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ORIGINAL PAPER

Trend analysis of temperature and precipitation in the Syr Darya Basin in Central Asia

Junqiang Yao · Yaning Chen

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Abstract By investigating temperature and precipitation data from eight meteorological stations in the Syr Darya Basin (SDB) during 1881–2011 and 1891–2011, we analyzed trends using the Mann-Kendall (MK) test. Our results indicated that there was a notable increasing trend in annual temperature of 0.14 °C/decade ($P<0.05$) and step change points in 1989 ($P<0.05$). Similarly, annual precipitation showed a significant rising trend ($P<0.001$) at a rate of 4.44 mm/decade and step change points in 1991 ($P<0.05$). Overall, temperature and precipitation increases were more rapid in the plains than in the mountain areas. Furthermore, we found that temperature in the SDB region is strongly associated with the Asian Polar Vortex Area Index (APVAI, correlation coefficient: $R=-0.701$, $P<0.01$) rather than with carbon dioxide emissions, especially in the plains area. For precipitation, the correlation coefficient is strongly associated with the Tibet Plateau Index (TPI, $R=0.490$, $P<0.01$), followed by the Antarctic Oscillation Index (AAOI, $R=0.343$, $P<0.01$), and the correlations in the plains are higher than those in the mountains. It is anticipated that the results of this study will further the understanding surrounding climate change in the SDB.

J. Yao
College of Resources and Environment, Xinjiang University, Urumqi 830046, China

J. Yao
Key Laboratory of Oasis Ecology of Ministry of Education, Xinjiang University, 14, Shengli Road, Urumqi 830046, China

Y. Chen (✉)
State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, CAS, 818, Beijing Nanlu, Urumqi 830011, China
e-mail: chenyn@ms.xjb.ac.cn

1 Introduction

Under global warming, climate change is significantly impacting the environment, water resources, industrial production, agricultural activities, and human lives (Shi and Xu 2008), but the effects are particularly intense in arid regions such as Central Asia (Siegfried et al. 2012). While scientific observations and research have pointed to worldwide increases in average air temperature (IPCC 2007), meteorological observations confirm that surface temperatures rose in Central Asia by 0.65 °C between the two 30-year climate reference periods of 1942–1972 and 1973–2003 (FOEN 2009). Concurrently, much of Central Asia experienced increasing precipitation levels (FOEN 2009). The results of Chen et al. (2011) showed that annual precipitation variations in the arid region of Central Asia showed a general rising trend from 1930 to 2009. From the Climatic Research Unit (CRU) database, we can also see a rising trend (0.7 mm/10 a) in winter, along with marked regional differences. Based on the ERA-40 reanalysis data in the larger Tian Shan region of Central Asia, Bothe et al. (2012) described moisture levels as being primarily due to the midlatitude westerlies, with contributions from higher latitudes. Hence, monthly interannual precipitation variability relates to the variability of hemispheric circulation patterns.

The arid area in Central Asia covers mostly desert and gravel plains, and few of the drainage basins are located in areas hosting population and socioeconomic activities. The Syr Darya River is one of the two major international rivers in the region. Savoskul et al. (2003) showed that, in the Syr Darya basin, temperature increase is in the range of 0.7–1.0 °C; furthermore, according to CRU, precipitation variability increased over the 1900–1995 time frame. Meteorological observations in the region (Savoskul 2000) also suggest that variability climate parameters correlate with climate humidity: in other words, the more arid the climate, the less is the long-term variation. In estimating the interannual variations of the discharge of Amu Darya and Syr Darya by global atmospheric precipitation data, Nezlin et al. (2004) discovered that the discharge of Syr Darya had not decreased since 1985.

Understanding the impacts of such warming on atmospheric circulation is of substantial importance for realizing climate change and its attribution (Li 2010). Li (2012a, b) and Chen et al. (2014) found that the variations of temperature, precipitation, and their extremes in the arid region of Northwest China have a strong association with the atmospheric circulation, e.g., the Tibetan Plateau Index and Siberian High. We suspected that the direct causes for the temperature and precipitation dynamics might be related to those regional atmospheric circulations, particularly the polar vortex. The polar vortex is large-scale cyclonic circulation system in the upper-middle troposphere and the center of the polar region. It is linked to surface weather and has immense influence on the weather and climate patterns in most parts of the Northern Hemisphere (Wang and Ding 2009). Hu et al. (2005) revealed an opposite, warming trend of the northern polar vortex in boreal early winter since the late 1970s.

Frauenfeld and Davis et al. (2003) assessed the relationship between Northern Hemisphere polar vortex variability and air temperature, which implies that the vortex trends are also similar to observed surface warming trends in Eurasian. Gu and Yang (2006) considered that weakening of the polar vortex and its association with climate anomaly in almost all of Asia resulted in increased temperature and more precipitation. However, only little research has been conducted on the relationship between Asian polar vortex variability and climate factors, especially in a basin scale in Central Asia. For this reason, the Asian polar vortex was the primary factor under examination in this study. We intended to find out if the Asian polar vortex had a similar effect on a typical basin in Central Asia.

