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Climate change with elevation and its potential impact on water resources in the Tianshan Mountains, Central Asia

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Abstract

Climate change in complex mountain regions has an impact on the change of water resources, especially in arid areas. Here, we use long-term meteorological and hydrological station observation data to analyze the time series of climate indices and runoff to study the variability of climate in the Kaidu River Basin. The analysis results are as follows: 1) the variability rate of low temperature indices are of greater magnitude than high temperature indices; 2) overall, for the river basin, frost days and ice days all exhibited decreasing trends, and growing season lengths increased considerably; 3) during the past 50 years, overall precipitation has increased in the river basin, but there are some differences in some seasons, and precipitation from June to August accounts for approximately 66% of the annual precipitation; and 4) temperature lapse rate and precipitation of the mountain region are major factors influencing the change of runoff for the Kaidu River Basin, temperature lapse rates are the main factor influencing the run off change in the spring and fall, and precipitation in the mountain region is the major factor influencing the runoff change in the summer. Generally, climate change in complex mountain regions will be expected to seriously affect water resources in arid regions.

Keywords: Climate change; Temperature indices; Precipitation indices; Runoff analysis; Kaidu River Basin

1 Introduction

Climate change is a natural process of climatic systems. Climate change has received much attention in recent decades due to its effect on ecosystems and water resources. Meteorological station observation data are an important data source for studying climate change, in that they enable a better understanding of wet, dry, warm, or cool conditions, and facilitate accurate simulation of future climate change. A series of studies based on observation station data has been conducted to analyze regional climate change, e.g., in Australia (Alexander et al., 2007; Fu et al., 2010), Canada (Vincent and Mekis, 2006), China (Gemmer et al., 2004; Ding et al., 2007; Fu et al., 2013), and Europe (Rowell and Jones, 2006; Casanueva et al., 2014). These studies exhibited that air temperature showed increasing trends globally, and the precipitation change in different spatial and temporal scales has not been uniform during the past century. However, the observation stations are concentrated in low elevation regions, but are sparse in mountain regions. Mountain regions are particular geographical units and are important water resources (Immerzeel and Bierkens, 2012). In fact, almost all rivers are fed from mountain regions, and mountain regions are considered to be the “water towers of the world” (Immerzeel et al., 2010).

Temperature and precipitation change in mountain regions have an influence on water resource availability for downstream basins (Miller et al., 2012; Lutz et al., 2014). In complex terrain regions, the change of temperature is related to altitude (Gardenr et al., 2009; You et al., 2010). Moreover, lapse rate change may affect climate model simulation results in mountain regions (Buytaert et al., 2010), especially in dry seasons (Beniston, 2003). Linear regression models of temperature and elevation were utilized to determine temperature lapse rates (Rolland, 2003; Minder et al., 2010). For example, Li et al. (2013) demonstrated that for mainland China, the temperature lapse rate exhibits a banded spatial distribution from southeast to northwest, and there are relatively large values in northwest China.

In examining the past 50 years, it is clear that temperature and precipitation exhibited a step change in the late 1980s in the arid region of northwest China (ARNC) (Chen et al., 2014). Specifically, it has been more warm and humid in the ARNC since the mid-1980s than before the mid-1980s (Shi et al., 2002; Chen et al., 2006). Previous studies have indicated that the cold indices had significant decreases, warm indices had significant increases (Wang et al., 2013b), and most precipitation extreme indices had increasing trends (Wang et al., 2013a; Jiang et al., 2013). In the ARNC, mountain regions are important sources of water, and rivers are all supplied by the melt water in mountain regions. Moreover, climate changes in mountain regions may affect the melted water characteristics (Li et al., 2012). However, previous studies have focused on the spatial and temporal change of climate in the ARNC, and little attention has been paid to climate change with elevation.

In this article, we focused on the climate change with elevation in the Kaidu River Basin in the ARNC. We conducted analyses in two aspects: (1) characterizing the variability of temperature and precipitation indices with elevation in the study area; and (2) quantifying the impact of temperature lapse rate on runoff. The paper is organized as follows: Section 2 describes the study area, data collection, and methods in this study. Section 3 focuses on climate changes with elevation in the Kaidu River Basin. The discussions are provided in Section 4, and Section 5 presents the conclusions.

2 Materials and Methods

2.1 Study area

[Insert Figure 1 about here]

The Kaidu River Basin is located in the southern slope of the Tianshan Mountains and north of Yanqi Basin, is about 4.79×10^4 km^2 in size largely defined by 41°47′-43°21′N and 82°58′-86°55′E, as shown in Fig. 1. From source of the Tianshan Mountain to the Bosten Lake, the length of Kaidu River is about 560 km. The water vapor in the Tianshan Mountain region is mainly controlled and affected by westerly flow (Liu et al., 2009). Therefore, the Kaidu River Basin is located in the southern slope of the Tianshan Mountains, which belongs to the leeward region. The Kaidu River originates from the mountain region (i.e., higher than 5,000 m above sea level) of the Tianshan Mountains. It flows into the oasis region through the Dashankou hydrological station. The river basin in the mountains is about 1.86×10^4 km^2 in size. The Kaidu River Basin includes both mountain and oasis regions. According to the variability of mean temperature, precipitation, soil, and vegetation with elevation (Table 1), the Kaidu River Basin is divided into the high mountain region (higher than 2,200 m), middle mountain region (between 1,500 m and 2,200 m), and oasis region (below 1,500 m).

[Insert Table 1 about here]

Kaidu River is one of the richest runoff rivers in the southern slope of the Tianshan Mountains. The Kaidu River Basin is an important headwater of Bosten Lake, supplying water for drinking, industrial, and agriculture use. It also has important effects on the local ecological environment and economic development. In the river basin, annual snow accumulation begins in November and ends in March (due to the daily mean temperature below 0℃ in high mountains regions during this terms). Land surface temperature rises quickly in MAM (March, April, and May), and the snow-melt water supplies the Kaidu River. In JJA (June, July, and August), snow, glacial melt, and precipitation supply the Kaidu River (Fan et al., 2013).

2.2 Data collection

We collected five meteorological stations' observation data from National Climate Center (http://ncc.cma.gov.cn). Specifically, two of the stations are located in the large area mountain region (i.e., Bayanbulak and Balguntay), and the other stations are distributed in the oasis region (Fig. 1). The Yanqi station data for the period of record begin in 1952 and end in 2010, with the timescale of daily observation data. The Bayanbulak and Balguntay station data for the period of record are from 1958 to 2010, also with timescale of daily observation data. The Heshou and Hejing station data for the period of record are between 1960 and 2010, with the timescale of monthly observation data. Daily flow data were measured at the Dashankou hydrological station in the Kaidu River Basin for the period from 1956 to 2012 (Fig. 1). Summary details of the meteorological and hydrological data for the Kaidu River Basin are provided in Table 2.

[Insert Table 2 about here]

2.3 Methods

2.3.1 Mann-Kendal trend test

The trend test is an important aspect of time series in climatic and hydrologic research. Numerous statistical tests are able to detect trends in time series data (Hamed and Ramachandra, 1998). Climatic and hydrologic time series possess some of the following characteristics: no normal data, missing values, censoring, and serial dependence. Thus, parametric statistical tests for detecting trends are commonly confounded (Hirsch and Slack, 1984). However, the Mann-Kendall trend test is a commonly used non-parametric and powerful statistical test for trend detection. Thus, it is widely used to detect long-term trends of climatic and hydrologic time series (Hirsch and Slack, 1984; Hamed and Ramachandra, 1998; Kahya and Kalaycl, 2004; Chen and Xu, 2005). The three steps of the Mann-Kendall test are as follows: 1) according to the n time series value $x_1,x_2,x_3,\cdots x_n$, calculate their relative rank r_i ($i=1,2,3,\cdots n$); 2) calculate statistic Z value, $Z=|S|/\alpha^{0.5}$; and 3) if $Z>Z_{\alpha/2}$, then the trend is significant at the level of α. A positive value of S indicates an upward trend, and a negative value indicates a downward trend.

