Chin. Geogra. Sci. 2020 Vol. 30 No. 2 pp. 249–265
https://doi.org/10.1007/s11769-020-1104-5

Springer Science Press
www.springerlink.com/content/1002-0063

# Characteristics of Climate Change in Northern Xinjiang in 1961–2017, China

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**Abstract:** Xinjiang is located in the core China's 'Belt and Road' development, and northern Xinjiang is an important region for economic development. In recent years, due to the strong influence of global climate change and human disturbance, regional climate instability and ecological-economic-social system sensitivity have grown. In this paper, seasonal, interannual, interdecadal, spatial, abrupt, and periodic variations of temperature and precipitation in northern Xinjiang were analyzed using daily surface air temperature and precipitation data from 49 meteorological stations during 1961–2017. At the same time, the driving factors of climate change are discussed. Methods included linear regression, cumulative anomaly, the Mann-Kendall test, and Morlet wavelet analysis. The results indicated that during the study period, annual mean temperature and annual precipitation increased significantly at rates of 0.35℃/10 yr and 13.25 mm/10 yr, respectively, with abrupt changes occurring in 1994 and 1986. Annual mean temperature and annual precipitation in all four seasons showed increasing trends, with the maximum increases in winter of 0.42℃ /10 yr and 3.95 mm/10 yr, respectively. The general climate in northern Xinjiang showed a trend towards increasingly warm and humid. In terms of spatial distribution, the temperature and precipitation in high mountainous areas increased the most, while basins areas increased only slightly. Periodic change analysis showed that annual mean temperature and annual precipitation experienced two climatic shifts from cold to warm and dry to wet, respectively. Population change, economic development and land use change are important factors affecting climate change, and more research should be done in this field.

**Keywords:** northern Xinjiang; climate change; driving factors; temperature; precipitation

**Citation:** HE Binbin, SHENG Yu, CAO Wei, WU Jichun, 2020. Characteristics of Climate Change in Northern Xinjiang in 1961–2017, China. *Chinese Geographical Science*, 30(2): 249–265. https://doi.org/10.1007/s11769-020-1104-5

## 1 Introduction

In the last few decades, the impacts from climate change and rising global temperatures have received a great deal of attention from governments and communities throughout the world. Climate change and its impacts are topics of numerous current research projects. The Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) stated that globally averaged surface temperatures have increased over the past 100 yr by about 0.85℃ (IPCC, 2013). Global climate change has significantly impacted many natural ecosystems. Many studies have shown that under the backdrop of global warming, arid areas are among the most sensitive ecosystems to impacts of climate change (Yu et al., 2014; Huang et al., 2016; Gu et al., 2018).

Since the end of the Little Ice Age in the 19th century, northwest China has fluctuated between cycles of warming and drying. After 1987, there was a sudden increase in warming and wetting signals (Shi et al.,

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Received date: 2019-04-02; accepted date: 2019-06-13
Foundation item: Under the auspices of the National Key Research and Development Program of China (No. 2017YFC0405101), National Natural Science Foundation of China (No. 91647103)

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2003). Rainfall, glacial melt, and runoff have increased annually since 1987, leading to a series of ecosystem changes that have been especially concentrated in northern Xinjiang, China (Chen et al., 2015; Luo et al., 2018b).

Xinjiang occupies a key location along the Silk Road and is China's largest cotton base and one of the areas with the most development potential for agricultural production and animal husbandry. It is also a core area for current 'Belt and Road' development plans (Bai and Wang, 2014; Toops, 2016). Xinjiang is located in the hinterlands of Eurasia, far from the source of water vapor, with sparse precipitation that arrives with uneven spatial and temporal distributions. Overall, the climate is dry and evaporation is large, typical of an arid or semi-arid region (Ding and Shou, 2001). Although arid, the water resources in northern Xinjiang are relatively abundant, allowing for the future potential development of agriculture and animal husbandry.

At present, most studies of temperature and precipitation have focused on the whole Xinjiang region (Wang et al., 2013b; He et al., 2015). However, due to their geographical characteristics, the Tianshan Mountains in the central part of Xinjiang are divided into two distinct climate regions, the southern and northern areas (Guan et al., 2016). Northern Xinjiang is more developed in terms of economy and culture and has higher annual precipitation (over 200 mm/yr) than southern Xinjiang (over 50 mm/yr), as well as a larger rise in temperature (Zhang et al., 2013). When studying the regional processes of global climate change, it is practical to study changes in the northern Xinjiang separately, to better cope with the future risks and impacts from climate disasters.

Recently, there has been significant research on the impacts of climate change in Xinjiang (Xu et al., 2008; Liu et al., 2009; He et al., 2011; Yuan et al., 2017). Li et al. (2011) showed that the temperature in Xinjiang rose at a rate of 0.28℃/10 yr during 1956–2005. Zhang et al. (2012) showed that annual precipitation in Xinjiang also exhibited an increasing trend, at a rate of 9.5mm/10 yr during 1960–2005. Tang et al. (2013) established precipitation and temperature sequences for three regional climate change scenarios over the 2011–2050 period (for the Tianshan Mountains and southern and northern Xinjiang), and indicated that temperatures will continue to increase, that the increase in precipitation may decrease in mountainous regions but will increase in the basin, and that the speed of glacial ablation in Xinjiang will continue to accelerate. Jiang et al. (2013), Zhang et al. (2015) and Tang et al. (2016) analyzed the variations in extreme temperature and precipitation events in Xinjiang, and concluded that the probability of occurrence of both extremes would increase in the future.

Most of the above studies were focused on the whole Xinjiang region, there were several that focused on the northern Xinjiang region (Xu et al., 2015; Yang et al., 2018). Some researchers have divided Xinjiang into two regions to further define more granular spatial climate trends in southern and northern Xinjiang (Yuan et al., 2004; Ma and Gao, 2006; Wu et al., 2010; Wang, 2013a; Luo et al., 2018a). He et al. (2015) and Tao et al. (2017) found that the magnitudes of increase in temperature and precipitation were greater in northern Xinjiang than in southern Xinjiang. But the previous studies always focused on a single meteorological element such as temperature or precipitation, and did not consider the length of the meteorological data or ensure that the number of meteorological stations analyzed was consistent.

Based on daily surface air temperature and daily precipitation data from 49 meteorological stations in northern Xinjiang during 1961–2017, this paper analyzed the seasonal, interannual, interdecadal, spatial, abrupt, and periodic variations of temperature and precipitation using diverse methods such as linear regression, cumulative anomaly, the Mann-Kendall test, and Morlet wavelet analysis. Under the background of global climate warming, this paper strengthened the understanding of climate change characteristics in northern Xinjiang, and discussed the driving factors of climate change. This will have extremely important practical significance and reference value for protecting the ecological environment and dealing with the problems brought by climate warming in northern Xinjiang region. Moreover, this paper can provide a strong climate basis for agricultural production activities and infrastructure construction in northern Xinjiang.

## 2 Data and methods

### 2.1 Study area

The study area, northern Xinjiang, is located north of the Tianshan Mountains and is composed by several mountain ranges, including the northern and eastern parts of the Tianshan Mountains, the southern part of the Altai Mountains, Junggar Boundary Mountains and Junggar Basin. The whole region ranges from 42°26′N to 49°18′N, 79°87′E to 126°41′E and a total area of $44.76 \times 10^4$ km$^2$ (Fig. 1). The study area is in the deep middle latitudes of the Eurasian hinterland in a temperate continental climate, where the climate is dry, precipitation is rare, the ecological environment is fragile, and the desert is vast. It is cold in winter, while summers are short and hot and spring and autumn are not easily discernable (Guli·Jiapaer et al., 2015). The geomorphology of the region is varied, ranging from flat basins to heavily undulating mountains and elevations ranging from 191 m to 6067 m.