Besides the polar vortex, in this study, we also detected if there exist associations between the temperature/precipitation variation and other major atmospheric circulations that may affect the region, as well as the carbon dioxide emissions (CDE). The atmospheric circulations we tested include the Tibet Plateau Index (TPI), Antarctic Oscillation (AAO), North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Siberian High Index (SHI), and Westerly Circulation Index (WCI). The Tibetan Plateau affects the atmospheric circulation and is a key factor for the climates in Asia (Chen et al. 2014). The TPI is defined as an accumulative value of all geopotential height monthly values at 500 hPa after removing the hundreds in the area ranging from 30°N to 40°N and 75°E to 105°E. It roughly reflects the activities of low vortex and high pressure at 500 hPa over the Tibetan Plateau (Wang and Wu 1997). The air column over the Tibetan Plateau descends and ascends in different seasons, working as an air pump and regulating the atmospheric circulation (Wu et al. 2007). There is an anticyclone circulation in the north of the Tibetan Plateau and a cyclone circulation in the south of the Tibetan Plateau (Wu et al. 2007). Therefore, this will cause a moisture increase from the Caspian Sea into Central Asia, which will become wet and hot. The AAO is a major mode of Southern Hemispheric (SH) extratropical atmospheric circulation and is a good indicator of extratropical circulation (Fan and Wang 2006). The AAO refers to a large-scale alternation of atmospheric mass between the midlatitude and high latitude surface pressure (Gong and Wang 1999) and has impacts on climate variations in the East Asian-western Pacific sector (Fan and Wang 2004; Ho et al. 2005). Fan and Wang (2004) suggested that AAO is closely related to the East Asian circulation during both boreal winter and spring. The Antarctic Oscillation Index (AAOI) is defined as the difference in the normalized monthly zonal-mean sea level pressure (SLP) between 40°S and 70°S (Nan and Li 2003). The status of other four atmospheric circulations (NAOI, AOI, WCI, SHI) can be seen in relevant references (Li and Wang 2003a, b; Hurrell and Deser 2009; Chen and Sun 2001; Gong and Ho 2002).

Taking the main typical basin in Central Asia as a focus, this study presents a comparative analysis of temperature and precipitation changes since 1881 or 1891, which is expected to lay a scientific basis for regional climate change in the Syr Darya Basin (SDB). The objectives of this study are as follows: (1) to reveal temperature and precipitation trends and their variations via the M-K method, (2) to explore correlations between temperature and precipitation using the Person's correlation method, and (3) to probe the potential causes of climate change. All of the tests are based on the temperature and precipitation series collected from eight meteorological stations in the Syr Darya Basin from 1881(1891) to 2011.

2 Study area

The Syr Darya Basin, which covers an area of 444,000 km^2, is one of the two major basins in Central Asia. The Syr Darya River source flows out of the Tian Shan Mountains of Kyrgyzstan, located to the north of the Pamirs. It has two main tributaries—the Naryn and the Kara Darya—which merge in eastern Uzbekistan to form the Syr Darya proper, running approximately 2,500 km through Kyrgyzstan, Tajikistan, Uzbekistan, and Kazakhstan, before finally flowing into the Aral Sea (Fig. 1).

