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ORIGINAL PAPER

Temperature and precipitation changes in different environments in the arid region of northwest China

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Abstract Using 51 meteorological stations in the arid region of northwest China in the mountain, oasis, and the desert areas obtained from 1960 to 2010, this paper conducted a comparative analysis for detecting temperature and precipitation changes in the diverse environments. In recent 50 years, temperature has increased at 0.325, 0.339, and 0.360 °C per decade in the mountain, oasis, and the desert areas, respectively; and also, precipitation has increased at 10.15, 6.29, and 0.87 mm per decade, but in which the increasing trend of precipitation in desert area was not significant. Before the 1990s, the increase in temperature was the fastest in the desert area, up to 0.214 °C per decade, but was the slowest in the mountain area, only 0.103 °C per decade. The temperature rising was faster after the 1990s, 0.606 °C per decade, in the oasis area was fastest, but was the slowest in the desert region with 0.402 °C per decade. The precipitation in each area was stable from 1960 to 1986, but an increase in the oasis and mountain area was larger from 1987 to 2010.

1 Introduction

The arid region of northwest China, herein referred to as ARNC (Fig. 1), is the vast area in the hinterland of the Eurasian continent. It is located between the western Helan Mountain–Zaocys Ridgeline and the northern Kunlun Mountains. In terms of administration, it includes the Xinjiang Uygur Autonomous Region, the middle and west parts of the Inner Mongolia Autonomous Region, most part of the Ningxia Hui Autonomous Region, and the Hexi Corridor region in the Gansu Province. The total area is about 2.5 million square kilometers, accounting for over one fourth of China's total territory. The average annual temperature is about 8 °C, and annual rainfall is less than 300 mm on mean, gradually decreasing from east to west.

ARNC holds a strategical important position in China's economic development due to its vast area, abundant mineral resources, and high agricultural productive potential (thanks to the great amounts of light and heat it receives). The area with long sunshine and strong radiation has very abundant solar energy resources. However, the area belongs to typical arid eco-fragile area due to water resources shortage, widespread desertification, and sparse vegetation. However, during the past several decades, ARNC has been experiencing considerable environmental change, featured by oasis degradation, glacier retreat, water shortage, desertification expansion, just to name a few (Hao et al. 2008), which has exacerbated the conflicts between human societies and natural ecosystems in the region. In fact, the effects of climate change on natural environment in the arid region cannot be neglected. Many scholars explored the environment evolution and mechanism in the arid region (Yang et al. 1995; Wang et al. 2010). The research of Stewart et al. (2001) indicated that the climate condition in the arid region was more sensitive to climate change; Shi and Zhang (1995) analyzed the climate change process in the arid region and found that the climate trend in the arid region of northwest China turned to warmer and wetter; Chen et al. and Xu et al. studied the effect of climate change in the arid region on water resources in the typical river basin (Chen et al. 2007; Chen et al. 2008; Chen et al. 2010; Xu and Peng 2010; Xu et

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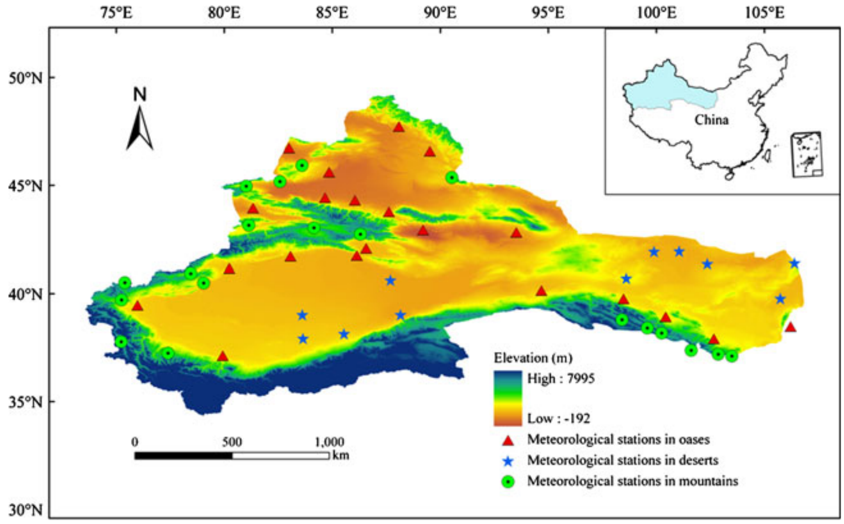