2.3.2 Climate indices

Climate indices are calculated from acquired temperature and precipitation daily observation data. In the study area, the timescales of the Bayanbulak, Balguntay, and Yanqi are daily observation data. These stations are part of the national standard meteorological station system, whose observations time series are continuous and without missing values. Therefore, these stations are representative in each elevation band. So, we have chosen the three meteorological stations that were consistently available for the period from 1958 to 2010 (Fig. 1 and Table 1). Using these data, we calculated all of the 15 temperature and precipitation indices supported by RClimDex (1.1) (http://etccdi.pacificclimate.org/software.shtml) and Matlab (R2013a), including 10 indices (TNn, TXx, FDO, IDO, SU25, GSL, Pav, CWD, CDD, and R10) by RClimDex (1.1) and five indices (TNm, TMn, Tav, TMx, and TXm) by Matlab code. Details regarding temperature and precipitation indices (including ID, name, definitions, and units) are presented in Table 3.

[Insert Table 3 about here]

2.3.3 Temperature lapse rate

Linear regression models are utilized to analyze variability of temperature with elevation (Kattel et al., 2013; Chiu et al., 2014). There is an estimated error when the lapse rate was calculated using the estimated linear regression model. Harlow et al. (2004) used a 10 day running mean of the temperature to eliminate a possible estimated errors effect. In this research, we employed the monthly running mean of the mean temperature to exclude the possibility of an estimated errors effect.

To compute the temperature lapse rate, we chose station data of the period from 1960 to 2010. The linear regression model, shown in equation (1), was used to compute temperature lapse rates in different altitude regions:

$$T = a - tlr * \Delta H \quad (1)$$

where T is the temperature at a second location; a is the temperature at the base location, which is here the temperature of the oasis region stations; tlr is the temperature lapse rate (℃/km); and ΔH is the difference in altitude between the two locations.

Then,

$$tlr = (a - T) / \Delta H \quad (2)$$

where tlr is the temperature lapse rate (℃/km); T is the temperature at the second location; a is the temperature at the base location; and ΔH is the difference in altitude. In this study, we will utilize the temperature lapse rate at annual and monthly scales.

Pearson's correlation test (Chen et al., 2014) was employed to analyze the correlations of the runoff with temperature lapse rate and precipitation.

2.3.4 Agriculture and urbanization contributions

Climate changes are different in mountain and oasis regions. Mountain region temperature change is mostly derived from natural forcing. However, temperature change in oasis region may not accurately reveal the true nature of temperature variability, because urban and agricultural areas are concentrated in oasis regions. Therefore, agriculture and urbanization effects are computed by using the following equation (Zhou et al., 2009):

$$\Delta T_{ca} = T_o - T_m \tag{3}$$

where ΔT_{ca} is the agriculture and urbanization effects; T_o is the temperature trend in the oasis region, which is caused by natural and anthropogenic activity forcing; and T_m is the temperature trend in the mountain region and represents natural variability. Therefore, ΔT_{ca} is the temperature variability due to anthropogenic activity forcing. Then, agriculture and urbanization are calculated by the following equation:

$$\beta = \Delta T_{ca} / |T_o| \tag{4}$$

where β is the contribution of agriculture and urbanization; $|T_o|$ is absolute value of T_o. When (1) $\beta>0$, then the contribution of agriculture and urbanization is positive; (2) $\beta=0$ indicates that the contribution of agriculture and urbanization is insignificant; and (3) $\beta<0$ shows that the contribution of agriculture and urbanization is negative.

3 Results

3.1 Climatic indices

3.1.1 Temperature indices

The trend analysis indicated that the mean air temperature (Tav) in the Kaidu River Basin increased in the past 53 years. In the upward directions, Tav had statistically significant positive trends in the oasis region and middle mountain region, and was significant at $p<0.01$, with rates of 0.037 and 0.036℃/a, respectively. In the high mountain region an increasing trend was observed for Tav; however, it was only significant at the 0.05 level, and the rate was 0.023℃/a.

[Insert Figure 2 about here]

Figure 2 clearly shows the variability of the daily temperature indices in these three sub-regions. In the oasis region, among the daily temperature indices (Min Tmin, Mean Tmin, Min Tmean, Mean Tmean, Max Tmean, Mean Tmax, and Max Tmax), the increasing rate of Min Tmin (4.2℃/50a) was the strongest, followed by those of Mean Tmin (2.53℃/50a), Min Tmean (3.51℃/50a), Mean Tmean (1.82℃/50a), Max Tmean (1.29℃/50a), Mean Tmax (0.79℃/50a), and Max Tmax (0.59℃/50a). In the middle mountain region, among the daily temperature indices, the increasing rate of Mean Tmin (3.61℃/50a) was the strongest, and only the Max Tmax variability rate of -0.54℃/50a became a decreasing trend. In the high mountain region, the increasing rate of Min Tmin (1.56℃/50a) was the strongest, and the variability rate of Max Tmax (-0.33℃/50a) was the lowest.

[Insert Figure 3 about here]

The summer and winter variability rates of the temperature indices are shown in Fig. 3. In summer, only the variability rate of Max Tmax (-0.54℃/50a) in the middle mountain region showed a decreasing trend, and the other temperature indices showed increasing trends. The increasing rate of Mean Tmin (3.71℃/50a) in the middle mountain region was the largest (Fig. 3A). Moreover, the variability rate of the temperature indices in winter exhibited increasing trends (except the Max Tmax decreasing trend in the oasis region); whereas, the increasing rate of Min Tmin (4.2℃/50a, in the oasis region) was larger than the other regions (Fig. 3B).

The variability rate of low temperature indices (Min Tmin, Mean Tmin, and Min Tmean) had a stronger trend than high temperature indices (Max Tmean, Mean Tmax, and Max Tmax) in the Kaidu River Basin (Fig.2 and 3). At the same time, it can be seen that the range of variability of temperature indices in the high mountain region showed relative stability, and were less than the variability range of temperature indices in the middle mountain region and oasis region.

Table 4 presents the trend analysis results of frost days (FDO), ice days (IDO), and summer days (SU25) in the Kaidu River Basin. The frost days had significant decreasing trends in all three sub-regions (i.e., oasis region, middle mountain region, and high mountain region), with rates of -0.38 day/a, -0.59 day/a, and -0.37 day/a, respectively. The trend of ice days for the three sub-regions was not significant at the 0.05 level. Summer days had positive trends in the oasis region (at the level of 0.01) and middle mountain region (at the level of 0.05). However, the trend of summer days for the high mountain region was not significant at the level of 0.05, and this may be related to a characteristic of high mountain region (i.e., in these regions, which are above 2200 m, days in which the daily maximum temperature is greater than 25℃are relatively rare).

[Insert Table 4 about here]

[Insert Figure 4 about here]

Analysis results show that frost days had a significant decreasing trend, and summer days had a significant increasing trend in the Kaidu River Basin during the past 50 years, indicating that the accumulated temperature (the sum of mean temperature >=10℃) for cultivation increased in the local area. Consequently, the changes of accumulated temperature for cultivation would affect the length of growing seasons. Figure 4 reveals positive increasing trends of growing season length (GSL) in the high mountain region, the middle mountain region, and the oasis region. After the late 1980s, the GSL had significant increasing tends in the middle mountain region and oasis region (Fig. 4). Although longer GSLs will increase crop areas and yield in the local region, it will also tend to strain the water resource supply.