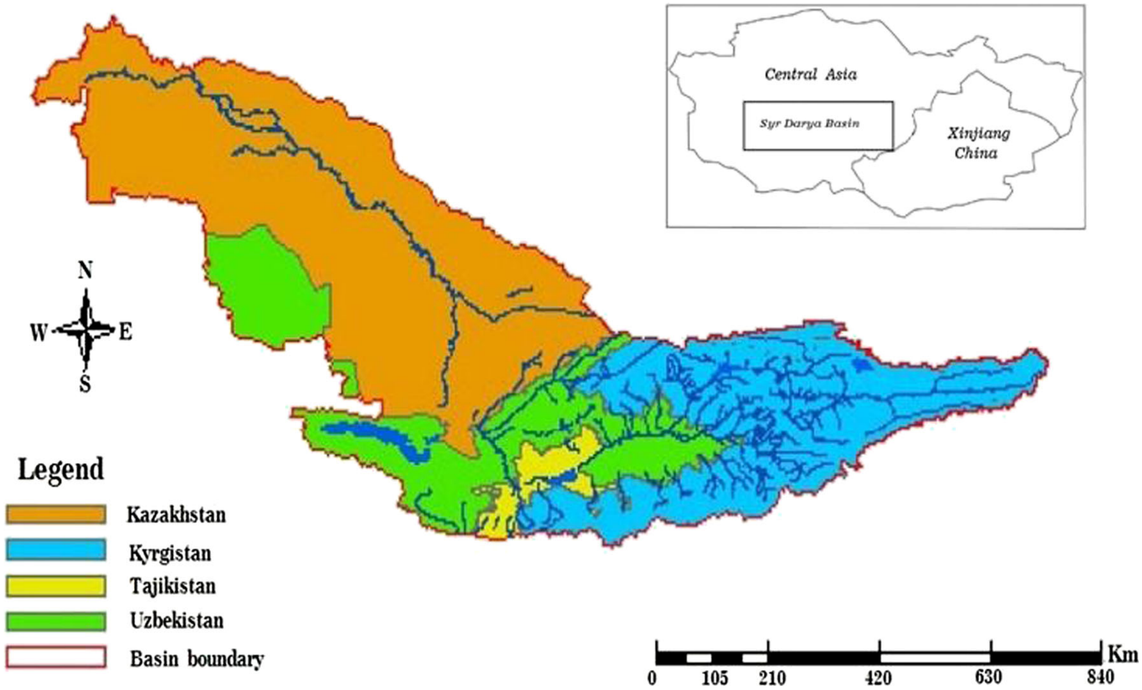


Fig. 1 Countries of the Syr Darya Basin

The topography of the Syr Darya basin can be subdivided into the upper mountainous portion and the lower plains (Fig. 2a). Figure 2b shows the distribution of the basin according to elevation. Mountains (i.e., terrain above 1,500 m) cover an area

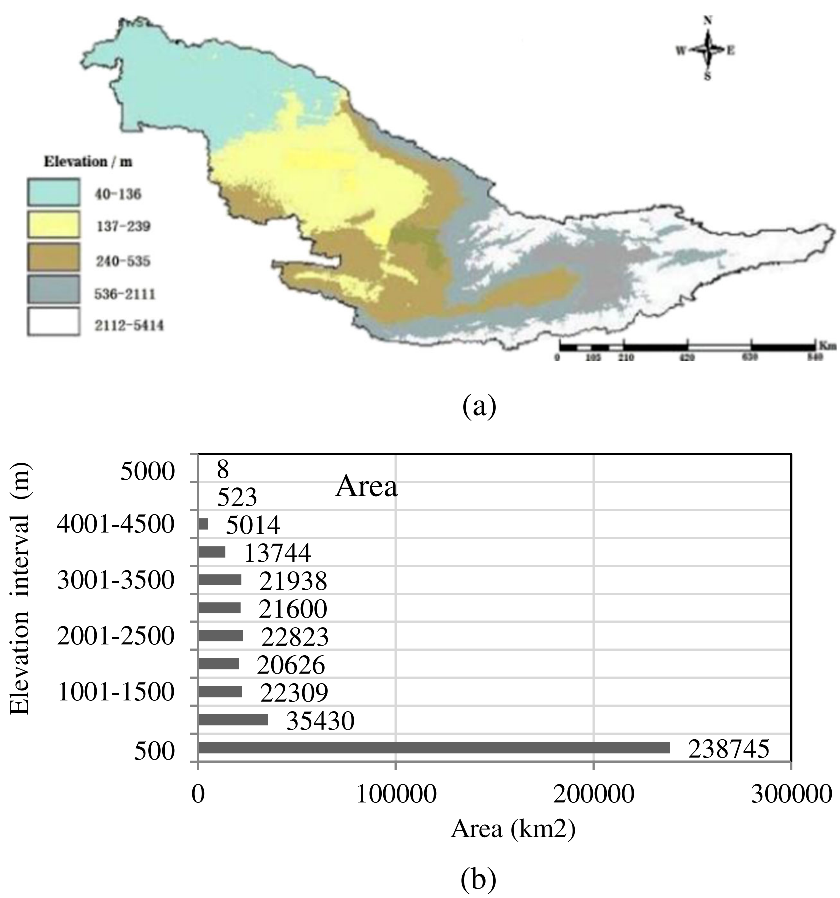


Fig. 2 Hypsometry of the Syr Darya Basin (**a**) and distribution of the Syr Darya Basin area according to elevation (**b**)

Table 1 Basin information of the meteorological station in Syr Darya Basin

Region	WMO code	Stations	Latitude/°N	Longitude/°E	Elevation/m	Country
Mountains	36974	Naryn	41.43	76.00	2039	Kyrgyzstan
	36982	Tian Shan	41.92	78.23	3614	Kyrgyzstan
Plains	38618	Fergana	40.37	71.75	578	Uzbekistan
	38457	Tashkent	41.27	69.27	477	Uzbekistan
	38198	Turkestan	43.27	68.22	206	Kazakhstan
	38062	Kzyl-orda	44.77	65.53	128	Kazakhstan
	35746	Aralskoye	46.78	61.67	62	Kazakhstan
	35849	Kazalinsk	45.77	62.12	66	Kazakhstan

of approximately one third of the total basin area. This portion of the river is chiefly fed by glaciers and snowmelt formed in the upper mountainous area, located in the Tian Shan Mountains, and dissipates in the piedmont plains and desert. The climate here is strongly determined by alpine vertical zonality and thus is moderately humid at high elevations and arid at lower elevations. The average annual temperature in the basin is 14.2 °C, with a range of −15 to 8 °C in January and 18 to 38 °C in July. Annual precipitation ranges from 60 mm in the plains to 502 mm in the mountain areas, and evaporation ranges from 1,150 to 1,420 mm throughout the basin (Savoskul 2000)

3 Data and methods

3.1 Data collection

In this paper, we used monthly temperature and monthly precipitation data from the Royal Netherlands Meteorological Institute (RNMI) for eight ground-based meteorological stations for the periods of 1881–2011 and 1891–2011 to characterize temperature and precipitation variations in the study area. To guarantee consistency, the monthly data were checked to ensure that they met the expected standards. The standard requires strict quality control processes including consistency check, extreme inspection, and others before releasing these data. Most of the meteorological stations are located in the SDB in Central Asia (Table 1). Data from two stations in the mountainous area were available for this study, with the average elevation of the stations being 2,826 m. In the plains area, data was available from six stations located at an average elevation of 253 m.