## 2.2 Data sources

In order to ensure that the data series from each station was synchronized and the observation period was relatively long, analysis was performed using daily mean temperature and daily precipitation data from 49 meteorological stations in northern Xinjiang from 1961 to 2017. Study data were obtained from the China Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn/home.do). The missing data from each station were supplemented using observational data from adjacent stations using the multiple regression difference method (Ning et al., 2012). The demographic and GDP data used in the discussion were obtained from the Xinjiang Statistical Yearbook (Gao et al., 2018). The land use data came from the Resource and Environmental Science Data Center at the Chinese Academy of Sciences (http://www.resdc.cn).

## 2.3 Methods

For this paper, the seasonal, interannual, interdecadal, spatial, abrupt, and periodic variations of temperature and precipitation in northern Xinjiang were studied. The seasons were divided into spring (March to May), summer (June to August), autumn (September to November) and winter (December to February of the next year) (Luo and Jin, 2014). The change trends of the data series were analyzed using linear regression and cumulative anomaly method. The Mann-Kendall test as recommended by the International Meteorological Organization (IMO) was used to detect any climatic abrupt changes in the element sequence and to identify abrupt change years and climate change trends (Gavrilov et al., 2018). Morlet wavelet analysis method was used to identify the periodic size of the scale contained in the climatic element sequence, then strong and significant periods were extracted to analyze the periodic structure of the climate data and abnormal changes characteristics (Cui, 2016).

### *2.3.1 Mann-Kendall test*

Abrupt climate change is an important phenomenon in the climate system, defined as a sudden and large change from one stable climate state (or stable and persistent change trend) to another stable state (or stable and persistent change trend). This abrupt change is

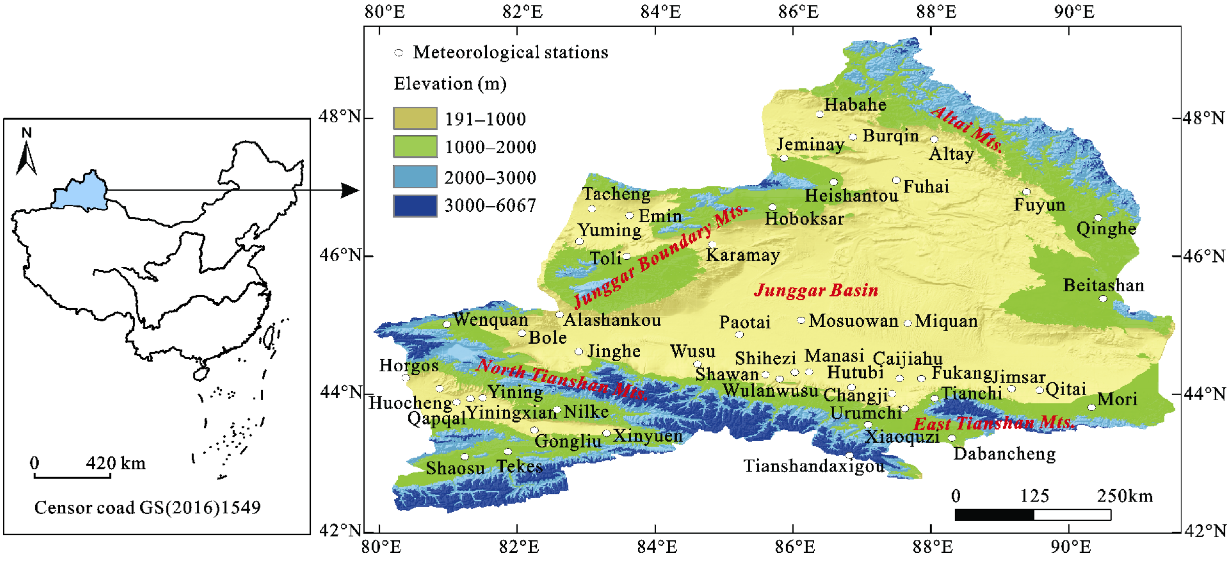

**Fig. 1** The location of northern Xinjiang and distribution of meteorological stations

manifested in the data via a change from one statistical characteristic to another in time and space. In this paper, the Mann-Kendall non-parametric test was adopted to analyze abrupt changes. The advantages of this method are that the samples do not need to follow a certain distribution, the analysis is not negatively affected by a few outliers, and the calculation is relatively simple (Wei, 2007).

The basic principle of the Mann-Kendall (Cui, 2016) test method is as follows: let the climatic sequence be $x$ ($x_1$, $x_2$, … , $x_n$), when $x_i > x_j$, $r = 1$; $x_i \le x_j$, $r = 0$ ($1 \le j \le i$), where $s_k$ denotes the cumulative number of samples $x_i \ge x_j$, and statistic sk is defined as:

$$s_k = \sum_{i=1}^{k} r_i \, , \quad k = 2, 3, \cdots, n \tag{1}$$

Under the assumption of random independence of the time series, the mean value and variance of $s_k$ are:

$$\begin{cases} E(s_k) = n(n-1)/4 \\ V_{ar}(s_k) = n(n-1)(2n+5)/72 \end{cases} \tag{2}$$

While $s_k$ is standardized as,

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{V_{ar}(s_k)}} \, , \quad k = 2, 3, \cdots, n \tag{3}$$

where $k$ and $n$ are constants, $UF_k$ is the standard normal distribution, given a significance level $\alpha$. If $A > B$, it indicates that the sequence has a significant change trend. Then, the chronological order is reversed to $x_n$, $x_{n-1}$, … , $x_1$ , and the above process is repeated where $UF_k = -UB_k$, ($k = n$, $n-1$, … ,1), $UB_1 = 0$ at the same time. If the values of $UF_k$ and $UB_k$ are greater than zero, it indicates that the sequence has an upward trend, while if the values are less than zero, it indicates a downward trend. When the curve exceeds the critical line, it indicates that the upward (downward) trend is significant. If the intersection of the $UF_k$ and $UB_k$ curves is between the critical lines, then the moment of intersection is the time when the abrupt change begins.

### *2.3.2 Wavelet analysis*

Wavelet analysis has the advantages of Fourier analysis in that it not only shows different scales of power in a climate time series, but also shows the time position of changes. At the same time, wavelet analysis can objectively separate data structures of different wavelengths so that the wave amplitude can be displayed on the graph. Wavelet analysis has been widely used as a tool for studying the long-term changes in power and amplitude of different meteorological variables (Xu et al., 2009; Gao et al., 2015; Zhao et al., 2016). For time series function $f(t)$, the wavelet transform is defined as:

$$W_f(a,b) = \frac{1}{\sqrt{a}} \int_{+\infty}^{-\infty} f(t) \bar{\psi}\left(\frac{t-b}{a}\right) \mathrm{d}t \tag{4}$$

where, $W_f(a, b)$ is the wavelet coefficient; $a$ is the frequency parameter that determines the width of the wavelet; $b$ is the time parameter, reflecting the position of the wavelet; $t$ is time; and $\bar{\psi}$ is the complex conjugate of $\psi$. In this paper, the Morlet wavelet in the wavelet analysis toolbox of MATLAB was used as the generating function to perform a continuous wavelet transform (Hu et al., 2008). Its analytical form is as follows:

$$\psi(t) = C\mathrm{e}^{-\frac{t^2}{2}} \cos(5t) \tag{5}$$

The wavelet variance ($W_p(a)$) is:

$$W_p(a) = W_f(a,b)^2 \tag{6}$$

where $C$ is a constant. At certain time scale, the wavelet variance represents the intensity (energy size) of periodic fluctuations of the time series at a given scale. The wavelet variance with scale can reflect the characteristics of both the time scale (period) and intensity (energy size) across the time series. The scale corresponding to the peak value is the main time scale, or period, of the sequence.