Fig. 1 The locations of meteorological stations in the arid region of northwest China

al. 2011); Ding et al. (2006) analyzed glacier change trend under climate change trend and found retreating glaciers, increasing runoff of glacial melt water. Xu et al. (2009) researched the effect of climate change on species distribution in the arid region. Recently, regional climate change and the effect of region underlying surface on the climate change are paid more attention (Almazroui 2011; Endler and Matzarakis 2011; Krol and Bronstert 2007; Cabre et al. 2010; Mahlstein and Knutti 2010; Samuels et al. 2010; Bukovsky and Karoly 2011; Chen et al. 2011; Roy et al. 2011; Yang et al. 2011; Sun et al. 2010); however, there are limited researches on climate change process and its difference of the mountain, oasis, and desert area in ARNC (Lu et al. 2004).

This study investigates the changes of temperature and precipitation in the mountain, oasis, and desert areas in ARNC in the past 51 years. Mountains are "reservoirs" in ARNC, which receive relatively great amount of precipitation and where glaciers are located. Mountains also enjoy high biological diversity in complex ecosystems. Oases occupy less than 5 % of the total area, but carry 95 % of the population and more than 90 % of GDP (Wang 1995). Deserts are featured by vast area, sparse vegetation, and simple and fragile ecosystems. An investigation of the discrepancies in the impacts of the climate change on these different areas may provide scientific basis for planning sustainable development, particularly sustainable use of water resources in ARNC.

2 Data and methods

2.1 Data

We used the data from the meteorological stations in the three types of areas to detect and analyze the temperature and precipitation changes in the three landscapes (Fig. 1). Immerzeel et al. (2010) found that the areas above 2,000 m are the main water supply regions in Asia. Accordingly, in this study, we used 2,000 m as the threshold to define the mountain areas in ARNC and selected meteorological stations whose altitudes are above this threshold to represent this type of areas. We also considered that the selected stations should be located in areas with few human activities. A total of 19 meteorological stations were selected for the mountain areas, with a mean altitude of 2,363 m. For the oases, we selected those meteorological stations that are located in the large- and medium-sized urban area with dense populations to reflect the impact of human activities. A total of 21 such meteorological stations were selected, with a mean altitude of 879 m. The number of meteorological stations in the desert areas is very limited. We selected 11 meteorological stations to represent the desert areas. They are either actually located in the desert with fragile ecosystems or in small oases surrounded by deserts and featured by small population, little human activity, and sparse vegetation.

All the 51 meteorological stations selected for this study had been maintained following the standard of the National Meteorological Administration of China. The standard requires strict quality control processes including extreme inspection, time consistency check, and others before releasing these data. From these 51 stations, we acquired annual temperature and precipitation data for the period 1960–2010.

2.2 Methods

We used the Mann–Kendall nonparametric statistical test (Mann 1945; Kendall 1975) to detect the trends in the time series of air temperature and precipitation. For a time series

$X = \{x_1, x_2, \ldots, x_n\}$, when $n > 10$, the standard normal statistic Z is estimated as follows:

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{var}(S)} & S > 0 \\ 0 & 0 \\ (S+1)/\sqrt{\mathrm{var}(S)} & S < 0 \end{cases} \tag{1}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{2}$$

$$\mathrm{sgn}(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{3}$$

$$\mathrm{var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] \Big/ 18 \tag{4}$$

where t is the extent of any given tie, and $\sum_t$ denotes the summation of all ties.

Furthermore, the nonparametric Mann–Kendall–Sneyers test (Mann 1945; Kendall 1975; Sneyers 1975) was applied in this study for determining the occurrence of step change points of temperature and precipitation. $x_1, \ldots, x_n$ represent the data points. The numbers m_i of elements x_j preceding it ($j<i$) such that $x_j<x_i$ are computed for each element x_i. Under the null hypothesis (no step change point), the normally distributed statistic t_k can be described as follows:

$$t_k = \sum_{i=1}^{k} m_i \quad (2 \leq k \leq n) \tag{5}$$

t_k as mean and variance of the normally distributed statistic can be calculated as follows:

$$\bar{t}_k = E(t_k) = k(k-1)/4 \tag{6}$$

$$\mathrm{var}(t_k) = k(k-1)(2k+)/72. \tag{7}$$

u_k as the normalized variable statistic is given in following formula:

$$u_k = (t_k - \bar{t}_k)/\sqrt{\mathrm{var}(t_k)}. \tag{8}$$

To compare with the change trends of temperature and precipitation in different environments, in this study, long-term trends in temperature and precipitation were detected as the slope of linear regression line of mean air temperature and precipitation during 1960–2010. To further reflect the climate changes of the three landscapes in different periods, we divided the 51 years into two periods: before and after step changes in general; this paper makes a comparison of temperature and precipitation of the two periods. Between the air temperature and precipitation in mountains, oases, and deserts considered in this study, we calculate Pearson's correlation coefficient to detect the association between them.

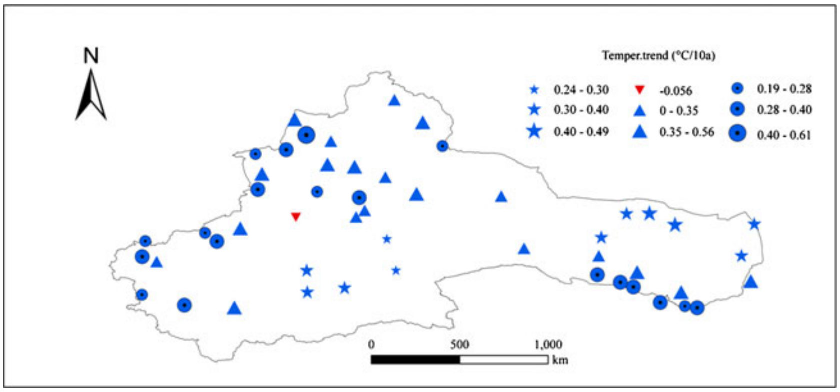
3 Results and analysis

3.1 Temperature

3.1.1 Trend of air temperature

The Mann–Kendall test found that the mean temperatures of all three landscapes have significant increasing trends for the period 1960–2010 ($P<0.01$). Figure 2 shows the linear tendencies of temperature at the 51 stations for the period 1960–2010. This map, to some extent, presents the spatial distribution of temperature variation in ARNC for the study

Fig. 2 The temperature trends at the meteorological stations in the three landscapes for the period 1960–2010 (The *red* implies decrease, the *blue* implies increase, and the *pentagram*, *triangle*, and *circular* imply meteorological station in deserts, oases, and mountains, respectively)



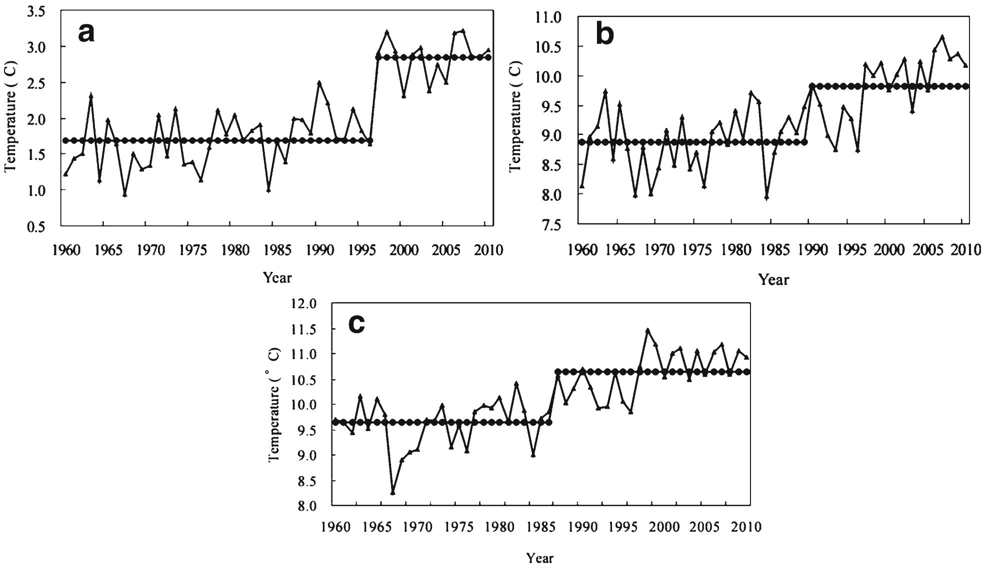


Fig. 3 Step change of temperature in mountain (**a**), oasis (**b**), and desert (**c**) landscapes

period. Among the 51 stations, only one has a slightly decreasing trend with a slow rate of 0.056 °C per decade; all the others have increasing trends. The mean temperature of the 51 stations has a gentle increasing trend, with a rate of 0.341 °C per decade.