Monthly data for the AAOI during 1891–2011 are from Jianping Li's Home Page (http://ljp.lasg.ac.cn/). Monthly data for the TPI, Asian Polar Vortex Area Index (APVAI), and Asian Polar Vortex Intensity Index (APVII) during the 1950–2011 period are from the National Climate Center (NCC) of China Meteorological Administration (CMA). Monthly data for CDE in the world from 1960 to 2005 are from the World Development Indicators (WDI) (http://data.worldbank.org).

3.2 Methods

3.2.1 Regression to evaluate hydro-meteorological relationships

In this study, regression was used to evaluate climate change in the characteristics of annual mean temperature and total precipitation time series. The linear regression equation for estimating meteorological-hydrological parameters was developed as (Chen et al. 2010)

$$y = \beta_1 t + \beta_0 \quad (1)$$

where y is temperature (degree Celsius), precipitation (millimeter) or runoff (10^8 m^3), β_1 and β_0 are regression slope and intercept, respectively, and t is time (year).

3.2.2 Mann-Kendall test

The Mann-Kendall rank statistics test is an effective method for testing monotonic trends and abrupt time series changes (Kadiogu 1997; Smadi and Zghoul 2006). This paper used the Mann-Kendall monotonic trend test (Yue et al. 2002; Ling et al. 2012), the nonparametric test, and the abrupt change test method to analyze change trends and possible transition points for temperature and precipitation in the SDB.

In this method, H0 represents distribution of random variables and H1 represents possibility of bidirectional changes. The test statistic S is given by

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i) \quad (2)$$

in which x_k and x_j are the sequential data values, n is the length of the data set, and

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

In particular, if the sample size is larger than 10, the statistic S is nearly normally distributed, i.e., the statistic

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{var}(S)}}, & S > 0, \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{var}(S)}}, & S < 0; \end{cases} \quad (4)$$

is a standard normal random variable, whose expectation value and variance are

$$E(S) = 0 \quad (5)$$

$$\mathrm{var}(S) = \left[n(n-1)(2n+5)-\sum_t t(t-1)(2t+5)\right]/18 \quad (6)$$

in which t denotes the extent of any given tie and Σ denotes the summation over all ties.

Furthermore, the nonparametric Mann-Kendall test (Mann 1945; Kendall 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 them ($j<i$) 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:

$$t_k = \sum_{i=1}^{k} m_i \quad (2 \le k \le n) \quad (7)$$

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

$$\overline{t_k} = E(t_k) = k(k-1)/4 \quad (8)$$

$$\mathrm{Var}(t_k) = k(k-1)(2k+5)/72 \quad (9)$$

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

$$u_k = (t_k-\overline{t_k})/\sqrt{\mathrm{Var}(t_k)} \quad (10)$$

4 Results

4.1 Temperature

4.1.1 Temperature trends

The Mann-Kendall (MK) statistical test showed that there was a significant increasing trend in the mean annual temperature (MAT) in the SDB during the 1881–2011 time frame ($P<0.05$), at a rate of 0.14 °C/decade. It also indicated step change points in 1989 ($P<0.05$). The rate is consistent with rising average global temperatures (0.13 °C/decade) and rising temperatures in Central Asia (0.16 °C/decade, 1901–2003a) (Brohan et al. 2006; IPCC 2007; Wang et al. 2008), but is much lower than the average in the East Asian Monsoon area (0.19 °C/decade, 1901–2003a) (Wang et al. 2008) and northwestern China (0.34 °C/decade, 1961–2009a) (Li et al. 2012a).

Of the mountain and plains landscapes, the latter has the higher increasing rate (0.14 °C/decade), while the former has the lower (0.12 °C/decade). This is likely due to widespread snow and glacier, vegetation diversity, and high ecosystem stability in the mountain areas, exerting a buffer action on global climate change (Li et al. 2012b). The coefficient of variation (Cv) measures variation statistics of observed values and variation degrees of the variable (i.e., temperature and precipitation) in time series. In the SDB, temperature has weak variability and the Cv is 0.096. The Cv of temperature in each landscape ranges from 0.09 to 0.331 and is the smallest in the plains, indicating weak variability, and largest in the mountains, indicating moderate variability.

4.1.2 Temperature variations in different periods

Figure 3 illustrates MAT variations in different periods by anomaly and 13-year moving average methods. The results indicate differences in interdecadal variations that could be related to the unique geographical position and climatic conditions of the landscapes under study. Since the anomaly and moving average analysis shows that the entire region and two landscapes had relatively abrupt changes around 1970, we divided the 130-year time frame into two periods, spanning the years before and after 1970, and conducted detailed analyses of each. As illustrated in Fig. 3, temperatures in the post-1970 period are markedly higher across all landscapes.

