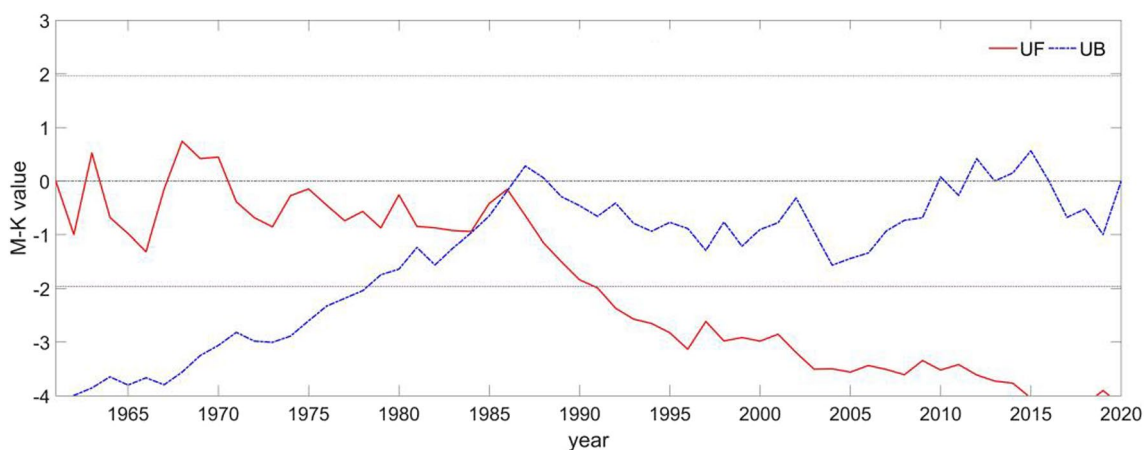

Fig. 8 Xinjiang annual AI mutation detection results (0.05 significance level)

only in 1997, 2001, and 2019 while again increasing in the other individual years. Thus, the climate in Xinjiang tended to get wet after 1986.

Analysis of the spatial and temporal characteristics of the dryness/wetness climate in Xinjiang

To further understand the spatial distribution characteristics of Xinjiang's dryness/wetness climate, the annual AI values at 99 stations were expanded using the empirical orthogonal function (EOF). The results showed that the first three eigenvectors were the main components, with variance contribution rates of 40.62%, 26.15%, and 10.16%, respectively, and a cumulative contribution variance rate of 76.93%. The variance contribution rate of each feature vector after the third feature vector was small and thus could be ignored.

The first eigenvector (Fig. 9a) values of the EOF decomposition were negative in the whole Xinjiang region, representing the consistent change in the dryness/wetness climate in Xinjiang; that is, the climate in Xinjiang was generally either dry or wet. The intensity of this change varied among different regions. The eastern and southern Xinjiang basins were the main large-value areas and control areas of the first mode. The time coefficient PC1 (Fig. 9b) corresponding to the first mode shows an evident, abrupt change over time, with the time coefficients for the 1961–1986 period being predominantly negative, indicating that the climate in Xinjiang was generally dry during this period, with the lowest coefficient observed in 1985, corresponding to the driest period in this region. Since 1987, the time coefficient has been dominated by a positive orientation, indicating that the first eigenvector is driving a trend of reduced aridity from 1987.

The second eigenvector (Fig. 9c) differed significantly from the first eigenvector. The eigenvector values of the northern and southern Xinjiang basins were negative. At the same time, those of the Tianshan Mountains were positive, reflecting the opposite spatial distribution characteristics of the dryness/wetness climate in northern and southern Xinjiang compared to those in the Tianshan Mountains. The negative large-value area is located in the southeastern Tarim Basin, and the positive large-value area is in Turpan. The time coefficient PC2 (Fig. 9d) corresponding to the second mode shows the same trend as the large PC1 value; before 1987, the values were mainly negative, and since 1987, they were mainly positive.

The third eigenvector (Fig. 9e) was positive in most parts of Xinjiang and negative only in southern Bazhou, Turpan, and southern Hami, thus representing the consistent change in dry and wet conditions in most parts of Xinjiang. In contrast, Turpan, southern Hami, and southern Bazhou showed the opposite change. The positive high-value areas of the modal eigenvector were located in Hotan and Kashgar. The time coefficient PC3 (Fig. 9f) corresponding to the third mode was reflected spatially in the alternation of heavy and light drought events in southern Bazhou, Turpan, and Hami with most of western Xinjiang. The time coefficient was the smallest in 1974, thus accurately reflecting the severe drought events that occurred at this time in most of Xinjiang.