3.1.2 Precipitation indices

In the Kaidu River Basin, most precipitation is concentrated from May to September, with high air temperature occurring during this period. To analyze seasonally variability, annual precipitation was calculated for the past 50 years, as shown in Fig. 5A-C. Figure 5 shows that JJA (from June to August) precipitation accounts for approximately 66% of the annual precipitation in the three sub-regions (i.e., oasis region, middle mountain region, and high mountain region). In spring time, the proportion of MAM (from March to May) precipitation exhibited an increasing trend from 1958 to 2010 in the oasis region, while it showed decreasing trends in the mountain region. In summer, the proportion of JJA precipitation in the annual precipitation had a decreasing trend in the oasis region, and had an increasing trend in the middle mountain region; however, the change trend of the proportion of JJA precipitation is not obvious. In autumn, the proportion of SON (from September to November) precipitation in the annual precipitation was approximately 14%. It exhibited increasing trends in the oasis and high mountain regions, and had a decreasing trend in the middle mountain region.

[Insert Figure 5 about here]

In the oasis region, the rise of precipitation in MAM and SON are major contributors to the rise of annual precipitation during the past 50 years (Fig. 5A). The annual precipitation reveals that the significant increase of the middle mountain region was caused by the significant increase of precipitation in JJA (Fig. 5B). In the mountain region, however, the increase of precipitation in SON and JFD contributed most to the increase of annual precipitation (Fig. 5C).

Based on these results, it can be concluded that the wet trend began in the mid-1980s in the Kaidu River Basin. However, precipitation showed similar negative anomalies after the 2000s in the middle mountain region (Fig. 5B) and the oasis region (Fig. 5A); whereas, a positive anomaly appeared in the high mountain region (Fig. 5C).

[Insert Figure 6 about here]

Precipitation exhibited an increasing trend (about 6.6 mm/10a) in the Kaidu River Basin during the past 50 years. The R10 and CWD had increasing trends, with rates of 0.16 day/10a and 0.07 day/10a, respectively. Figure 6 shows correlations between annual precipitation and R10 and CWD over the period of 1958 to 2010. It indicated that there are significant linear correlations between annual precipitation and R10 (R^2=0.67, P<0.01) and CWD (R^2=0.27, p<0.01). The R10 and CWD are extreme precipitation indices, and the R10 is an intensity indices and CWD is a consecutive indices. At the same time, the climate extremes are closely related to the climate average state during the past 50 years in the arid region of the northwest China. Meanwhile, the relationship with R10 is stronger and CWD is weaker. This may be due to that the R10 had a relatively strong increasing trend (i.e., 0.16 day/10a) higher than CWD (i.e., 0.07 day/10a) during the past 50 years. The significant linear correlation indicates that there is adequate evidence to conclude that the R10 and CWD were major factors in the rise of precipitation during the past 50 years in the Kaidu River Basin.

3.2 Temperature lapse rate

Figure 7A presents the annual mean temperature lapse rate for our observation station data. The annual mean temperature lapse rate (tlr) is -8.6 ℃/km, indicating that the mean temperature lapse rate of the Kaidu River Basin is steeper than the free-air moist adiabatic lapse rate (about -6.5 ℃/km) and closer to the dry adiabatic lapse rate (-9.8 ℃/km). From figure 7b, it can be seen that the largest monthly mean temperature lapse rate occurs in February, and the smallest monthly mean temperature lapse rate occurs in October. The seasonal variability of the mean temperature lapse rate decreased in summer and then increased in winter. Therefore, the winter half-year mean temperature lapse rate was steeper than the summer half-year.

[Insert Figure 7 about here]

The year-to-year variability is then examined by analyzing the distribution of the monthly mean temperature lapse rate calculated from the observation station data from 1958 to 2010. Specifically, the median, inner-quartile range (IQR), full range and extremes of monthly mean temperature lapse rate are identified, as shown in Fig. 7B. The IQR is equal to the difference between the upper and lower quartiles (IQR=Q3-Q1); the IQR shows the mean temperature lapse rate typical variations, which varies from 0.436 ℃/km (Jul) to 3.427℃/km (Dec). The full range of monthly mean temperature lapse rate is smallest in summer (Jun-Aug) and largest in winter (Dec-Feb) (Fig. 7B). In addition, year-to-year variability of the monthly mean temperature lapse rate in some years was even steeper than -10℃/km (steeper than the dry adiabatic lapse rate) in

Jan-Mar. These differences may be affected by local climatic features, such as the seasonal cycle of snow cover in mountain regions, cold air masses from Siberia-Mongolia, and local circulation.

3.3 Runoff analysis

Figure 8A shows the change characteristics of runoff for yearly and seasonal scales in the Kaidu River Basin. Results from this figure indicate that the runoff in summer (JJA) was the largest and was greater than other seasons (i.e., MAM, SON, and JFD). At the same time, the runoff had a significant increasing trend in the mid-1980s to 2000; however, this trend did not continue on or after the year 2000. Figure 8B shows year-to-year variability in monthly mean runoff from 1956 to 2012 of the Kaidu River Basin. From this figure, we can see that the variability of monthly mean runoff was larger during the summer months (Jun, Jul, and Aug) than the winter months (Dec, Jan, and Feb). These differences may indicate that the main sources of runoff are base-flow in the winter, and glacier meltwater and precipitation in the summer (Fan et al., 2013). Moreover, the inter-annual variability of base-flow is less than the precipitation.

[Insert Figure 8 about here]

Figure 9 shows comparisons between the change of runoff and change of temperature lapse rates and precipitation. Results from the comparison analysis indicated that for the change of runoff, temperature lapse rates play an important role in the Kaidu River Basin (Fig. 9A). It is clearly seen that the runoff will have a lower flow period during steeper temperature lapse rate value periods (i.e., in the 1970-2000 year) during the past 50 years, and vice versa. The reason of reverse changes in the 1970-2000 is the steeper temperature lapse rates will lead to lower air temperature in the higher mountain region, which decreases the runoff. Figure 9B shows that the relationship between runoff and precipitation is positively correlated over the past 50 years, and the correlation coefficient values (Table 5) indicated that the runoff has a significant positive correlation with precipitation in MAN (R^2=0.28, p<0.05) and in JJA (R^2=0.75, P<0.01). From Table 5, it can be seen that temperature lapse rates are a dominant factor affecting the runoff in MAM and SON, and precipitation is the major factor for the runoff in the summer; whereas, in winter, the temperature lapse rates and precipitation contribution were much less. Identifying these relationships will help us to elucidate how temperature lapse rates and precipitation changes could affect runoff in the Kaidu River Basin.

[Insert Figure 9 about here]

[Insert Table 5 about here]

4 Discussion

In this paper, detailed analyses are performed regarding the variability of climatic indices with elevation in the Kaidu River Basin during the past 50 years.

The results showed that the low temperature indices change at a greater rate than the high temperature indices. This may be due to that the large scale atmospheric circulation (i.e., wind field, Siberian High index) (Li et al., 2012; You et al., 2011) and human activity (Fig.10) lead to cold extremes decreased faster (Wang et al., 2013c). At the same time, the oasis region temperature has been rising faster than that in the mountain region. This may be due to that human activity (i.e., cities and agricultural activity) is concentrated in the oasis region. For instance, from 1990 to 2010, the agricultural land area increased from 2269.19 km^2 to 3804.34 km^2, an increase of 67.6%; while residential and industrial land grew from 208.64 km^2 to 306.76 km^2, an increase of 47% (Wang et al., 2014). The cities and agricultural activities for the Tmean, Tmin and Tmax of the oasis region (Fig.10) exhibited increases of 0.029 ℃/10a, 0.08 ℃/10a and 0.064 ℃/10a, respectively. So, the cities and agricultural contribution to the Tmean increase is 8.8%, to the Tmin increase is 15.7%, and to the Tmax increase is 22.9%. Human activities (i.e., agriculture, residential, and industrial) on a large scale tend to produce aerosols and greenhouse gases, with consequent strong effects on temperature change (Mahlstein and Knutti, 2010). Thus, the extension of cities and agriculture areas will contribute to the temperature increases in the oasis region during the past score years. Therefore, the impact of human factors on natural factors results in the air temperature showing significantly increasing trends in the oasis region (Chen et al., 2013; Tao et al., 2011; Xu et al., 2008).