In this paper, we compared the MAT in 1970–2011 with that in 1881–1969. The comparison revealed a post-1970 increase of 1.18 °C for the entire region. The plains area showed the largest jump, increasing by 1.19 °C, while the mountain area showed the smallest, increasing by 1.13 °C. In general, temperatures in the plains area of the SDB rose more than the mountain area, which could be due to the mountain area's highly stable ecosystem and low population density (little human activity or impact).

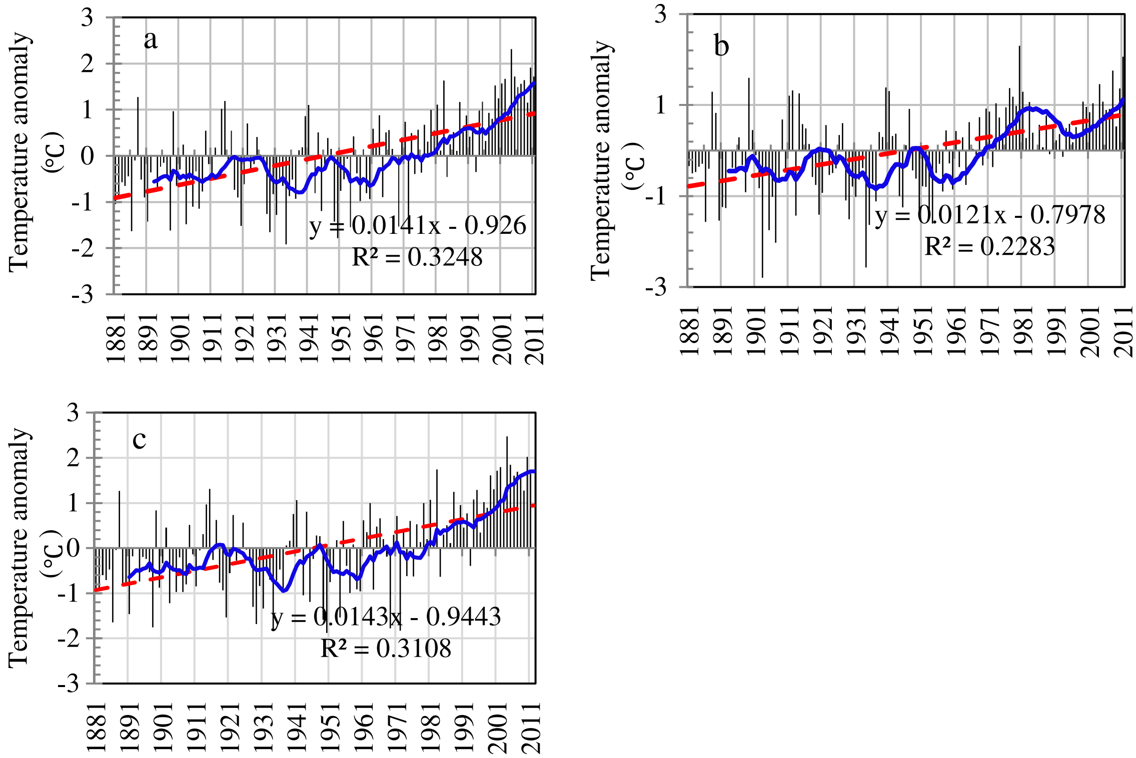


Fig. 3 The trends of the average annual air temperature anomaly in **a** the Syr Darya River Basin, **b** the mountainous areas in this region, and **c** the plain areas in this region, for the period of 1881–2011, based on eight meteorological stations (the *red color* implies linear fitting; the *blue color* implies 13-year moving average fitting)