Conclusion and discussion

According to the average value of the AI from 1961 to 2020, the northern and western parts of southern Xinjiang were arid and semi-arid, The Tianshan Mountains, including parts of the Ili River Valley and the southern mountainous areas of Urumqi, were found to be semi-humid areas, and the rest of Xinjiang, especially the eastern and southern basins, was found to contain extremely arid areas. The total station ratio of arid and extremely arid areas showed a decreasing trend, while the semi-arid areas, and humid and semi-humid areas showed increasing trends, especially since the twenty-first century.

In the past 60 years, the annual AI of Xinjiang showed a significant downward trend, and the climate tendency rate was 2.4/10a; that is, the climate of Xinjiang has become wetter over the past 60 years. The changes in the three subregions all showed consistent wetting trends, especially in southern Xinjiang, showing the most significant decline rate of 5.23/10a. The wavelet analysis and abrupt change detection showed that the dryness/wetness changes were most pronounced in a 6-year cycle. From the interdecadal spatial evolution characteristics of the dryness/wetness climate in Xinjiang, it can be seen that the dryness/wetness climate trend reversed in the 1980s–1990s, with a significant abrupt change occurring in 1992. The dry area in the southern Xinjiang basin expanded slightly in the 2000s and shrank again in the 2010s, while the dry area expanded in the 2010s in eastern Xinjiang. The first EOF decomposition mode was consistent in Xinjiang; that is, the climate in Xinjiang was generally either dry or wet, and the eastern and southern Xinjiang basins were the main large-value areas. The second mode reflected the opposite spatial distribution characteristics of dryness/wetness climate change in southern and northern Xinjiang compared to the Tianshan Mountains.

The AI of each subregion in Xinjiang showed a decreasing trend with different degrees from 1961 to 2020; that is, the overall climate showed a 'wetting' trend, which is consistent with most previous studies on dryness/wetness changes in Xinjiang (Jiang et al. 2009; Zhang et al. 2010). Yao et al. (2021a, b, c) also pointed out that since 1997, the climate in Xinjiang has shown a strong signal change from "warm and humid" to "warm and dry." In this study, we found that Xinjiang did show a significant dry trend in 1997, but after this year, the AI remained at a high level but still
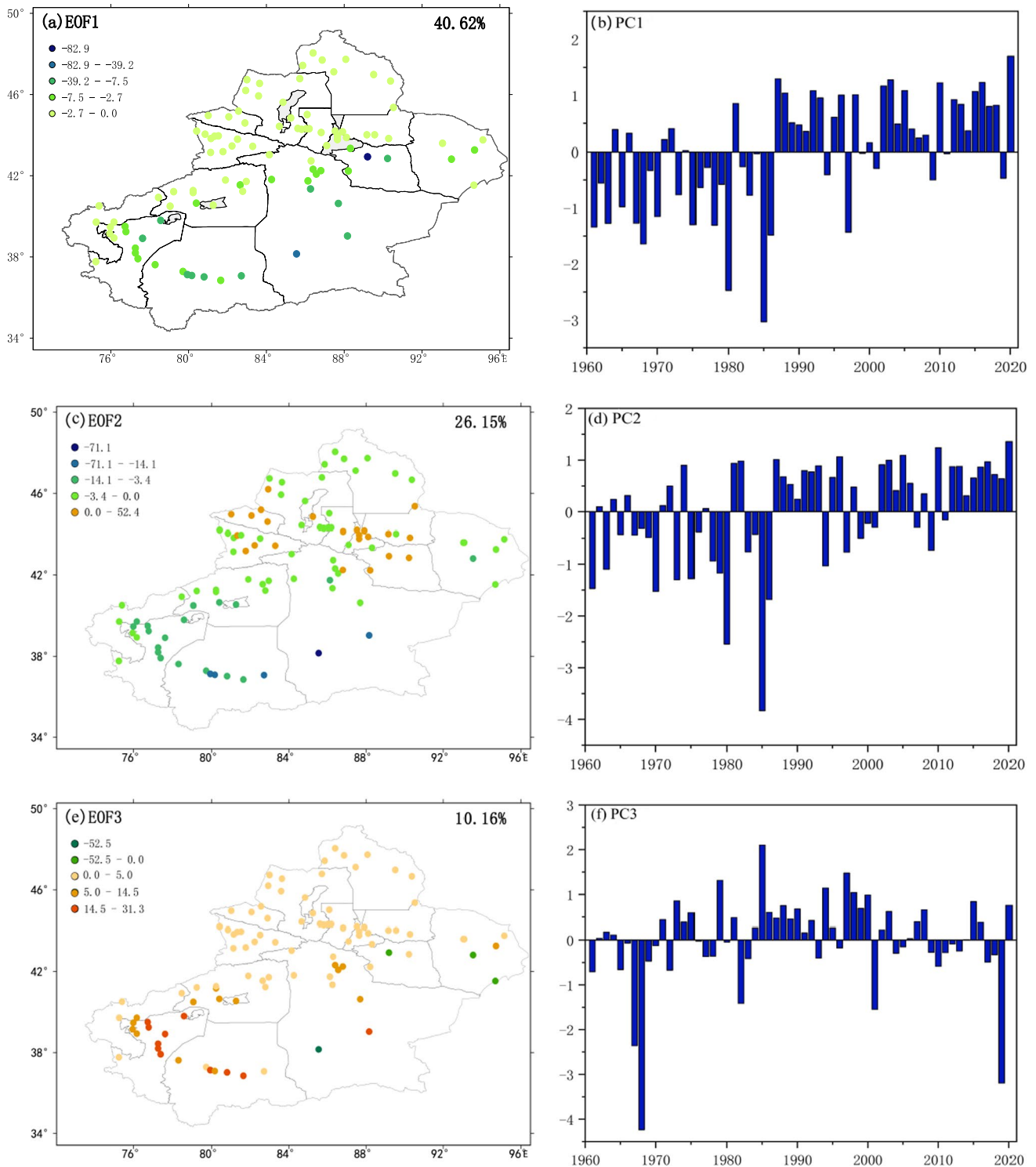
Fig. 9 First three spatial modes (**a**, **c**, and **e**) and their corresponding time series (**b**, **d**, and **f**) of the EOF expansion results of the annual AI values in Xinjiang from 1961 to 2020