[Insert Figure 10 about here]

Topographical effects are important factors in the variations of temperature indices with elevation. One possible reason for this may be due to the large area glaciers and seasonal snow cover in the high mountain region. Seasonal glaciers and snow melt will lead to increases in high mountain region soil moisture, which will cause temperature changes to exhibit relative stability in the high mountain region.

In addition, topography and snow cover are the main factors affecting the variability of the temperature lapse rate in the Kaidu River Basin. Some researchers have recognized that temperature lapse rate variability may be influenced by local climate features (Minder et al., 2010; Kattel et al., 2013; Chiu et al., 2014), such as the seasonal cycle of snow cover in mountain regions, cold air masses, and local circulation. The results of the present study indicated that the temperature lapse rate (i.e., -8.6℃/km) is steeper than -6.5℃/km (free-air moist adiabatic lapse rate); in some months (Jan, Feb, and Mar), it is even steeper than -10℃/km. This may be due to that the Kaidu River Basin is located in the southern slope of the Tianshan Mountains, which belongs to the leeward side region. So, the dry air in the leeward side region during these months (Jan, Feb, and Mar), and the air-upward process with elevation is similar to the dry-adiabatic process. On the other hand, the high mountain region has a larger area snow and glaciers cover, which exerts a cooling effect due to the albedo increase (Groisman et al., 1994). At the same time, the low altitude region (i.e., the oasis region) is located in the Yanqi Basin with terrain occlusion, resulting in obstruction of cold air in winter.

In mountainous regions, the temperature lapse rate is a sensitive factor that affects snowmelt runoff (Jain et al., 2010; Minder et al., 2010). The Kaidu River runoff is an important water resource in the local area. The Kaidu River sources of replenishment of runoff are melt water (snow and glacial) and precipitation (Fan et al., 2013). And different runoff formats affected by climate factors are different in the Kaidu River

Basin. Fan et al., (2013) suggest that precipitation processes have impact on quick flow, and temperature processes on baseflow. Meanwhile, the solid precipitation (i.e., snow) present in the winter half-years will supply the river runoff and underground water when the air temperature rises in the late-spring and summer months. The results of the analysis also revealed that the effects of temperature lapse rates on runoff are complex in the Kaidu River Basin, which may be due to the complex correlations between temperature lapse rate and snow melt water and precipitation. For example, in the MAM, the runoff had a significant positive correlation with temperature lapse rates. This may be due to the rise of spring temperature, which makes the runoff increase with the snow melt water increase in the mountain regions. Nevertheless, there was a significant negative correlation between runoff and temperature lapse rates in the SON. This is due to that the precipitation in the annual precipitation was approximately 14% (Fig. 8a) in autumn; thus, glacier and snow melt water are major sources of the river runoff. Therefore, the temperature lapse rate is an important factor in the runoff change during autumn. Specifically, this is because the troposphere of direct heat sources comes from near surface long-wave radiation. So, steeper temperature lapse rates will lead to lower air temperature in the higher mountain region, which decreases the runoff; conversely, shallower temperature lapse rates will cause higher air temperature in the higher mountain region, which increases the runoff. Thus, when the mountain region warns (cools), the glacier and snow melt water will correspondingly increase (decrease). Therefore, the temperature lapse rates determine the runoff by strongly influencing the snow and glacier melt in the mountain regions.

The present study has largely focused on analyzing how temperature lapse rates affect runoff variability. This research contains one limitation in that how well each station represents its entire elevation band cannot be ascertained due to the use of only one station in each band. However, this work makes a unique contribution to the literature, in that it utilized empirical equations based on data from five stations to calculate temperature lapse rates. On the one hand, based on the previous literature, lapse rate and runoff are not sufficient to interpret the relationship between climate extremes. On the other hand, there are a series of factors, i.e., temperature, topographic features and local circulation patterns, which have affected temperature lapse rate variability. Therefore, identifying the influence of these factors on temperature lapse rate variability will constitute an important aspect of our next research.

5 Conclusions

In this study, the variability of temperature and precipitation indices with elevation were analyzed in the Kaidu River Basin based on daily observation data during the past 50 years. From the results, we conclude that runoff characteristics are affected by temperature lapse rate changes in the Kaidu River Basin.

During the past 50 years, the air temperature had significant positive trends in the study area; moreover, the increasing rate of temperature in the oasis region was higher than the mountain region. At the same time, we discovered that the rising rate of low temperature indices was larger than the high temperature indices. With the daily minimum temperature increasing, the growing season length exhibited a significant increasing trend after the late 1980s. There are also differences of seasonal variability for precipitation in these three sub-regions. It was found that heavy precipitation days (R10) and maximum consecutive wet days (CWD) contributed most to the increasing precipitation.

Snow and glacier melt are important water source supplies of runoff for mountain regions, and changes in temperature lapse rates have significant effects on runoff characteristics. Therefore, the temperature lapse rate should be viewed as critical factor when forecasting and simulating the runoff change of mountain regions in the future.

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Tables:

Table 1 Vertical region in the southern slope of the Tianshan Mountain (Zhou and Chen, 1998).

Region	Elevation(m)	Daily average temperature ≥ 5℃ days (day)	Precipitation (mm)	Soil	Vegetation
Oasis	<1500	>210	<100	brown desert soil	desert shrub
Middle Mountain	1500-2200	210-150	150-300	brown desert soil brown calcic soil	semi-desert and desert grassland
High Mountain	2200-3100	150-70	no data	chestnut soil subalpine meadow soil	Alpine grassland
	3100-3600	70-40	no data	alpine meadow soil	alpine meadow
	>3600	<40	no data	primitive soil bare ice	cushion sparse vegetation

Table 2. List of selected stations, including three meteorological stations and one hydrological station

Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Period of record	Timescales	Annotation
Balguntay	42.73	86.3	1753	1958-2010	daily	Meteorological station
Bayanbulak	43.03	84.15	2458	1958-2010	daily	Meteorological station
Yanqi	42.08	86.57	1056	1952-2010	daily	Meteorological station
Heshou	42.25	86.8	1082	1960-2010	monthly	Meteorological station
Hejing	42.32	86.4	1067	1960-2010	monthly	Meteorological station
Dashankou	42.22	85.73	1340	1956-2010	daily	Hydrological station

Table 3. Temperature and precipitation indices

ID	Name	Definitions	Units
	Temperature indices		
TNn	Min Tmin	Monthly minimum value of daily minimum temperature	℃
TNm	Mean Tmin	Monthly mean value of daily minimum temperature	℃
TMn	Min Tmean	Monthly minimum value of daily mean temperature	℃
Tav	Mean Tmean	Monthly average value of daily mean temperature	℃
TMx	Max Tmean	Monthly maximum value of daily mean temperature	℃
TXm	Mean Tmax	Monthly mean value of daily maximum temperature	℃
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	℃
FDO	Frost days	Annual count when daily minimum temperature <0℃	days
IDO	Ice days	Annual count when daily maximum temperature<0℃	days
SU25	Summer days	Annual count when daily maximum temperature >25℃	days
GSL	Growing season Length	Annual (1^{st} Jan to 31^{st} Dec in NH, 1^{st} July to 30^{th} June in SH) count between the first span of at least 6 days with TG>5ºC and the first span after July 1 (January 1 in SH) of 6 days with TG<5ºC	days
	Precipitation indices		
Pav	Precipitation total	Annual total PRCP on wet days (RR>=1mm)	mm
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	days
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	days

Table 4. Trend analysis results of annual temperature indices (FDO, IDO, and SU25) in the Kaidu River Basin. Mean ± SE (day/a) are the mean of temperature indices ± standard error (SE). Trend rate (day/a) was used to calculate the slopes of temperature indices in the past 53 years. A Mann-Kendal test (Z) was used to detect the trends of temperature indices.