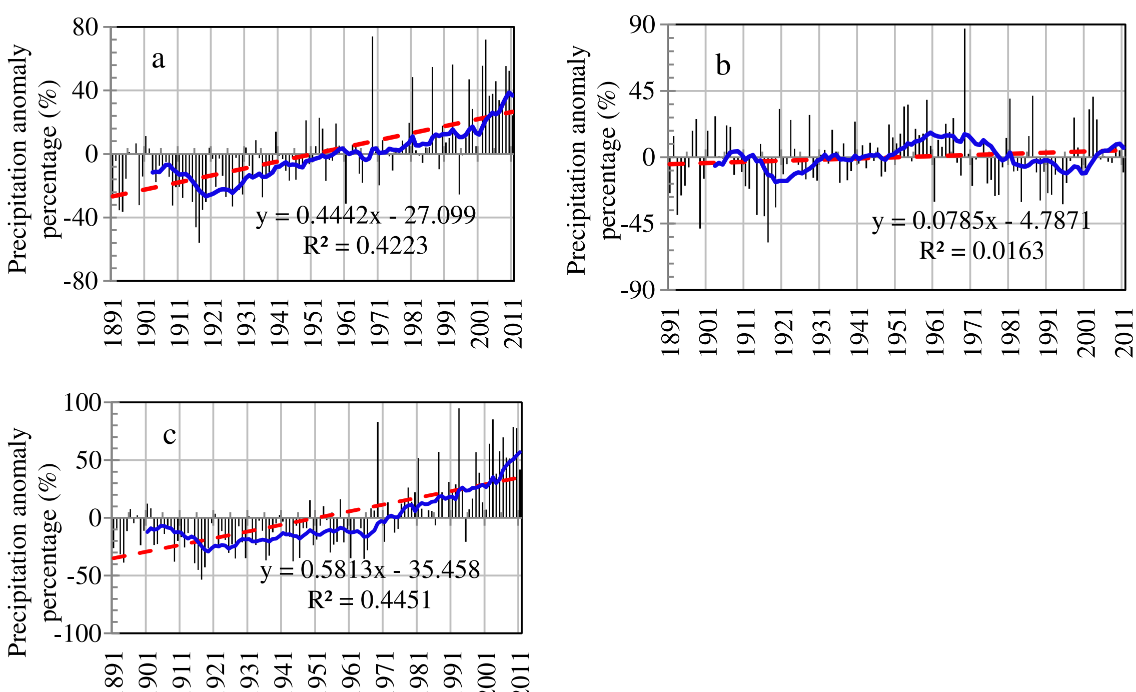


Fig. 4 The trends of the annual precipitation anomaly in **a** the Syr Darya River Basin, **b** the mountainous areas in this region, and **c** the plain areas in this region, for the period of 1881–2011, based on eight meteorological stations (the *red color* implies linear fitting; the *blue color* implies 13-year moving average fitting)

Table 2 Pearson's coefficient between temperature and precipitation in the diverse environments

Item	Mean temperature	Mountain temperature	Plain temperature
Mean precipitation	0.284**	0.225*	0.282**
Mountain precipitation	−0.193*	−0.268**	−0.168
Plain precipitation	0.400**	0.356**	0.388**

*P<0.05; **P<0.01 (significant at these levels)

4.2 Precipitation

4.2.1 Precipitation trends

Over the past 130 years, the average increasing rate of precipitation in the SDB was 4.44 mm per decade and step change points occurred in 1991 (P<0.05). The plains saw the fastest increasing rates (5.81 mm per decade), while the mountains experienced the slowest rate (0.78 mm per decade). In the SDB, precipitation showed moderate variability, ranging from 0.215 to 0.304, which indicates moderate variability. The Cv of precipitation was the smallest in the mountains and largest in the plains.

4.2.2 Precipitation variations in different periods

We found that the interdecadal variations of precipitation in various landscapes were different and that abrupt changes in the entire region and plains area occurred in 1970, but the abrupt changes occurred in 1930 and 1980 in the mountains area. Accordingly, we divided the 130-year time frame into two periods in the entire region and plains area. As shown in Fig. 4a, c, precipitation in the post-1970 period is markedly higher across all landscape types. We then further divided the 130-year time frame into three periods in the mountains area: 1891–1930, 1931–1980, and 1981–2011, finding that precipitation in the second period was higher than in the other periods (Fig. 4b).

During the period of 1891–1970, the mean changing rate was 3.23 mm per decade. The mountain landscape had a similar rate of 3.36 mm per decade, and the rate of plains landscape was 1.17 mm per decade. Overall, the precipitation changes in the entire and all types of areas are small during 1891–1971. The Mann-Kendall test revealed that the precipitation in the entire and mountain landscape exhibited increasing trends at the 0.05 significance level. From 1971 to 2011, the mean rate of the eight stations was 11.49 mm per decade; the precipitation change is not consistent across the plains and mountain areas in this period. The plains landscapes had a rising trend with a mean rate of 15.9 mm per decade, but the precipitation in mountain landscape increased slightly with only 3.74 mm per decade. Overall, the increase of precipitations during this period occurred mostly in the plains landscape. The precipitation in the mountains landscapes changed a little. The Mann-Kendall test showed that the precipitation in the plains landscape exhibited significant increasing trends at the 0.01 significance level; the others were at the 0.05 significance level.

For the mountains landscapes, the mean rate of precipitation change during the three periods was 0.39, −0.58, and 3.35 mm per decade. The Mann-Kendall test revealed that all exhibited increasing trends at the 0.05 significance level, respectively. The change indicates that the precipitation had the largest increase in the mountains landscapes since 1980.

4.3 Correlation between temperature and precipitation

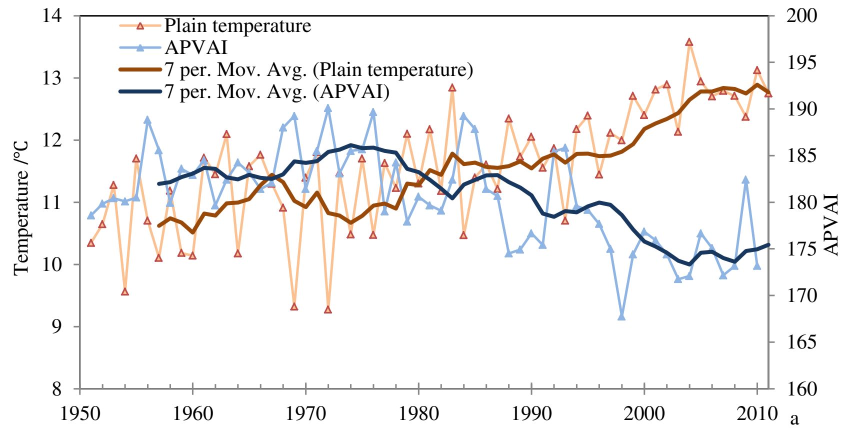
The correlation between temperature and precipitation is statistically significant, at P<0.01 level across the mean and same landscapes (Table 2). There are two interesting significant characteristics in these correlation coefficient values: (1)