Among the three landscapes, the desert has the highest increasing rate, which is 0.360 °C per decade; it is followed by the oasis with a rate of 0.339 °C per decade; the mountain has the lowest rate of 0.325 °C per decade. A possible reason for that the mountain has the slowest increasing rate is the widespread snow and glacier, vegetation diversity, and high ecosystem stability in the mountain area have a certain buffer action on the global climate change while the desert region is vice versa.

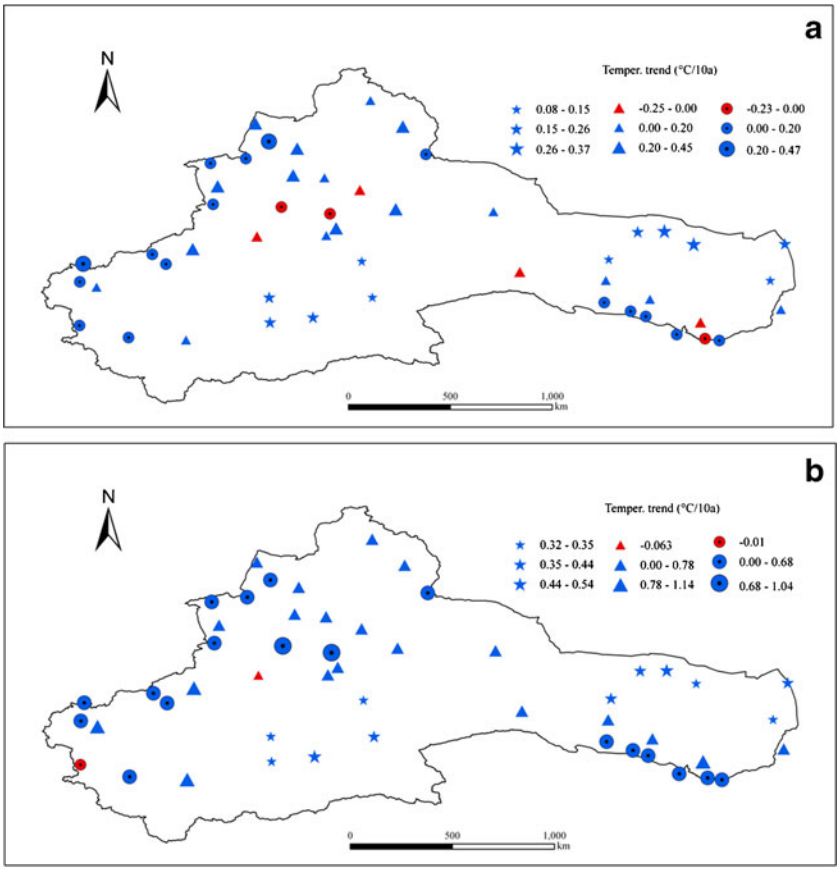


Fig. 4 The temperature trends in different landscapes for period 1960–1989 (**a**) and 1990–2010 (**b**) (The *red* implies decrease, the *blue* implies increase, and the *pentagram*, *triangle*, and *circular* imply meteorological station in deserts, oases, and mountains, respectively)