Regions	Indices	Mean ± SE	Trend rate	Z value	Significance
	FDO	162±9.26	-0.38	-5.37	***
Oasis	IDO	54±11.48	-0.028	0.19	-
	SU25	127±8.62	0.22	2.91	***
Middle	FDO	164±13.54	-0.59	-4.68	***
Mountain	IDO	42±11.71	-0.15	-1.4	-
	SU25	66±10.21	0.23	2.37	**
High	FDO	260±9.36	-0.37	-4.61	***
Mountain	IDO	139±14.05	-0.22	-1.7	*
	SU25	1.1±1.35	0.01	0.87	-

"*" $p<0.1$; "**" $p<0.05$; "***" $p<0.01$

Table 5. The Pearson's correlation coefficient shows the season runoff, temperature lapse rate, and mountain precipitation in the Kaidu River Basin. MAM are the months of March to May, JJA are the months of June to August, SON are the months of September to November, and DJF are the months of December to February of the following year.

	MAM		JJA		SON		DJF	
	TLR	Precipitation	TLR	Precipitation	TLR	Precipitation	TLR	Precipitation
Runoff	0.28*	0.29*	0.09	0.75**	-0.37**	0.21	0.04	0.19

"*"is $p<0.05$; "**"is $p<0.01$

Figure Captions:

Figure 1. Study area and the meteorological and hydrological stations

Figure 2. Variability of daily temperature indices in the Kaidu River Basin. The black straight line (the reference line) indicates increases over this line and decreases under this line (from 1958 to 2010).

Figure 3. Variability of seasonal daily temperature indices in the Kaidu River Basin, A: summer daily temperature indices, B: winter daily temperature indices. The black straight line (the reference line) indicates increases over this line and decreases under this line (from 1958 to 2010).

Figure 4. The trends of Growing Season Length (GSL) in the high mountain region (A), middle mountain region (B), and oasis region (C) (from 1960 to 2010).

Figure 5. The percentage analysis of seasonal precipitation of three sub-regions (A, oasis region; B, middle mountain region; C, high mountain region) in the Kaidu River Basin, MAM (from Match to May), JJA (from June to August), SON (from September to November), and JFD (January, February, and December in the same year). From top to bottom: results for Annual, MAM, JJA, SON, and JFD. From left to right: results for the oasis region, middle mountain region, and high mountain region.

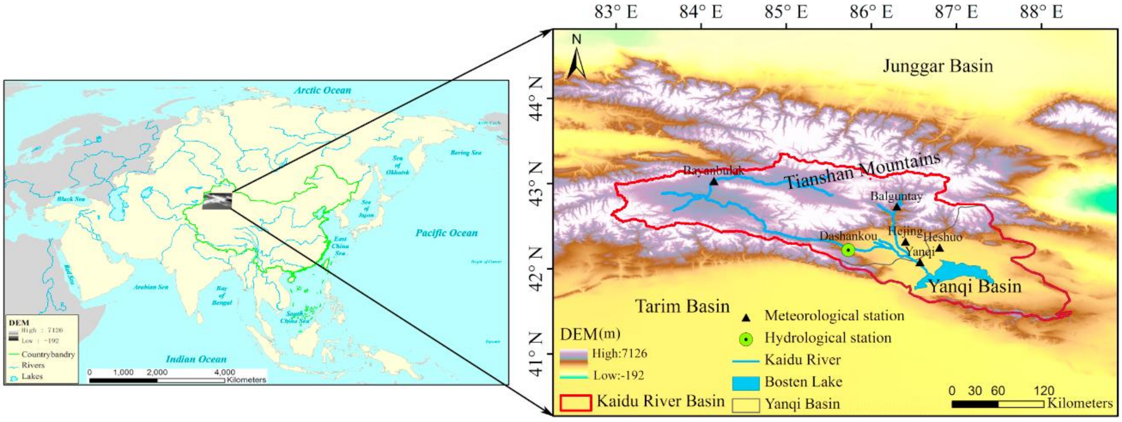
Figure 6. The correlations of the annual precipitation with R10 and CWD from 1958 to 2010 in the Kaidu River Basin. R10 is the annual number of days when PRCP>=10mm; CWD is the maximum number of consecutive days with RR>=1mm.

Figure 7. The analysis results of mean temperature lapse rate in the Kaidu River Basin during the past 50 years: A is mean temperature lapse rate for observation stations data in the Kaidu River Basin during 1960-2010, and the solid line is the linear fit for all data; B is year-to-year variability in monthly-mean lapse rates, thick horizontal lines show the month's median lapse rate calculated using the observation station data in the Kaidu River Basin from 1958 to 2010, boxes show the inner-quartile range, the whiskers show the full range of the data, and red plus sign shows the extreme values.

Figure 8. The trend analysis of runoff in the Kaidu River Basin, A: the trends of annual and season runoff change in the Kaidu River Basin, MAM, JJA, SON, and JFD (January, February, and December in the same year); B: year-to-year variability in monthly mean runoff in the Kaidu River Basin during 1956-2012.

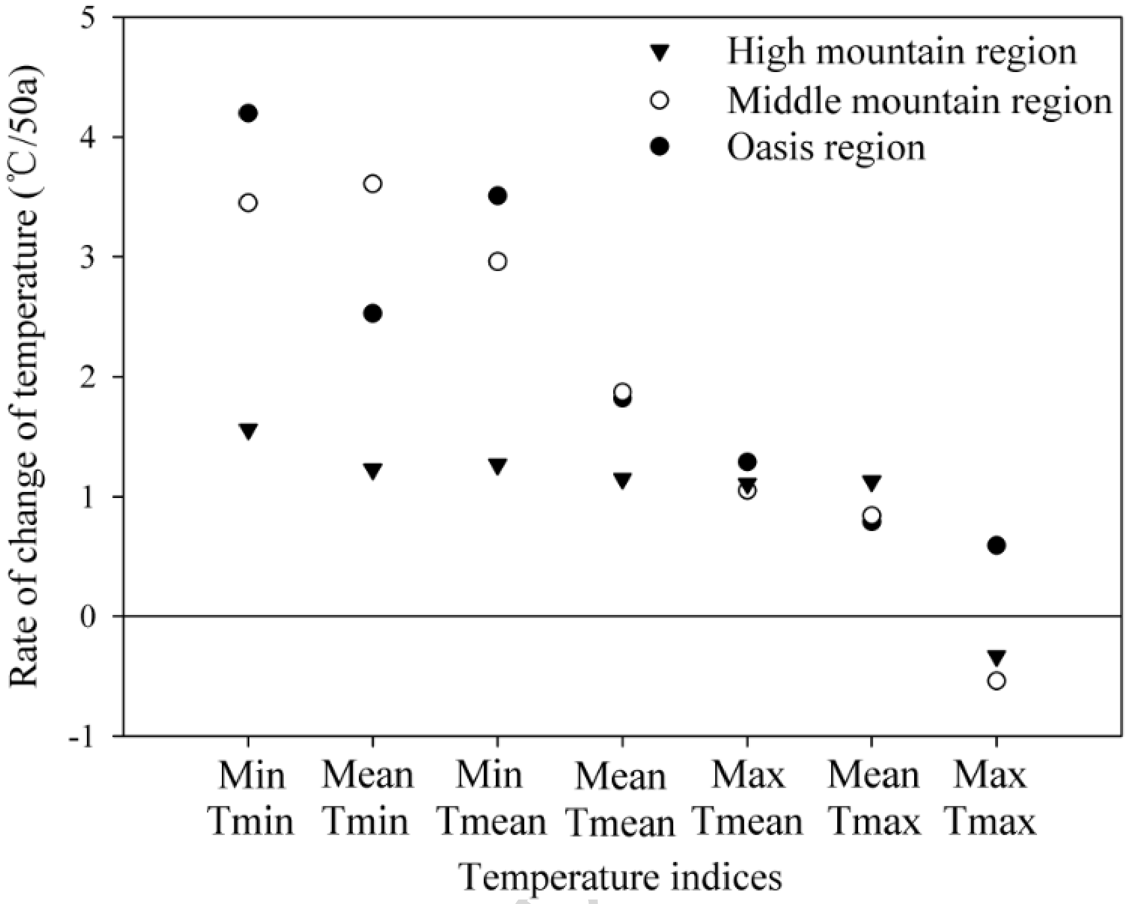
Figure 9. The comparison of the runoff with temperature lapse rates and annual precipitation in the Kaidu River Basin. The red line is runoff; the black lines are temperature lapse rates (A) and precipitation (B).