showed a decreasing trend; thus, the climate of Xinjiang was still becoming generally wetter. Although the area is affected by both precipitation and PET, Xinjiang, as an important component of the arid region of Northwest China, also has a strong signal of rising temperatures and increasing precipitation. However, due to its geographical location far from the ocean and distantly inland, such strong warming is accompanied by vast potential evaporation, and the absolute value

of the precipitation increase is thus not high (the annual precipitation increase rate in Xinjiang is only 10.14 mm/decade). Therefore, this trend of getting wet is not expected to change the nature of Xinjiang as an arid region in the short term and is insufficient to produce qualitative changes in the regional dryness/wetness conditions in the short term.

Vegetation in dryland is more sensitive to hydrological and climatic change (Peng et al. 2021; Jiang et al. 2018). The decreasing trend of the AI has maintained a good consistency with the improvement of the ecological environment in Xinjiang; the vegetation in this area has increased significantly by the vegetation leaf area index (LAI) since the 1980s (Chen et al. 2023), and the vegetation changes calculated by the normalized vegetation index (NDVI) showed that the vegetation in the western, northern Xinjiang and southern Hotan areas improved significantly from 1981 to 2001 (Shi et al. 2003; Yao et al. 2021a, b, c) which suggested that it significantly increased the tendency of vegetation to "turn green" during the period 1982–1997 in Xinjiang. However, ecological reversal showed that there have been significant negative impacts on Xinjiang's ecology since 1997, but the overall NDVI increased during the period 2000–2019 in Xinjiang (Xue et al. 2021). Although the hydrological characteristics, such as glaciers, runoff, and lakes, and ecological characteristics, such as vegetation in Xinjiang, have changed significantly under the background of warming and humidification, the current understanding only stays at the level of the linear relationship. The coupling mechanism between warming and humidification and hydrological and ecological characteristics is not clear. The effects of temperature and precipitation on hydrology and ecology are very complex (Peng et al. 2021.).

Simulations of the future climate change trends in Xinjiang and Northwest China show an overall wetting trend, showing differences in different periods and under different emission scenarios (Zhang et al. 2022a, b; Feng et al. 2019; Chen et al. 2023). Feng et al. (2019) predicted in their study that the annual average temperature in the northwest region is expected to increase, with more complex precipitation change and an overall increase in the aridity index by 2030. Zhang et al. (2022a, b) analyzed the dryness/wetness climate change trends of China from 2020 to the end of this century under the RCP4.5 and RCP8.5 scenarios. They concluded that under both scenarios, the wetting trend in the western part of China would be more pronounced with a larger range under the RCP8.5 scenario than under the RCP4.5 scenario. In the future, the northwest region may continue to be warm and humid. However, there are great uncertainties in the model prediction and trend extrapolation results, which can only provide a reference for formulating climate change measures. Future warm and wetting trend changes still need to continue to pay attention (Zhang et al. 2023). As an important part of the northwest region,

if the variation characteristics of the aridity index in different regions and times in Xinjiang continue in the future, the flood and drought events in northern and southern Xinjiang will also change greatly, thus critically impacting agriculture and society. Such issues will be analyzed in our future study.

Data availability The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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