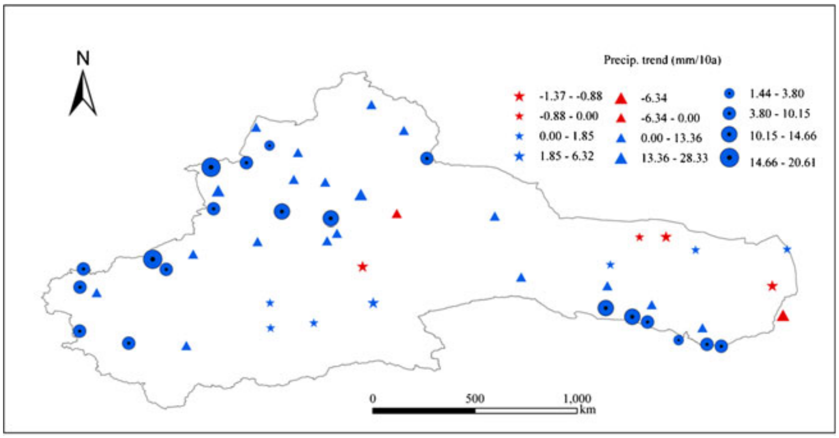


Fig. 5 The precipitation trend of each meteorological station during the period 1960 to 2010 (The *red* implies decrease, the *blue* implies increase, and the *pentagram*, *triangle*, and *circular* imply meteorological station in deserts, oases, and mountains, respectively)

3.1.2 The trends of temperature in different periods

Figure 3 shows that the first step change point in the mean temperature of desert occurred in 1987, followed by the oasis in 1990, and the mountain in 1997, which are related to the unique geographical position and climatic conditions in different landscapes. Since the step change analysis shows that all three landscapes had relatively abrupt changes around 1990, we divided the 51 years into two periods, before and after 1990, and conducted more detailed analysis to each. As shown in Fig. 3, the temperatures in the second period are markedly higher in all landscapes.

Before the 1990s, the temperature trends among the 51 stations were not consistent; seven stations had decreasing trends, and they were all located in the mountain and oasis areas (Fig. 4a). The overall trend of the 51 stations is a weak rising one, with a mean rate of 0.151 °C per decade. Sixteen of the 19 mountain stations had increasing trends, and the mean increasing rate of the mountain landscape is 0.103 °C per decade. Seventeen of the 21 oasis stations had increasing trends, and the mean increasing rate of this landscape is 0.138 °C per decade. All the stations in the desert areas had increasing trends in this period, with a mean rate of 0.214 °C per decade. One reason is that the ecosystem in the mountain area has high stability and the desert ecosystem has low stability; the other reason is that the arid area of northwest in this period has a small population density and few human interference activities on oasis and mountain.

After 1990s, the temperature increase of the entire area had a considerable faster pace (Fig. 4b). The mean of the increasing rates at the 51 stations is 0.517 °C per decade. The oasis areas had the highest rising rate of 0.60 °C per decade, followed by the mountain areas' 0.542 °C per decade. Both oasis and mountain areas had 95 % of their stations showing increasing trends. While all stations in the desert areas had increasing trends, their mean rate is only 0.402 °C per decade, the lowest among the three landscapes. We suspect that human activity is a major factor in forming this pattern. Since 1990, ARNC has experienced a rapid population growth, along with fast expansion of industrialization, tourism, and urbanization.

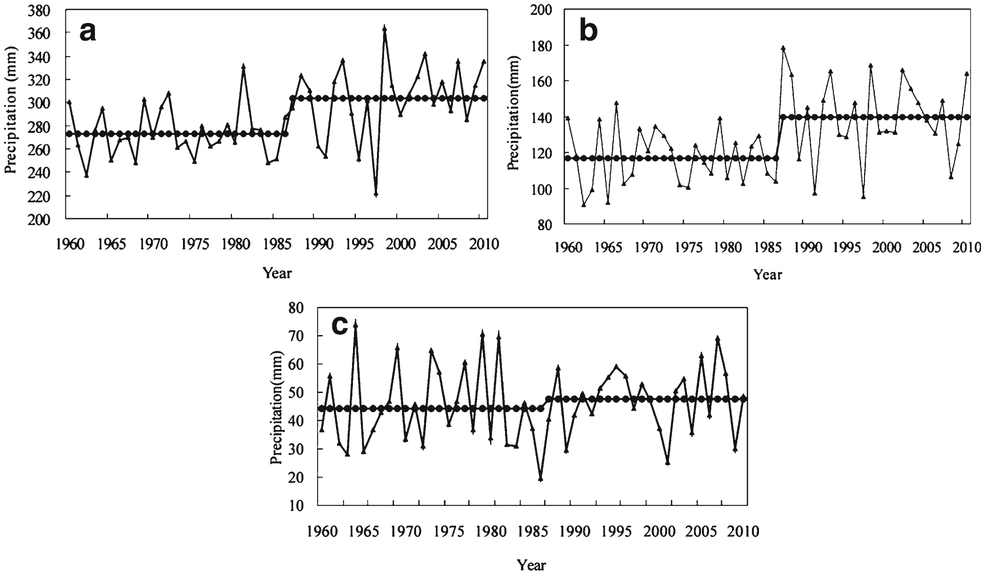


Fig. 6 Step change point of precipitation in mountain (**a**), oasis (**b**), and desert (**c**) areas