Figure 10. The cities and agricultural effects for the temperature change (A), and the city and agricultural contributions for the temperature change (B). The analysis results of city and agricultural effects and contributions are based on the equations in Section 2.3.4.



Arctic Ocean
Pacific Ocean
Indian Ocean
83° E
84° E
85° E
86° E
87° E
88° E
44° N
43° N
42° N
41° N
N
Junggar Basin
Tianshan Mountains
Bayanbulak
Balguntay
Dashankou
Hejing
Heshuo
Yanqi
Yanqi Basin
Tarim Basin
DEM(m)
High:7126
Low:-192
Meteorological station
Hydrological station
Kaidu River
Bosten Lake
Kaidu River Basin
Yanqi Basin
0 30 60 120
Kilometers

Fig. 1



768

769 Fig. 2

770

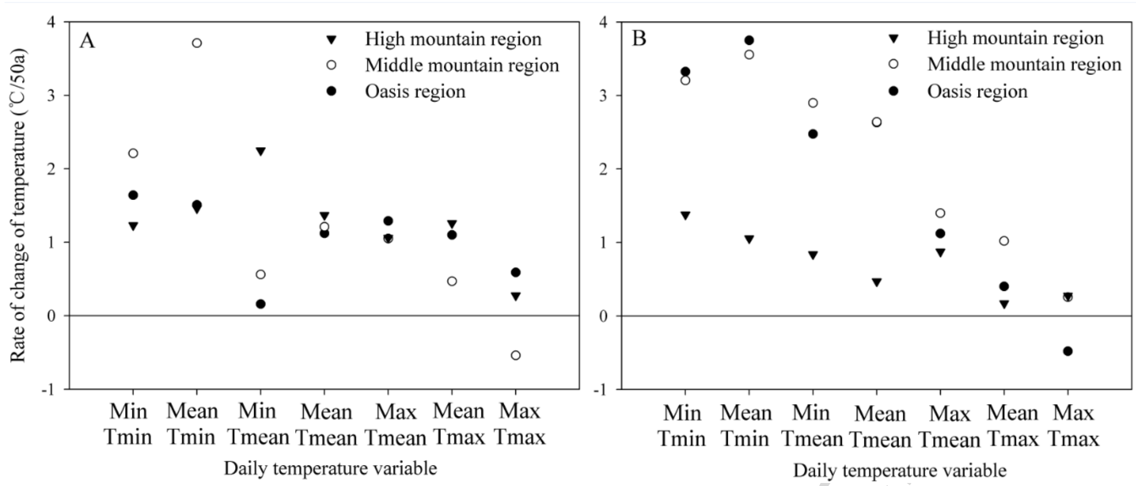
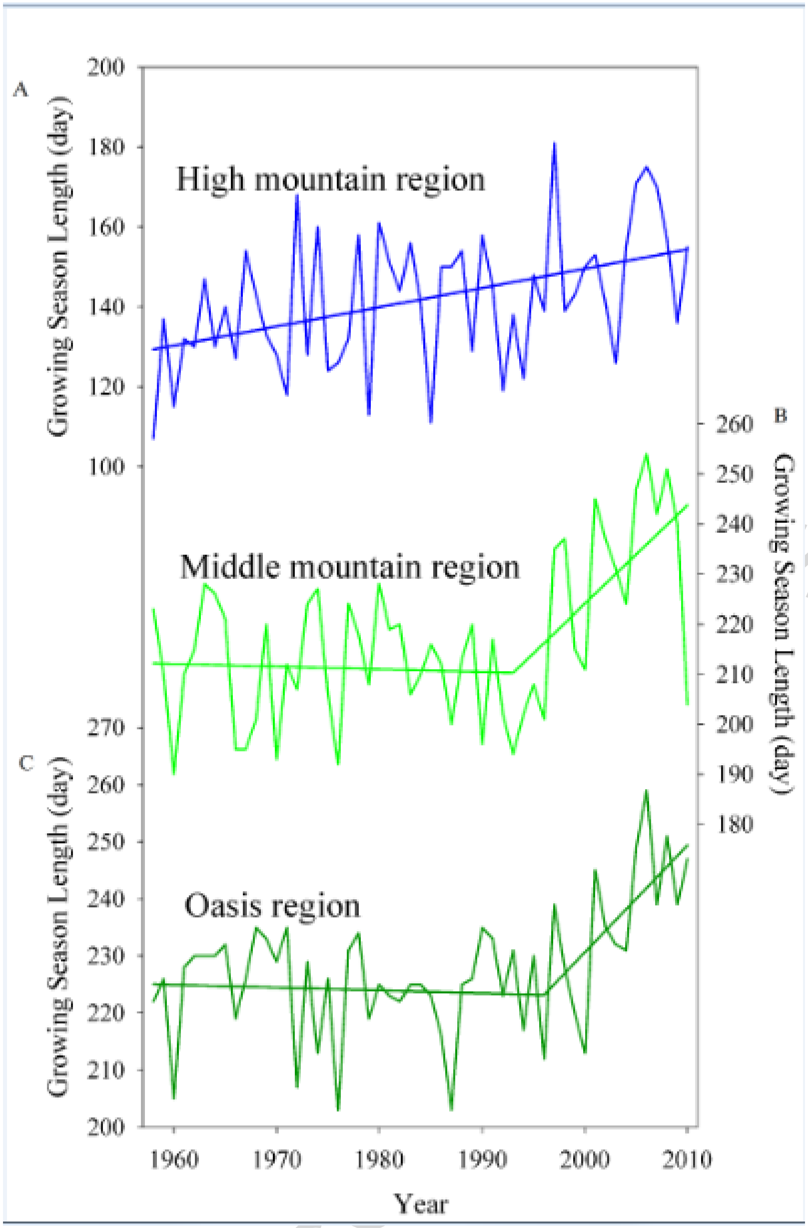

A
B
High mountain region
Middle mountain region
Oasis region
Rate of change of temperature (℃/50a)
Min Tmin
Mean Tmin
Min Tmean
Mean Tmean
Max Tmean
Mean Tmax
Max Tmax
Daily temperature variable
4
3
2
1
0
-1