## 3 Results and Analysis

### 3.1 Interannual variation of climatic series

From 1961 to 2017, the annual mean temperature in northern Xinjiang ranged from 5.13℃ to 7.80℃, with an overall average of 5.66℃. The annual mean temperature gradually increased at a rate of 0.35℃/10 yr, which was significantly higher than the mean temperature increase rate in China of 0.22℃/10 yr (Zhang, 2014). The mean temperature in the four seasons in northern Xinjiang showed an upward trend, with the largest increase in winter of 0.42℃/10 yr, followed by 0.38℃/10 yr in autumn, 0.33℃/10 yr in spring and the smallest increase in summer of 0.26℃/10 yr (Fig. 2). The warming rates of the mean temperature across all

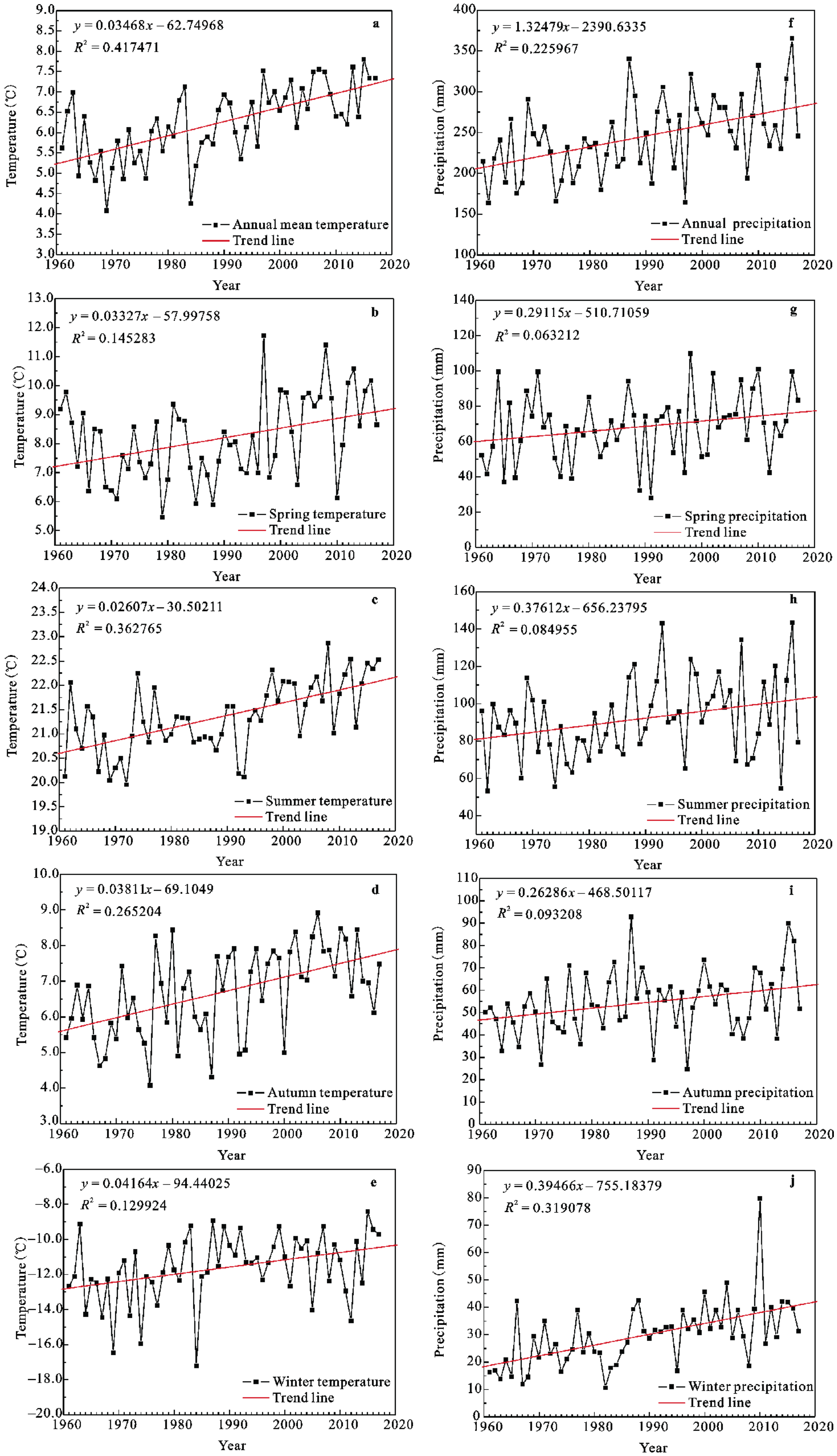

**Fig. 2** Variation of annual and seasonal temperature and precipitation in northern Xinjiang. (a) Annual temperature; (b) Spring temperature; (c) Summer temperature; (d) Autumn temperature; (e) Winter temperature; (f) Annual precipitation; (g) Spring precipitation; (h) Summer precipitation; (i) Autumn precipitation; (j) Winter precipitation

four seasons in China were 0.36℃/10 yr in winter, 0.23 ℃/10 yr in spring, 0.19℃/10 yr in autumn and 0.12℃/10 yr in summer (Ren et al., 2005). The change trends of annual mean temperature and seasonal mean temperature in northern Xinjiang were the same as that for China as a whole, but the rates of temperature increase in northern Xinjiang were significantly higher than across China.

From 1961 to 2017, the annual precipitation in northern Xinjiang was 244 mm, and the maximum and minimum values were 364.93 mm (in 2016) and 164.37 mm (in 1997), respectively. The annual precipitation gradually increased over time at a rate of 13.25 mm/10 yr. This differed from the decreasing trend of annual precipitation across China (Xu et al., 2015), but was similar to the increasing trend in northwest China (Shi et al., 2007). The annual precipitation across the four seasons in northern Xinjiang showed an increasing trend, with the largest increase in winter (3.95 mm/10 yr), followed by summer (3.76 mm/10 yr), spring (2.91 mm/10 yr), and finally autumn (2.63 mm/10 yr) (Fig. 2).

## 3.2 Interdecadal variation of climatic series

The interdecadal variation in temperature across northern Xinjiang showed a significant warming trend. The temperature during the 1960s, 1970s and 1980s were relatively cold, but the temperature showed an overall increasing trend during this period. The temperature began to warm in the 1990s, and both the absolute temperature and the rate of increase have increased annually since that time. The interdecadal variation in seasonal temperature also showed a uniform warming trend. The temperature in winter began to warm during the 1980s, while the temperature in summer and autumn began to warm during the 1990s, and the temperature in spring began to warm during the 2000s (Table 1).

The interdecadal variation in precipitation in northern Xinjiang showed an increasing trend. Precipitation increased significantly in the 1980s, and then both the amount and the rate increased every subsequent year on record. The interdecadal variation in seasonal precipitation also showed a consistent increasing trend, but it was not obvious. The most precipitation in the spring and winter seasons occurred during the 2000s, while the most precipitation in summer occurred during the 1990s, and from 2011–2017 in autumn (Table 2).

## 3.3 Spatial analysis of climate changes

Inverse distance weighted interpolation was used to interpolate the annual and seasonal climate trend coefficients of temperature and precipitation changes of the 49 meteorological stations investigated. The results were used to determine the spatial distribution of temperature and precipitation changes in northern Xinjiang (Fig. 3).