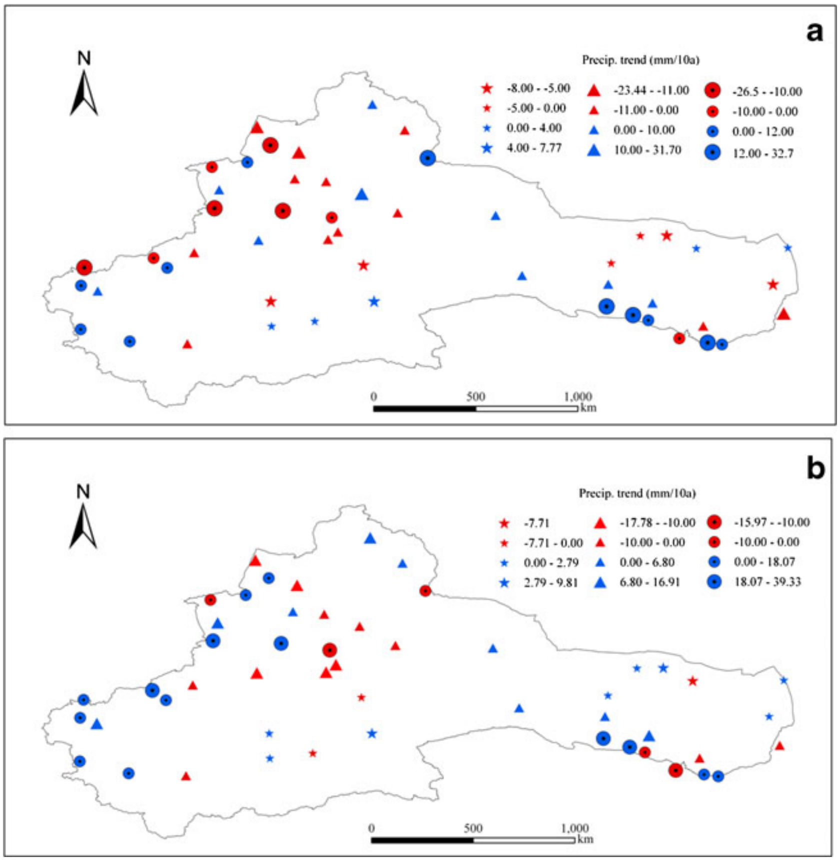


Fig. 7 The precipitation trend of each the meteorological station during the periods 1960–1986 (**a**) and 1987–2010 (**b**) (The *red* implies decrease, the *blue* implies increase, and the *pentagram*, *triangle*, and *circular* imply meteorological station in deserts, oases, and mountains, respectively)

Greenhouse emission and “urban heat island” effect may cause the difference among different landscapes over the background of global warming and regional climate change.

3.2 Precipitation

3.2.1 Trend of precipitation

Figure 5 shows the linear tendencies in precipitation of the 51 stations for the 51 years. Among the 51 stations, 45 stations had increasing trends for the period. The overall trend is increasing, and the mean rate of the 51 stations is 5.77 mm per decade.

The mountain landscape had an increasing rate of 10.15 mm per decade, the fastest among the three. It is followed by the oasis landscape with 6.29 mm per decade and the desert landscape with only 0.87 mm per decade. The Mann–Kendall test shows that the increasing trends of the mountain and oasis landscapes are statistically significant ($P<0.01$), while the trend of the desert landscape is not. There are mainly four reasons to explain the increasing precipitation (Yang et al. 2009): (1) local climate characteristics, for example high water vapor content in the air and favorable weather situation; (2) temperature rising can lead to increase the amount of the glacial and snow melt water and further promotes the formation of mountain precipitation condition; (3) temperature rising strengthens local circulation between the plain areas and mountain and improves air humidity in oasis area, which lead to the increasing precipitation in oasis area; and (4) the process of global warming-driven water circulation speeds up. Bengtsson (1997) has estimated that doubling of greenhouse gases could cause temperature rising and further leads to increase atmospheric water vapor content by 15 % and to increase precipitation by 8 %.