Fig. 3



774

775 Fig. 4

776

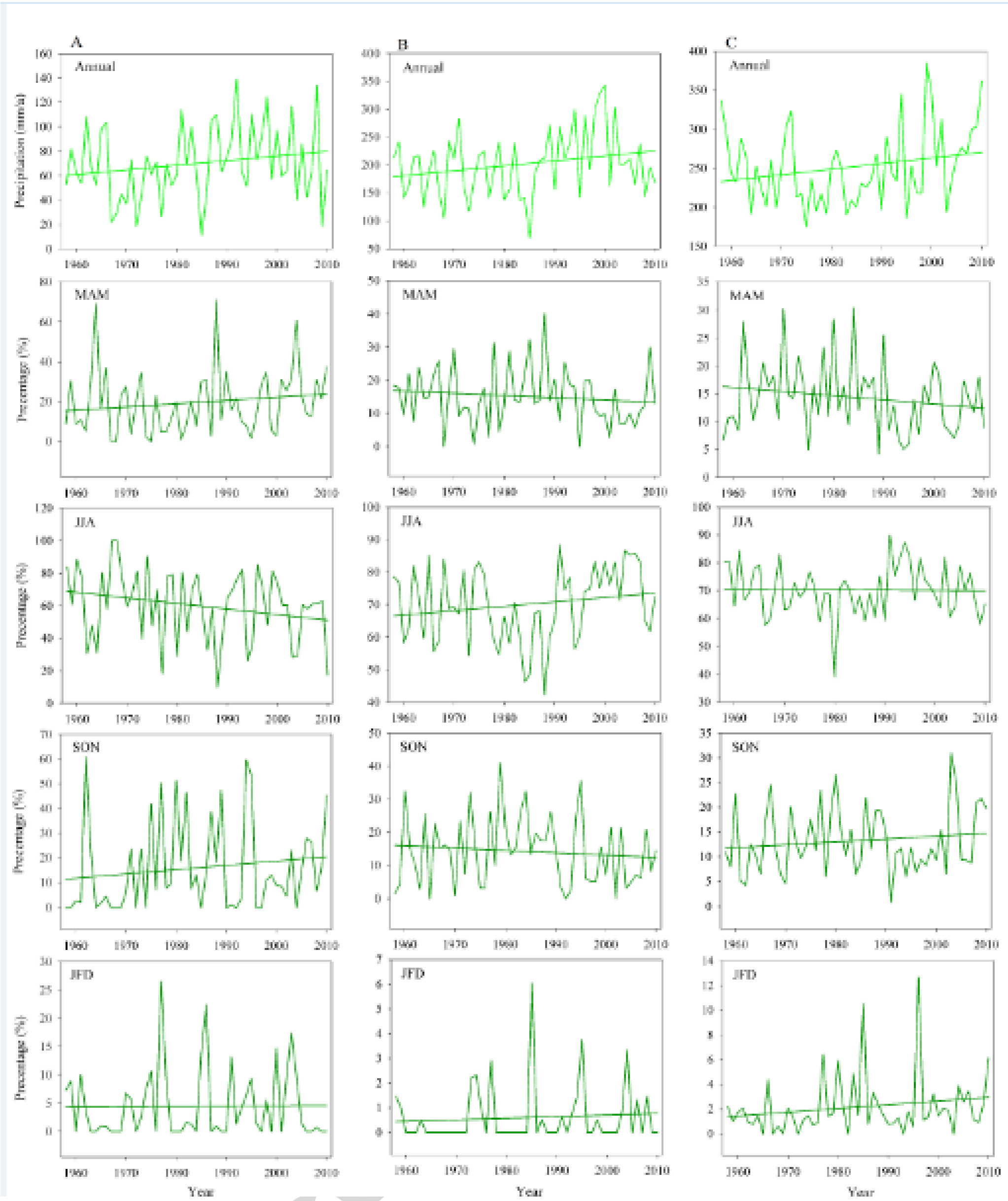
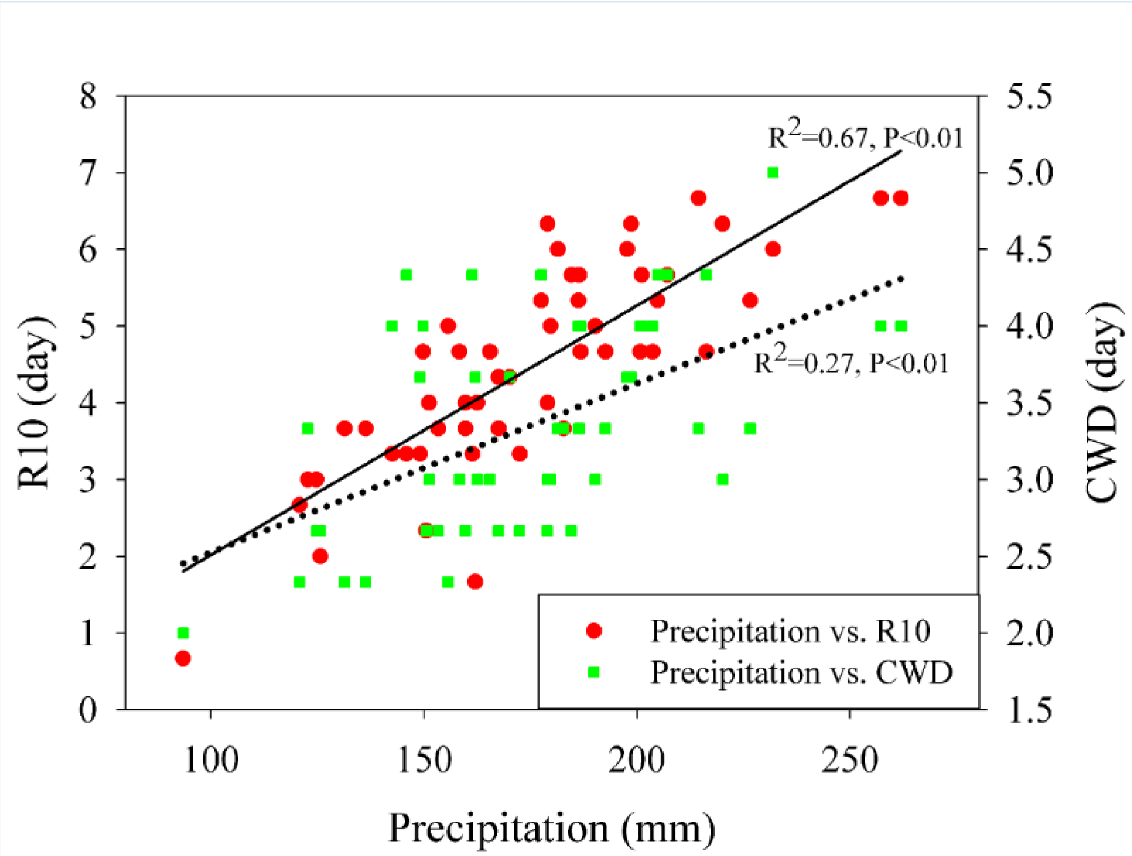
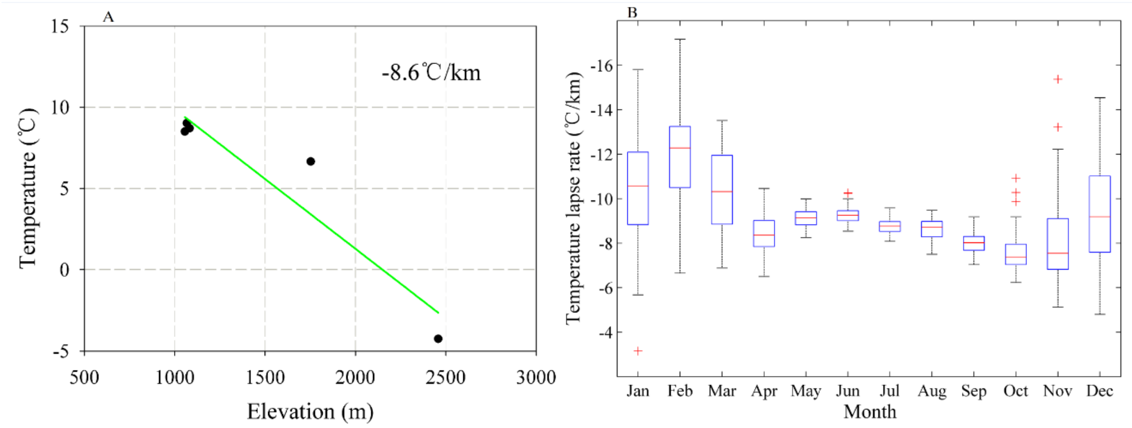