Table 3 The correlation coefficients between the temperature and precipitation in the entire region (the Syr Darya River Basin), mountains, and plains and certain factors that may affect the temperature

	Factor	WCI	SHI	AOI	AAOI	NAOI	TPI	APVAI	APVII
Temperature	Entire region	0.096	0.230	0.350*	0.311**	−0.188*	0.391**	*−0.701***	*−0.618***
	Mountains	−0.119	0.060	0.189	0.272**	−0.128	−0.055	−0.301*	−0.424**
	Plains	0.118	0.240	0.352*	0.303*	−0.191*	0.428**	*−0.714***	−0.610**
Precipitation	Entire region	0.016	−0.078	0.141	*0.343***	−0.059	*0.490***	−0.335*	−0.246
	Mountains	−0.131	0.127	−0.314*	−0.017	−0.398**	*0.385***	−0.121	0.097
	Plains	0.034	−0.149	0.258	0.390[b]	0.053	*0.442***	−0.335*	−0.298*

*P<0.05; **P<0.01 (significant at these levels)

Fig. 5 The Asian Polar Vortex Area Index and the temperature in the plain area of the SDB



Plains precipitation is significantly correlated with the temperature of all landscapes (including itself), but the mountain area has a negative correlation with the temperature of all landscapes (including itself). (2) The temperature of the plains area is more significantly correlated with precipitation, except for that on the mountain area.

4.4 Potential causes of climate change in the SDB

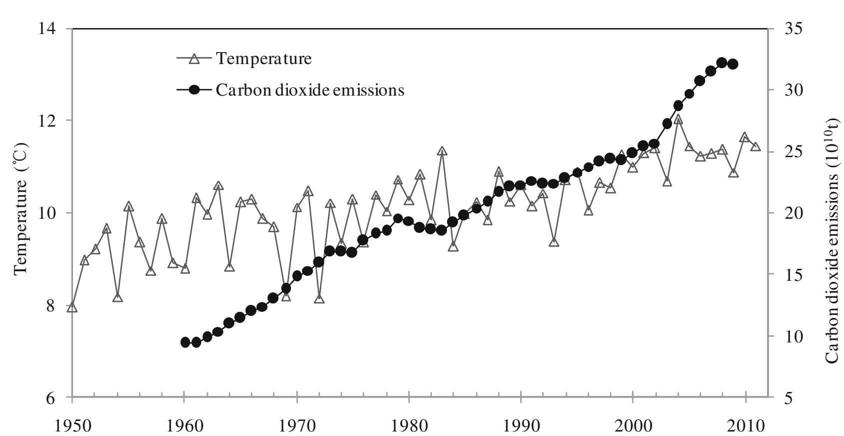
Both temperature and precipitation showed negative anomaly during the period of 1881–1970 and then an abrupt change, resulting in increasing temperature and somewhat increasing precipitation. Thus, the abrupt change in the temperature and precipitation might have associations with regional atmospheric circulation. The statistical relationships between the changes and eight atmospheric circulations, including WCI, SHI, AOI, NAOI, AAOI, TPI, APVAI, and APVII, were investigated.

Pearson's correlation coefficient values (Table 3) show that the MAT of the SDB in Central Asia has a strong and significant correlation with the APVAI (R=−0.701, P<0.01). The correlation was strong for the APVII (R=−0.618, P<0.01) and relatively strong for the TPI (R=0.391, P<0.01). The correlations between the MAT and the other circulations were weak or insignificant. It is worth mentioning here that the correlations in the plains are higher than those in the mountains, which means that the impacts of atmospheric circulations on temperatures in the plains are stronger than those in the mountains, which is consistent with the research results in the arid region of Northwest China (Li et al. 2012b). Figure 5 shows that the Asian Polar Vortex Area Index was remarkably negatively correlated with the MAT in the basin during 1950–2011. In particular, the Asian Polar Vortex Area Index had an obvious decreasing trend after the mid-1970s, along with a sustained temperature increase in the SDB.

Excessive greenhouse gas emissions are generally regarded as the main cause of global warming (Crowley 2000; Mahlstein and Knutti 2010; IPCC 2007). However, while the carbon dioxide emissions in the past 20 years showed a strongly increasing trend, temperatures in the SDB did not follow suit (Fig. 6). Based on the analysis above, we deduced that the rising MAT seems to be more associated with the Asian Polar Vortex Area Index than with carbon dioxide emissions.