### *3.3.1 Spatial analysis of temperature changes*

In the past 60 years, the annual mean temperature in northern Xinjiang increased, with a significant average increase of 0.35℃/10 yr across the 49 stations ($P < 0.05$). The regions with a larger temperature increase were located in the Altai Mountains, North Tianshan Mountains and Junggar Mountains, while the center of the area with the largest temperature increase was located in Fuyun (0.68℃/10 yr). The areas with smaller temperature increases were Junggar Basin and the East Tianshan Mountains, and the Tianchi area had the smallest temperature change (0.14℃/10 yr) (Fig. 3a).

In spring, the temperature showed a warming trend, with an average warming range of 0.33℃/10 yr that was significant at 73% of stations ($P < 0.05$). The spatial distribution was characterized by a gradual increase from low to high latitudes. The regions with a larger temperature increase ranged from 46°N to 48°N, and the

**Table 1** The interdecadal variation of annual, seasonal temperature anomaly in northern Xinjiang (℃)

| Interdecadal | Spring | Summer | Autumn | Winter | Annual |
|---|---|---|---|---|---|
| 1960s | –0.16 | –0.51 | –0.99 | –1.18 | –0.70 |
| 1970s | –0.98 | –0.28 | –0.26 | –0.82 | –0.59 |
| 1980s | –0.55 | –0.27 | –0.39 | 0.32 | –0.22 |
| 1990s | –0.03 | 0.02 | 0.05 | 0.80 | 0.21 |
| 2000s | 0.84 | 0.46 | 1.19 | 0.52 | 0.75 |
| 2011–2017 | 1.25 | 0.83 | 0.55 | 0.52 | 0.79 |

**Table 2** The interdecadal variation of annual, seasonal precipitation anomaly in northern Xinjiang (mm)

| Interdecadal | Spring | Summer | Autumn | Winter | Annual |
|---|---|---|---|---|---|
| 1960s | –5.06 | –3.64 | –6.49 | –9.55 | –24.74 |
| 1970s | –2.58 | –15.90 | –4.52 | –3.38 | –26.38 |
| 1980s | –3.05 | –1.52 | 6.21 | –3.39 | –1.75 |
| 1990s | –2.32 | 10.89 | –2.37 | 3.05 | 9.24 |
| 2000s | 10.69 | 3.34 | 0.62 | 9.05 | 23.70 |
| 2011–2017 | 3.32 | 9.76 | 9.36 | 6.03 | 28.48 |

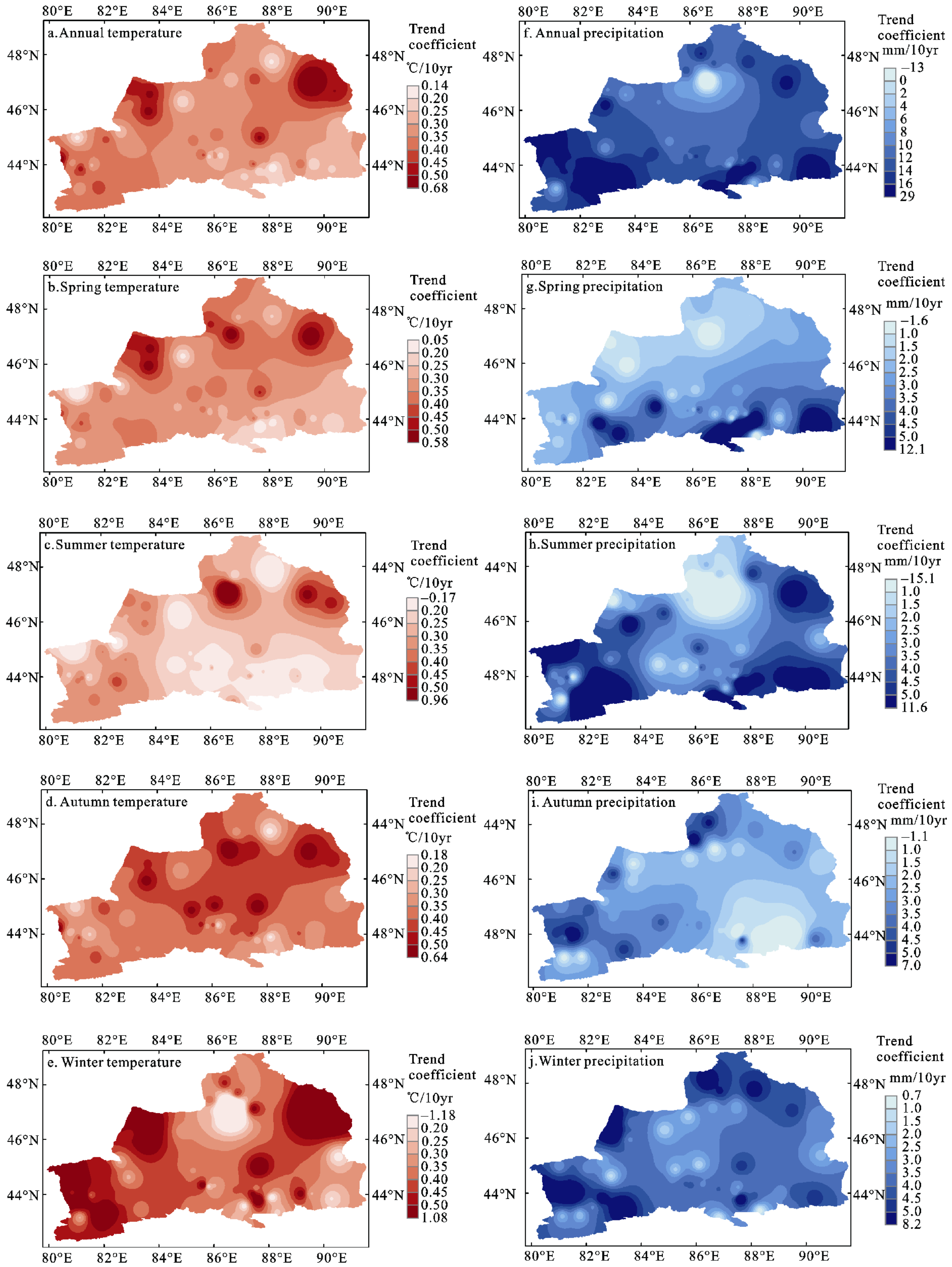

**Fig. 3** Distribution of climate trend coefficients for temperature and precipitation in northern Xinjiang. (a) Annual temperature; (b) Spring temperature; (c) Summer temperature; (d) Autumn temperature; (e) Winter temperature; (f) Annual precipitation; (g) Spring precipitation; (h) Summer precipitation; (i) Autumn precipitation; (j) Winter precipitation

maximum temperature increase was in Fuyun (0.58℃/10 yr). Smaller temperature increases were recorded in the East Tianshan Mountains and the minimum temperature increase occurred in Urumqi (0.05℃/10 yr) (Fig. 3b).

In summer, the range of the temperature increase was the smallest, with an average of 0.26℃/10 yr. The increasing temperature trends at 69% of stations was significant ($P < 0.05$). In terms of spatial distribution, temperature increases were larger in the Altai Mountains and the North Tianshan Mountains, and smaller in Junggar Basin and the East Tianshan Mountains (Fig. 3c).

In autumn, the temperature showed a warming trend, with an average of 0.38℃/10 yr. The warming trends at 94% of stations was significant ($P < 0.05$). Temperature increases were larger in the Altai Mountains, Junggar Basin and the Junggar Mountains, and smaller in the North Tianshan Mountains and the East Tianshan Mountains (Fig. 3d).