A
B
C
Annual
MAM
JJA
SON
JFD
Precipitation (mm/a)
Precentage (%)
Year

Fig. 5



R10 (day)
CWD (day)
Precipitation (mm)
R^2=0.67, P<0.01
R^2=0.27, P<0.01
Precipitation vs. R10
Precipitation vs. CWD
0
1
2
3
4
5
6
7
8
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
100
150
200
250

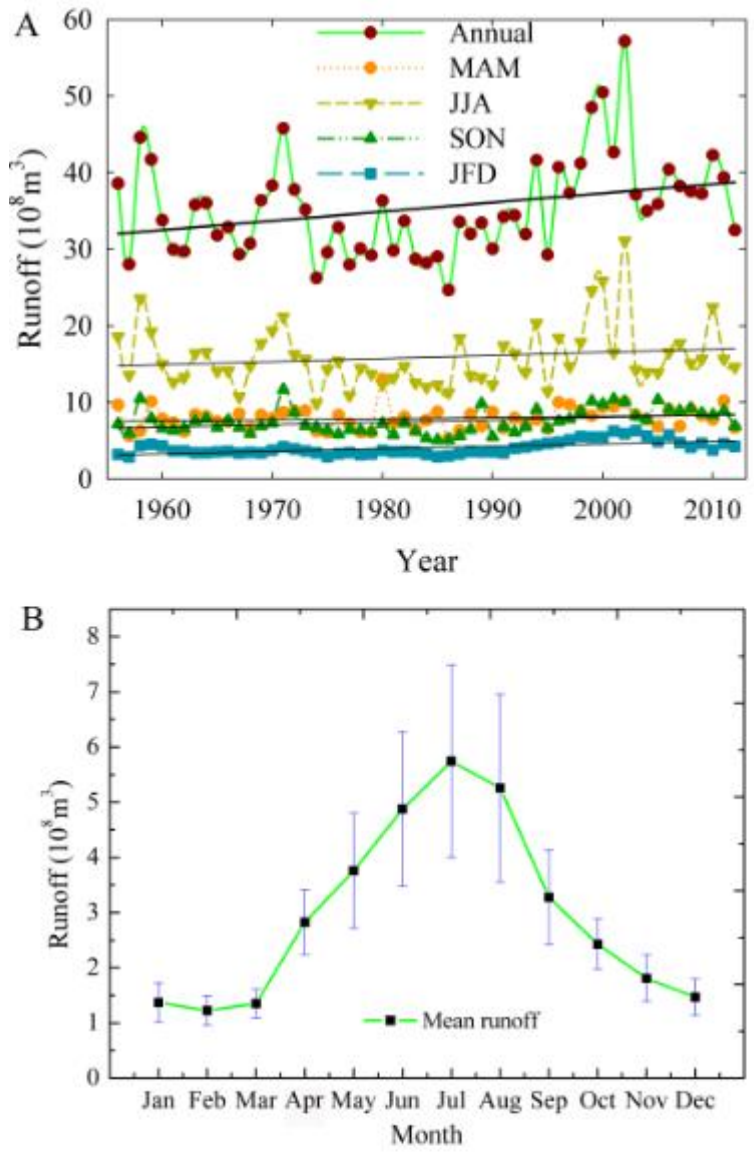
Fig. 6



783

784 Fig. 7

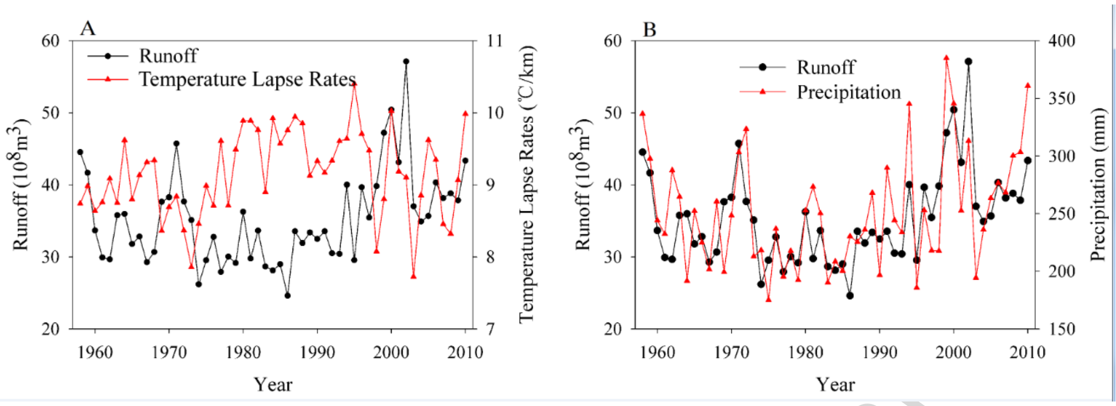
785



786

787 Fig. 8

788

789 

790 Fig. 9

791

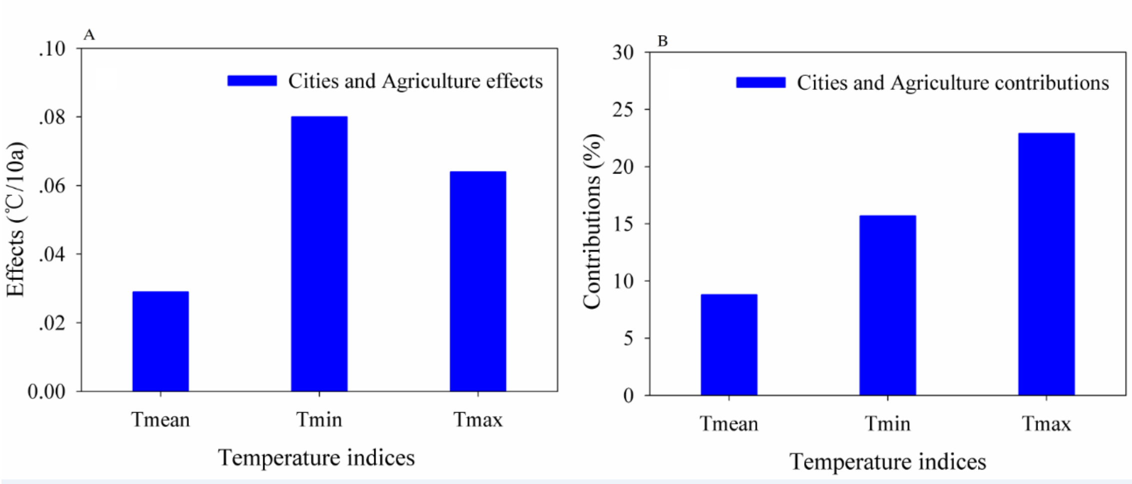

A
.10
.08
.06
.04
.02
0.00
Effects (°C/10a)
Cities and Agriculture effects
Tmean
Tmin
Tmax
Temperature indices
B
30
25
20
15
10
5
0
Contributions (%)
Cities and Agriculture contributions
Tmean
Tmin
Tmax
Temperature indices

Fig. 10

Highlights:

- We discovered that temperature lapse rates have significant effects on runoff.
- Rising rate of low temperature indices was larger than high temperature indices.
- Increasing rate of temperature in the oasis region was higher than mountain region.
- It was found that R10 and CWD contributed most to the increasing precipitation.