Precipitation of the SDB in Central Asia showed a strong and significant correlation with the TPI (R=

Fig. 6 The carbon dioxide emissions in the world and the temperature in the SDB



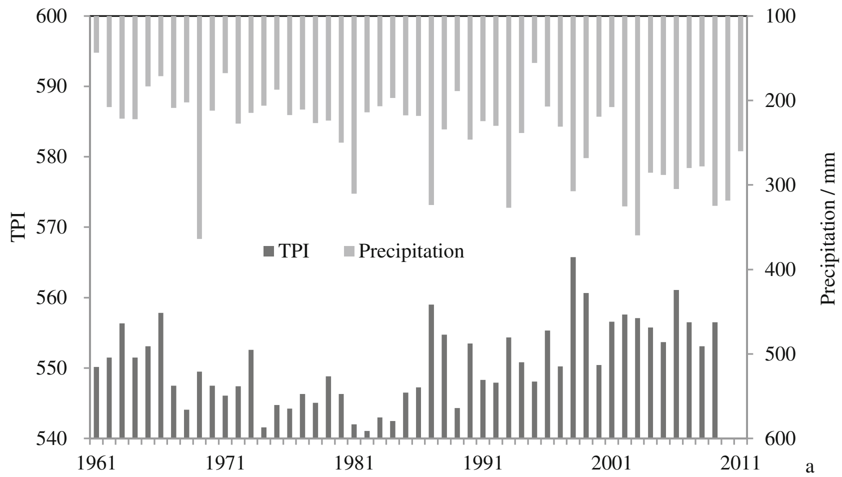


Fig. 7 The Tibet Plateau Index and the precipitation in the SDB

0.490, $P<0.01$), followed by the AAOI ($R=0.343$, $P<0.01$). The correlations between the precipitation and the other circulations were weak or insignificant. The correlations in the plains were higher than those in the mountains, implying a closer association with atmospheric circulations and precipitation in the plains than in the mountains (Table 2). The Tibet Plateau Index and its changes were in good agreement with precipitation in the SDB (Fig. 7). The Tibetan Plateau, which is more than 5 km above sea level, emits energy into the atmosphere in the form of dry heat and water vapor. This action is widely held to cause the plateau to serve as an important outside heat source that influences Asian climate. Specifically, the heating effect from the Tibetan Plateau locally enhances rainfall along its edge (Boos and Kuang 2010).

5 Conclusion and discussion

This work investigated climate change trends in the SDB over the past 130 years, with the findings furthering our understanding of climate change in the region. The results will assist and inform future planning and management of climate change programs in the SDB, especially against the background of global warming.

During 1881–2010, temperatures underwent a notable increase at a rate of 0.14 °C/decade ($P<0.05$) and showed step change points in 1989 ($P<0.05$). This rate is consistent with rising temperature rates in Central Asia and globally, but is much lower than that in the East Asian Monsoon area and northwestern China. Overall, temperatures showed weak variability, increasing more in the plains area than in the mountains. Also noteworthy is that temperatures in the SDB showed a strong association with the APVAI (correlation coefficient: $R=-0.701$, $P<0.01$) rather than carbon dioxide emissions, especially in the mountains.

During the same 130-year span, annual precipitation experienced a significant rising trend ($P<0.001$) at a rate of 4.44 mm/decade and indicated step change points in 1991 ($P<0.05$). As with temperature, precipitation rates increased more rapidly on the plains than in the mountains. Additionally, precipitation showed only moderate variability and had a strong and significant correlation with the TPI ($R=0.490$, $P<0.01$) and the AAOI ($R=0.343$, $P<0.01$), the correlations in the plains being higher than those in the mountains. In general, precipitation in the plains was found to be significantly correlated with temperatures across all landscape types, while the mountain area had a negative correlation.

There are various uncertainties in the climatic variability analysis, especially in the arid regions, which might arise from the input data and regional characteristics. First, the climatic variability analysis is based on the data for the observation data of meteorological stations in the SDB. There may be some human disturbances by building reservoirs, grazing, and so on. Second, the uncertainty due to the number and distribution of the meteorological stations in the various landscapes, within the mountain area in the SDB, is data from only two meteorological stations. The average statistics in the SDB will mainly reflect the information of stations in the plain area. Therefore, these uncertainties would influence computational results to a certain extent, and so estimation uncertainties should be further investigated in future studies.

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Appendix

The Polar Vortex Area Index (PVAI) was defined by Wang and Ding (2009) as

$$S = \frac{R^2\pi}{72}\sum_{i=1}^{n}(1-\sin\phi) \qquad (11)$$

The Polar Vortex Intensity Index (PVII) was defined as

$$I = \rho R^2 \Delta\phi\Delta\lambda\Sigma_t\Sigma_j\left[H_0(M)-H_{i,j}\right]\cos\phi_t \qquad (12)$$

where S is the Polar Vortex Area Index value for the specific region, I is the Polar Vortex Intensity Index value for the specific region, ϕ_i is the latitude value of lattice in the northern portion of the polar vortex southern boundary, R is the radius of Earth, ρ is air mass density, $\Delta\phi=\Delta\lambda=\pi/72$, $H_0(M)$ is the contour value of the polar vortex southern boundary, M is the location of southern boundary, $H_{i,j}$ is the height value of the northern lattice in the polar vortex southern boundary, and i, j is the number of lattices for longitude and latitude. The scope of latitude in the Asian polar vortex is 60°E–150°E.

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