In winter, the range of the temperature increase was the largest, with an average of 0.42℃/10 yr, and 90% of stations had a significant increasing temperature trend ($P < 0.05$). The amplitude of the temperature increase in the Altai Mountains and North Tianshan Mountains area was relatively large, while that in the middle Junggar Mountains, Junggar Basin and the East Tianshan Mountains area was relatively small (Fig. 3e).

Overall, the spatial distribution of surface air temperature in the northern Xinjiang area had relatively large ranges in the high mountain areas, while in the basin areas they were relatively small.

### *3.3.2 Spatial analysis of precipitation changes*

In the last 60 years, the annual precipitation in northern Xinjiang showed an overall increasing trend, with an average increase of 13.25 mm/10 yr that was significant at 82% of stations ($P < 0.05$). The largest increases in annual precipitation were located in the Altai Mountains, the North Tianshan Mountains, and the East Tianshan Mountains, while the maximum increase was located in Urumqi (29 mm/10 yr). The areas with smallest increases were Junggar Basin and the Junggar Boundary Mountains. The annual precipitation in the Heishantou area showed a decreasing trend of –13 mm/10 yr (Fig. 3f).

The precipitation in spring showed an increasing trend at 18% of stations ($P < 0.05$), with an average increase of 2.91 mm/10a. The spatial distribution trend gradually decreased from low to high latitudes. The areas with the largest precipitation increases were located in the East Tianshan Mountains and the North Tianshan Mountains, while the areas with the smallest increases were in the Junggar Mountains (Fig. 3g).

The precipitation in summer showed an increasing trend, with an average increase of 3.76 mm/10 yr. The increasing trends at 27% of stations was significant ($P < 0.05$). The Altai Mountains, North Tianshan Mountains and East Tianshan Mountains increased significantly, while the Junggar Basin and Junggar Mountains precipitation increased only slightly. In particular, the precipitation in the Heishantou, Jimunu, Buksel and Fuhai areas showed a decreasing trend (Fig. 3h).

The precipitation increases during autumn were the smallest, with an average increase of 2.6 mm/10 yr, and 27% of stations showed a significant increasing trend ($P < 0.05$). The Altai Mountains and North Tianshan Mountains showed the largest increases, while the Middle Junggar Basin increased only slightly. The precipitation in the East Tianshan Mountains showed a decreasing trend (–1.1 mm/10 yr) (Fig. 3i).

Winter precipitation showed an increasing trend, with a maximum increase of all seasons of 3.95 mm/10yr, and 94% of stations having a significant increasing trend ($P < 0.05$). The largest increases were seen in the Altai Mountains and North Tianshan Mountains, followed by the East Tianshan Mountains and Junggar Basin, and the smallest increases were seen in the Junggar Boundary Mountains (0.7 mm/10 yr) (Fig. 3j).

With respect to the overall spatial distribution of precipitation in the northern Xinjiang area, the precipitation in the high mountainous areas increased greatly, while it only increased slightly in the basin areas.

## 3.4 Abrupt change detection of climatic series

The Mann-Kendall test and the cumulative anomaly method were used to detect and analyze the abrupt changes of annual mean temperature and precipitation in 49 meteorological stations in northern Xinjiang from 1961 to 2017 (Table 3). The accumulated anomaly of annual mean temperature went through a process in which it first declined then rose, then demonstrated an abrupt change from low to high temperatures in 1994. The results of abrupt temperature change analysis show that 11 meteorological stations showed abrupt changes in the 1980s, 37 meteorological stations showed abrupt

**Table 3** Abrupt change years of the climatic series during 1961–2017 at meteorological stations in northern Xinjiang

| Station | Longitude (°E) | Latitude (°N) | Altitude (m a.s.l.) | Abrupt change years of temperature series | Abrupt change years of precipitation series |
|---|---|---|---|---|---|
| Habahe | 86.40 | 48.05 | 534.0 | 1989 | 1998 |
| Heishantou | 86.62 | 47.10 | 1226.2 | 1991, 1993 | 2002, 2005 |
| Jeminay | 85.87 | 47.43 | 983.9 | 1982, 1988 | 1990, 1997 |
| Burqin | 86.87 | 47.70 | 475.5 | 1989 | 1983 |
| Fuhai | 87.47 | 47.12 | 502.0 | 1993 | 1982, 1995, 2000 |
| Altay | 88.08 | 47.73 | 736.9 | 1989, 1992 | 1989 |
| Fuyun | 89.52 | 46.98 | 826.6 | 1988 | 1983 |
| Tacheng | 83.00 | 46.73 | 536.6 | 1991 | – |
| Yuming | 82.93 | 46.20 | 716.2 | 1993 | – |
| Emin | 83.65 | 46.55 | 523.3 | 1989, 1992 | – |
| Hoboksar | 85.72 | 46.78 | 1294.2 | 1989 | 2000, 2005, 2013 |
| Qinghe | 90.38 | 46.67 | 1220.0 | 1993 | 1984 |
| Alashankou | 82.58 | 45.18 | 286.4 | 1989 | 1998 |
| Bole | 82.07 | 44.90 | 532.9 | 1993 | 1997 |
| Toli | 83.60 | 45.93 | 1077.7 | 1989 | 2007 |
| Karamay | 84.85 | 46.28 | 445.6 | 1989 | 1987 |
| Beitashan | 90.53 | 45.37 | 1654.7 | 1996 | – |
| Horgos | 80.42 | 44.20 | 774.0 | 1994 | 1984 |
| Huocheng | 80.85 | 44.05 | 641.0 | 1997 | 1986 |
| Wenquan | 81.02 | 44.97 | 1353.9 | 1999 | 1986 |
| Jinghe | 82.90 | 44.62 | 321.2 | 1996 | 1980 |
| Wusu | 84.67 | 44.43 | 478.3 | 1990, 1993 | 1987, 1993 |
| Paotai | 85.25 | 44.85 | 337.8 | 1994 | 1986 |
| Mosuowan | 86.10 | 45.02 | 347.2 | 1995 | 1992 |
| Shihezi | 86.05 | 44.32 | 443.7 | 1994 | 1992 |
| Shawan | 85.62 | 44.33 | 523.2 | 1994 | 1998 |
| Wulanwusu | 85.82 | 44.28 | 469.0 | 2000 | 1986 |
| Manas | 86.20 | 44.32 | 472.2 | 2004 | 1992 |
| Caijiahu | 87.53 | 44.20 | 441.0 | 1998 | 1986 |
| Hutubi | 86.82 | 44.13 | 523.5 | 2004 | 1992 |
| Changji | 87.43 | 44.02 | 579.3 | 1983, 1986 | 1981 |
| Miquan | 87.65 | 44.97 | 601.2 | 1993 | 1983 |
| Fukang | 87.92 | 44.17 | 567.9 | 1996 | 1978 |
| Jimsar | 89.17 | 44.02 | 735.4 | 1993 | 1993 |
| Qitai | 89.57 | 44.02 | 794.2 | 1996, 1999, 2002 | 1993 |
| Chabusaier | 81.15 | 43.85 | 601.0 | 1997 | 1995 |
| Yining | 81.33 | 43.95 | 664.3 | 1997 | 1987 |
| Nilke | 82.57 | 43.80 | 1106.1 | 1998 | 1986 |
| Yiningxian | 81.53 | 43.97 | 771.0 | 1994 | – |
| Gongliu | 82.23 | 43.47 | 775.6 | 1996 | 1986 |
| Xinyuen | 83.30 | 43.45 | 929.1 | 1996 | 1986, 1988, 1992 |
| Shaosu | 81.13 | 43.15 | 1854.6 | 1996 | – |
| Tekes | 81.77 | 43.18 | 1210.9 | 1995 | 1971, 1992 |
| Urumchi | 87.62 | 43.78 | 918.7 | 2002 | 1980 |
| Xiaoquzi | 87.10 | 43.57 | 2161.0 | 2000 | 1986 |
| Tianshandaxigou | 86.83 | 43.10 | 3543.8 | 2000 | 1994 |
| Tianchi | 88.12 | 43.88 | 1935.2 | 1995 | 1978, 1994, 2002 |
| Dabancheng | 88.32 | 43.35 | 1104.2 | 1993 | 1986 |
| Mori | 90.28 | 43.83 | 1271.0 | 1992 | – |

Notes: '–"'denotes frequent fluctuation; a. s. l, above sea level changes in the 1990s and four meteorological stations showed abrupt changes in the 1980s.