Table 1 Pearson coefficient between temperature and precipitation in the diverse environments

Item	Mountain temperature	Oasis temperature	Desert temperature	Mean temperature
Mountain precipitation	0.390**	0.272	0.452**	0.381**
Oasis precipitation	0.291*	0.136	0.382**	0.275*
Desert precipitation	0.009	−0.097	−0.044	−0.047
Mean precipitation	0.342*	0.184	0.398**	0.315*

*significant at $P<0.05$, **significant at $P<0.01$

3.2.2 The changes of precipitation in different periods

The Mann–Kendall–Sneyers test found that the step change points of precipitations in the mountain and oasis areas occurred in 1987 ($P<0.05$), which is consistent with the findings of previous research (Chen and Xu 2005; Zhang et al. 2010). No step change point of precipitation was found for the desert areas (Fig. 6).

Based on the results of the step change analysis, we divide the 51 years into two periods: 1960–1986 and 1987–2010. The analysis revealed that precipitation of the mountain and oasis landscapes increased markedly after 1986.

During the period of 1960–1986, about a half of the 51 stations had increasing trends and the other half had decreasing trends (Fig. 7a). The mean changing rate was −4.35 mm per decade. The rate of mountain landscape was 0.98 mm per decade, with 11 among 19 stations having increasing trends. The oasis landscape had a rate of −1.17 mm per decade, with 12 among 21 stations having decreasing trends. The desert landscape had a similar rate of −1.12 mm per decade, with 6 among 11 stations having decreasing trends. Overall, the precipitation changes in all types of areas are small during 1960–1986.

From 1987 to 2010, more stations (31 stations) had increasing trends (Fig. 7b). The mean rate of the 51 stations was 3.59 mm per decade. The precipitation change is not consistent across the different landscapes during this period. The mountain areas had a rising trend with a mean rate of 12.20 mm per decade. Fourteen among 19 stations in the mountain areas had increasing trends, considerably more than that during the period of 1960–1986. The precipitation in the oasis area had a jump in 1987 (Fig. 6b) and since then has experienced large variance but maintained a relatively high mean (23.02 mm, considerably higher than the period of 1960–1986). The precipitation in desert area increased slightly with only 1.31 mm per decade. Overall, the increase of precipitations during this period occurred mostly in the mountain and oasis areas. The precipitation in the desert areas changed a little.

3.3 Correlation between temperature and precipitation

Table 1 lists the results of the correlation analysis on temperature and precipitation across the three landscapes. One can see two interesting patterns in these correlation coefficient values: (1) the temperature of the oasis areas is not significantly correlated with the precipitation of any landscape, including that of itself, which may be attributed to the "unnatural" temperature variation caused by the human influence, and (2) the precipitation of the desert areas is not significantly correlated with the temperature of any landscapes, including itself, reflecting the stability of precipitation in this unique landscape.

4 Conclusions

During 1960–2010, the temperature of the arid region of northwest China had a significant increase ($P<0.05$). The temperature variation has a step change point around 1990. Before this point, the increasing rate was relatively low, and after this point, the rate was markedly higher. In terms of the three landscapes considered in this study, from 1960 to 1989, the desert areas had the highest increasing rate at 0.214 °C per decade, whereas from 1990 to 2010, the oasis areas had the highest rate at 0.606 °C per decade and rate of the desert areas became the slowest at 0.402 °C per decade. This change might be an indication of that human factor which became an increasingly important factor in the temperature variation in this region.

From 1960 to 2010, all three landscapes enjoyed increased precipitation, but only in the mountain and oasis areas the increasing trends were statistically significant ($P<0.05$). From 1960 to 1986, the trend of precipitation in the region was not obvious. During the period 1987 to 2010, the amounts of increased precipitation in the mountains and oases were fairly large, while that in the desert areas was relatively small.

Correlation analysis shows that the temperature of the oasis landscape was not significantly correlated with the precipitation of any landscape, including that of itself, which might be an indication of the unnatural component in the temperature variation in such landscape. The analysis also shows that the precipitation of the desert landscape was not significantly correlated with the temperature of any landscape, including that of itself, which reflects the uniqueness of the precipitation process in this type of landscape.

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