The precipitation time series also decreased first and then fluctuated upward, showing an abrupt change from less to more precipitation in 1986. The abrupt change analysis results for precipitation showed that there were three meteorological stations with abrupt changes in the 1970s, 22 in the 1980s, 19 in the 1990s, four in the 2000s, and seven meteorological stations with frequent fluctuations in precipitation.

### 3.5 Periodic variation of climatic series

Wavelet Analysis was applied to analyze the periodic variations of annual mean temperature and annual precipitation in northern Xinjiang. Fig. 4a shows the real part time-frequency variations of the wavelet transform coefficients of annual mean temperature. The convex positive region indicates that the temperature was higher, while the concave negative region indicates that the temperature was lower. The annual mean temperature fluctuated intensely in the 10–18 yr, 25–31 yr and 45–50 yr time scales, with complete periodic changes having taken place.

The wavelet variance diagram of annual mean temperature (Fig. 4b) showed that the wavelet variance had extreme values at 47 yr, 28 yr and 14 yr. This implies that the annual mean temperature in northern Xinjiang had a significant period of 47 yr within the scale of 57 yr, with additional scale variation periods of 28 yr and 14 yr. By extracting the wavelet coefficients at the 47 yr

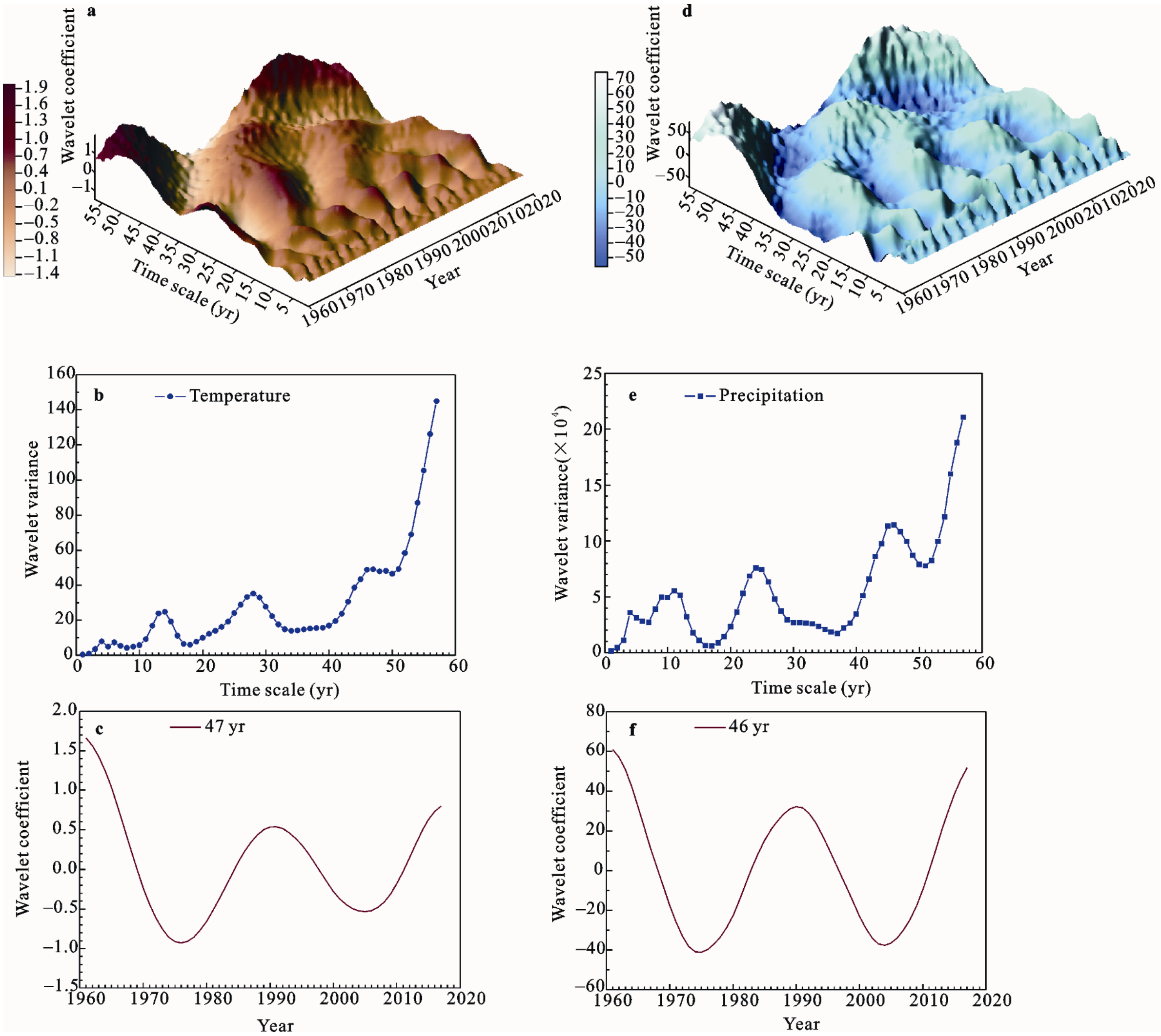

**Fig. 4** The isoline of the real part, wavelet variance and wavelet coefficient curves for the principle period scales. (a) The isoline of the real part of temperature; (b) Wavelet variance of temperature; (c) Wavelet coefficient curves of temperature; (d) The isoline of the real part of precipitation; (e) Wavelet variance of precipitation; (f) Wavelet coefficient curves of precipitation

scale, the annual mean temperature change under the main cycle was obtained. This reflected the change in positive and negative phase structure in annual mean temperature. The positive value indicated that the temperature was on the high side and the negative value indicated that the temperature was on the low side. As can be seen from Fig. 4c, the annual mean temperature in northern Xinjiang experienced a complete sinusoidal fluctuation from 1961 to 2017. The three stages of relatively high annual mean temperatures were: 1961–1969, 1985–1997, and 2012–2017, while the two stages of relatively low annual mean temperatures were: 1970–1984 and 1998–2011.

Fig. 4d shows the real part time-frequency variation of the wavelet transform coefficients for annual precipitation in northern Xinjiang. The positive region on the convex side indicates more precipitation, while the negative region on the concave side indicates less precipitation. The annual precipitation fluctuated intensively on time scales of 10–13 yr, 22–28 yr and 44–50 yr, with complete periodic changes. The wavelet variance diagram of annual precipitation (Fig. 4e) shows extreme values at 46 yr, 24 yr and 11 yr. Therefore, it can be concluded that the annual precipitation in northern Xinjiang had a significant period of 46 yr within the scale of 57 yr, with additional scale variation periods of 24 yr and 11 yr. By extracting the wavelet coefficients at the 46 yr scale, the annual precipitation change under the main cycle was obtained. This reflects the change in positive and negative phase structure of annual precipitation. The positive values represent wet years while the negative values represent dry years. From Fig. 4f, we can see that the annual precipitation in northern Xinjiang experienced a complete sinusoidal fluctuation from 1961 to 2017. The three stages of relatively high annual precipitation were: 1961–1968, 1983–1995 and 2012–2017, and the two stages of relatively low annual precipitation were: 1969–1982 and 1996–2011.

## 4 Discussion

By analyzing variations in temperature and precipitation in northern Xinjiang from 1961 to 2017, we found that both temperature and precipitation showed an upward trend, and the overall climate became warm and humid. In addition, northern Xinjiang showed the most significant warming and humidifying trends in Northwest China over the past 50 years (Liu and Zhang, 2011). Therefore, it is an indisputable fact that it has become warm and humid in northern Xinjiang. But what is the reason that caused the trend of warm and humid?

Climate warming is likely due to an increase in greenhouse gases, which may be caused by human activities (Jiang, 2010). Climate change is mainly caused by solar radiation, cosmic geophysical factors, atmospheric circulation, underlying surface factors and human activities (Zhou et al., 1991). In addition, the coupled effects of human activities and natural factors such as solar radiation forcing on climate change cannot be ignored, but there processes are extremely complex and difficult to quantify (Liu et al., 2014). In general, climate change factors can be divided into natural factors and human factors, of which human activities mainly affect climate change by changing atmospheric composition and land cover. This section focuses on the possible impacts of major human activities on regional climate change in northern Xinjiang, and discusses the current population change, economic development and land use change in northern Xinjiang.

### 4.1 The impacts of population change

Population change includes not only the change in total population, but also the change in population spatial distribution. At present, many scholars are very concerned about the impacts of population change on climate warming. O'Neill et al. (2009) collected time series data from multiple countries and regions around the world, and applied the model to analyze the net effects of population growth on $CO_2$ emissions while controlling for other factors. They found that there was a roughly one-to-one correlation between the two, or 1% population growth led to a 1% increase in $CO_2$ emissions. A study of the impacts of population changes on energy consumption in developed countries from 1970 to 1990 found that when total energy consumption growth was decomposed into population factors and economic and technological factors, the impacts of household numbers on warming were significantly greater than population size (Mackellar et al., 1995). In terms of the impact of population aging and urbanization on climate change, population aging in developed countries is an important factor affecting greenhouse gas emissions, while population urbanization in developing countries is particularly critical (Liu et al., 2014).

Fig. 5 shows the change in total population and household number in northern Xinjiang from 1988 to 2017. This paper did not test the impacts of total population and household number on regional warming in northern Xinjiang. However, the correlations between population and household number, annual average temperature and annual preciptation over the same period were all positive and passed the confidence test ($P > 0.01$). Therefore, as population increased, the annual average temperature increased. The total population and household number in northern Xinjiang increased by 44.06% and 123.47%, respectively, from 1988 to 2017. In addition, according to the sixth census of Xinjiang, in 2010, there were 1 414 100 elderly people over the age of 65, accounting for 6.48% of the total population, indicating that Xinjiang has become an aging society. The urbanization rate reached 49.38% in 2017 (Gao et al., 2018). The effects of population aging and urbanization on climate warming in northern Xinjiang region cannot be ignored.

### 4.2 The impacts of economic development

Economic growth has the greatest impacts on energy demand. For every 1% increase in GDP, energy demand will increase by 0.846%. The increase of greenhouse gas emissions in China is the inevitable result of economic development. Per capita GDP growth is the strongest driver of the increase in greenhouse gas emissions, with an average contribution rate of 15.82% that ranks first among all the drivers (Du, 2015). During industrialization, China's $CO_2$ emissions have been rising, accounting for 80% of greenhouse gases (Liu et al., 2018). With high speed industrialization, the development of secondary and tertiary industries will inevitably drive the increase of energy consumption. If the energy, population, and industrial structures are relatively stable, the growth of the economic aggregate that is positively correlated with carbon emissions will lead to the same proportion of carbon emissions growth. Carbon emissions in developing countries are mainly concentrated in production. The ratio of carbon emissions between enterprises and residents in developed countries is 3 : 7, while in developing countries it is 7 : 3 (Du, 2015). Wang and Wang (2006) believe that China's investment dependent economic growth mode and the economic structure dominated by the secondary industry are the main reasons for the increase in greenhouse gas emissions. Tan et al. (2008) found that the carbon emissions from industry are significantly different. Industrial carbon emissions account for the majority of total carbon emissions, ranging from 71% to 84%, and that is increasing. The rapid industrialization process has increased carbon emissions, and the resulting climate warming cannot be ignored.

Northern Xinjiang accounts for 24% of Xinjiang's total land area, while the GDP of the region reaches about 60%. The GDP of northern Xinjiang increased by 794% in 2017 compared with 2000: the secondary industry increased by 717% and the tertiary industry increased by 1029% (Table 4). The rapid development of secondary and tertiary industries increased greenhouse gas emissions, which was the main factor driving climate warming in northern Xinjiang. The per capita GDP of northern Xinjiang was 72 957.24 yuan (RMB) in 2017, seven times greater than 9 449.51 yuan in 2000. The increase of greenhouse gas emission along with the growth of per capita GDP was the one of driving factors of climate warming.

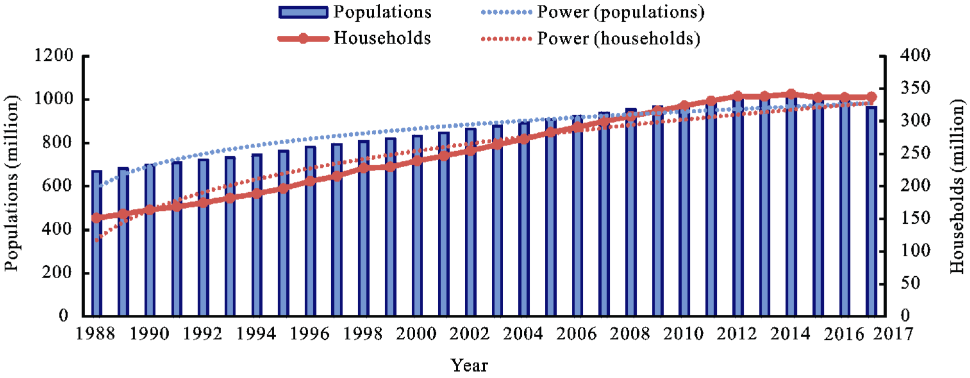

**Fig. 5** Population dynamics in northern Xinjiang during 1988–2017

**Table 4** The change of GDP in northern Xinjiang during 2000–2017(100 million yuan RMB)

| Industry type | 2000 | | 2010 | | 2017 | | GDP growth in | Increase (%) |
|---|---|---|---|---|---|---|---|---|
| | GDP | Ratio (%) | GDP | Ratio (%) | GDP | Ratio (%) | 2000–2017 | |
| Primary industry | 135.04 | 17.19 | 503.00 | 13.38 | 725.54 | 10.33 | 590.50 | 437 |
| Secondary industry | 335.45 | 42.71 | 1890.04 | 50.28 | 2741.28 | 39.04 | 2405.83 | 717 |
| Tertiary industry | 315.01 | 40.10 | 1366.31 | 36.34 | 3555.02 | 50.63 | 3240.01 | 1029 |
| Northern Xinjiang | 785.50 | 57.61 | 3759.35 | 69.65 | 7021.84 | 64.53 | 6236.34 | 794 |
| Xinjiang | 1363.56 | – | 5397.27 | – | 10881.96 | – | 9518.40 | 698 |

Notes: The GDP data from the Xinjiang Statistical Yearbook (Gao et al., 2018)

### 4.3 Land use and land cover change

Land Use and Land Cover Change (LUCC) directly affects the surface vegetation coverage and has an important impact on the local and regional climate systems. It is also an important driving factor of regional and even global climate change. LUCC may cause greenhouse gas emissions such as $CO_2$ and methane, and change the chemical composition of the atmosphere (Chen et al., 2015). LUCC can affect the exchange of energy and water between land and atmosphere by changing radiation, cloud, surface albedo and roughness. For example, deforestation in the tropics can reduce the surface roughness, resulting in a weakening of evaporation and a warming effect (Henderson-Sellers et al., 1993; Hahmann and Dickison, 1997). The extreme manifestation of LUCC is the urban heat island effect. The great difference in the nature of urban and natural underlying surfaces produce differentials in energy and water circulation, leading to local surface temperature rise (Chen and Zhang, 2013).

In northern Xinjiang, the ratios of land type area in 1995, 2005, and 2015 were ranked as grassland > unused land > cultivated land > forest land > water area > construction land (Fig. 6). The ratios of grassland and cultivated land were relatively large, indicating that agriculture and animal husbandry were the main forms of production in northern Xinjiang. Unused land accounted for 40%, and was made up of sandy land, Gobi, saline-alkali land, marshland, bare land, and bare rock texture, which are consistent with the characteristics of arid and semi-arid regions. In the past 20 years, cultivated land area in northern Xinjiang has increased continuously, forest land area has declined, and grassland has continued to decrease in a large area. Land reclamation and occupation, unreasonable grazing, excessive deforestation and the conversion of forests and grasslands to agricultural land have degraded natural vegetation and altered surface parameters. For example, the increase of surface roughness and the decrease of surface albedo can increase the temperature to some extent.

Although the ratio of construction land (urban and rural, working conditions, residential land) was small, it was the change largest in 1995–2015, at 72.77%. The construction land area continues to increase substantially, resulting in the urban heat island effect. Difference nature of urban and natural underlying surfaces cause differential energy and water circulation, which is one of the reasons for the warming and humidification in northern Xinjiang.

In recent decades, the total water area in the northern Xinjiang region continues has increased, glaciers have shrunk, glacier melt water has increased, annual average runoff has increased, and the area of reservoirs, lakes, glaciers, and permanent snow cover has expanded (Jiang et al., 2005; Bolch, 2007; Tang et al., 2013; Wang and Meng et al., 2016). In particular, the expansion of reservoir and lake areas is positively related to the increase in precipitation, and the expansion of natural and artificial oases have played a positive supporting role (He et al., 2018). Shi et al. (2003) selected Bosten Lake in the central Tianshan Mountains as an example. They concluded that the water levels had been declining until 1986, and then rose from 1987 onward, which was consistent with the analysis results of precipitation abrupt change in 1986 in this paper. The increase of precipitation exceeded that of evaporation and the climate became warm and humid. The transformation of Bosten Lake is considered to be a signal of the transition into a warm and humid climate in Northwest China.

## 5 Conclusions

Based on the analysis of the variations of different climate time series in northern Xinjiang from 1961 to

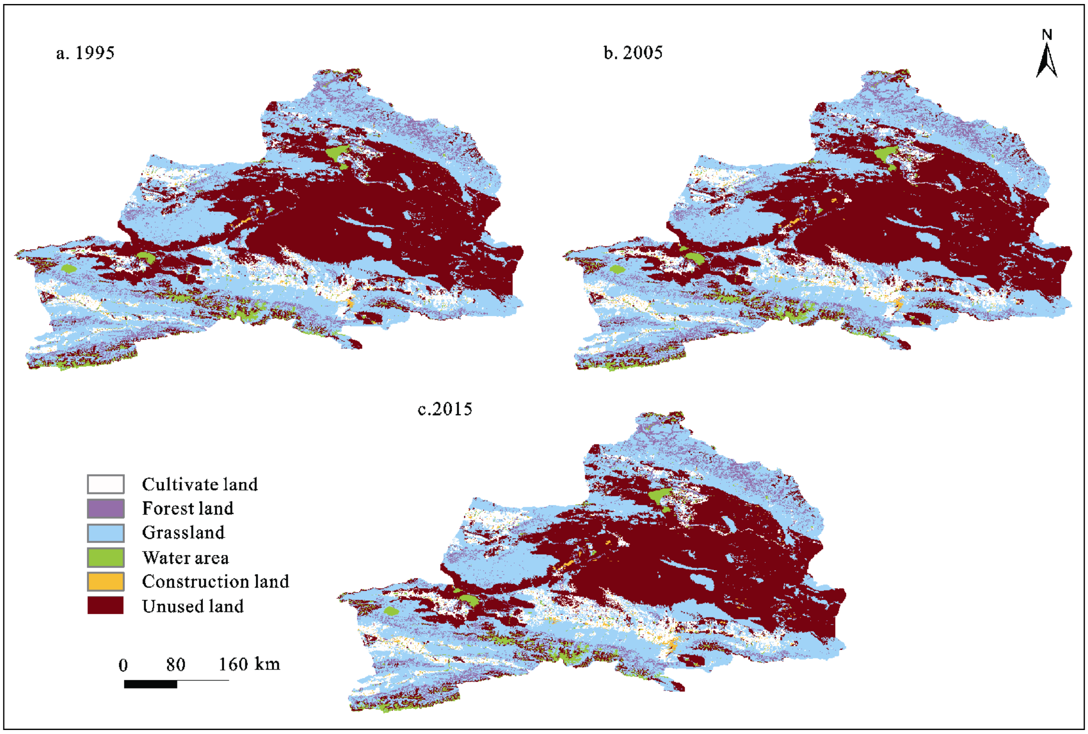

**Fig. 6** Land use and land cover change in northern Xinjiang in 1995, 2005 and 2015

2017, it was shown that the temperature and precipitation in northern Xinjiang have been trending upward and the overall climate has become more warm and humid. The conclusions are as follows:

1) The annual mean temperature in northern Xinjiang increased significantly at a rate of 0.35℃/10 yr ($P < 0.01$). The temperature in all four seasons showed an upward trend, with the largest increases in winter. The accumulated anomaly of annual mean temperature first declined and then rose, with an abrupt change occurred in 1994. The interdecadal variation in seasonal temperature also showed a uniform warming trend.

2) The annual precipitation in northern Xinjiang showed a significant increasing trend at a rate of 13.25mm/10 yr ($P < 0.01$). The precipitation over all four seasons showed an increasing trend, with the largest increases in winter. The precipitation time series also decreased first and then fluctuated upward, showing an abrupt change from less to more precipitation in 1986. The interdecadal variation in seasonal precipitation also had a consistent increasing trend, but the increasing trend was not obvious.

3) In the past 60 years, the regions with the largest temperature increase in northren Xinjiang were located in the Altai Mountains, the North Tianshan Mountains and the Junggar Boundary Mountains. Small temperature increases were seen in the East Tianshan Mountains and Junggar Basin. The regions with the largest precipitation increases in northern Xinjiang were located in the Altai Mountains, the North Tianshan Mountains and East Tianshan Mountains, while the regions with the small increases were found in the Junggar Boundary Mountains and Junggar Basin.

4) Wavelet analysis showed that the annual mean temperature in northern Xinjiang has a significant period of 47 yr. The strong periodic signal of 47 yr indicated that the annual mean temperatures experienced two climatic shifts from cold to warm. The annual precipitation in northern Xinjiang had a strong significant period of 46 yr. The 46 yr main period signal showed that the annual precipitation experienced two changes from dry to wet.

5) The impacts of population change, economic development, and land use change on climate trends in northern Xinjiang are objective. These effects have not only played an important role in the historical processes of atmospheric energy and water exchange, but also may be the key to control greenhouse gas emissions and

mitigate the degree of climate change in the future.

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