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Impact of Climate Change on Water Resources in the Tarim River Basin

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Abstract. The plausible association between climate change and the variability of water resources in the Tarim River basin, west China is investigated in this study. The long-term trend of the hydrological time series including temperature, precipitation, and streamflow are detected by using both parametric and nonparametric techniques. The possible association between the El Niño/Southern Oscillation (ENSO) and these three kinds of time series are tested. This study enhances the knowledge of the climate change impact on water resources in the Tarim River basin. The conclusion obtained in this investigation shows that the temperature experienced a significant monotonic increase at the 5% level of significance during the past 50 yr, and precipitation also exhibited an upward tendency during the past several decades. A significant jump is also detected for both time series around 1986. This may be resulted from the possible impact of climate change, although the interior climate mechanism needs further investigation. Although precipitation and the streamflow from the headwater of the Tarim River exhibited significant increase, decreasing trend has been detected in the streamflow along the mainstream of the river. It implies that anthropogenic activities instead of the climate change dominated the streamflow cessation and the drying-up of the river. Results also showed that no significant association exists between the ENSO and the temperature, precipitation and streamflow in the study area. This conclusion shows that the water curtailment, river desiccation, and ecosystem deterioration in the Tarim River basin may be mainly resulted from the impact of human activities.

Key words: climate change, ENSO, nonparametric test, parametric test, precipitation, water resources

1. Introduction

In recent years, the occurrences of extreme events such as droughts and floods have been on the rise almost worldwide. Some researchers speculated the prospect of increases in hydrological extremes in relation to climate change. The variability of runoff and water resources is particularly higher for drier climates, e.g., a higher percent change in runoff resulting from a small change in precipitation and temperature in arid or semiarid regions (Gan, 2000). It is very important for water resources managers to know and prepare to deal with the effects of climate change on the changes of hydrological cycles and streamflow regimes. The better understanding on the relationship between climate change, anthropogenic activities and the water resources availability as well as its withdrawal and use, will allow water resources managers to make more rational decisions on water allocation and management (Sullivan, 2001). Recently, the streamflow cessation and water curtailment occurred in the Yellow River basin has received wide attention everywhere in the world (Xu *et al.*, 2002). Being not so far from the Yellow River basin is the Tarim River, the largest continental river in China. With the development of economics in west China, significant improvements have been made in regulating the streamflow of the Tarim River for flood control, and water supply mainly for agricultural and domestic purposes during the past several decades. This improvement has made great contribution for the development of economics in Xinjiang Province. However, its negative influences such as deforestation, desertification and soil salinity were also considerable, especially the water curtailment of the downstream brought about great negative effects on the ecosystem in Tarim River basin. The complete drying-up of the mainstream of the Tarim River, occurred since 1974, has received significant attention by both local and central government (Qian, 2000; Deng *et al.*, 2001; Chen *et al.*, 2003a, b). It is, therefore, important to investigate the water resources availability and understand the causes resulting in water resources scarcity, and on the basis of this investigation to formulate a new vision for the future water resources in the study area.

Water resources availability for meeting reservoir storage, water supply diversion, and environmental instream flow requirements must be assessed based on various premises regarding future water management/use as well as climatic and hydrological conditions (Muttiah and Wurbs, 2002). This study, therefore, will investigate the possible impact of climate change and detect the plausible long-term trends of the temperature, precipitation, and the streamflow time series. The potential association between these hydrological processes and the El Niño/Southern Oscillation (ENSO) will be examined as well. The techniques used in this study will be presented in the following section. The third section of the paper will give an introduction on the study area and the data used in this paper. Result analysis will be given in the fourth section. The conclusion will be summarized in the last section.

2. Techniques Used for Detecting Climate Change

The hydrological cycle continuously replenishes the water resources for humankind and ecosystem. It has been found that both natural variability and human activities can influence the hydrological cycle. Even if the physical link between the hydrological cycle and the long-term climate change is still not well understood, the observed long-term trends in annual precipitation and river flows show that climate change is changing the hydrological cycle. Detecting plausible long-term climate change from hydrological processes is the first step to understand and tackle the vulnerability of water resources.

2.1. NONPARAMETRIC MANN-KENDALL TEST FOR MONOTONIC TREND

In this study, both parametric and nonparametric tests will be used. Due to the space limitation, the presentation on parametric test is not included here. The nonparametric Mann-Kendall method, which will be employed to detect possible trends in this study, is outlined below. In this approach, the test statistic is given as follows,

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

where

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

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

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

in which the x_k, x_i are the sequential data values, n is the length of the data set, t is the extent of any given tie, and Σ denotes the summation over all ties.

The magnitude of the trend is given as

$$\beta = \mathrm{Median}\left(\frac{x_i - x_j}{i - j} \right), \quad \forall j < i \tag{5}$$

in which $1 < j < i < n$. A positive value of β indicates an "upward trend," and a negative value of β indicates a "downward trend."

2.2. KENDALL'S τ(TAU) FOR ASSOCIATION BETWEEN TWO VARIABLES

In this investigation, the Kendall's τ, which is especially useful for the time series being not an independent, identically distributed normal random variable, is employed to detect the possible association between hydrological variables and ENSO. In Kendall's τ approach, the test statistic is given as

$$Z_c = \frac{S'}{\sqrt{\mathrm{Var}(S')}} \tag{6}$$

in which,

$$\begin{aligned}\operatorname{var}[S'] = {} & \frac{n(n-1)(2n+5) - \sum_x t_i(t_i-1)(2t_i+5) - \sum_y s_i(s_i-1)(2s_i+5)}{18} \\ & + \frac{\left[\sum_x t_i(t_i-1)(t_i-2)\right]\cdot\left[\sum_y s_i(s_i-1)(s_i-2)\right]}{9n(n-1)(n-2)} \\ & + \frac{\left[\sum_x t_i(t_i-1)\right]\cdot\left[\sum_y s_i(s_i-1)\right]}{2n(n-1)}\end{aligned} \tag{7}$$

where S' is the Kendall sum, and is estimated as $S' = L\text{-}M$, in which L is the number of cases where $y_i > y_j (i > j)$, and M the number of cases where $y_i < y_j$ $(i < j)$.

The strength of the association between two time series is measured by τ_a or τ_b (τ_b handles ties), which are estimated as follows,

$$\tau_a = \frac{S'}{n(n-1)/2} \tag{8}$$

$$\tau_b = \frac{2S'}{\sqrt{\left\{n(n-1) - \sum_{i=1}^{n_x} t_i(t_i-1)\right\}\left\{n(n-1) - \sum_{i=1}^{n_y} s_i(s_i-1)\right\}}} \tag{9}$$

in which n_x is the number of ties in the x-rankings, and n_y is the number of ties in the y-rankings. Kendall's τ_a/τ_b only takes on values between -1 and 1. The sign indicates the sign of the slope of the relationship, and the absolute value indicates the strength of the relationship.

2.3. WILCOXON TEST FOR ASSOCIATION BETWEEN TWO VARIABLES

For the purpose to further investigate the detailed correlation between hydrological variables and different ENSO episodes, the nonparametric Wilcoxon test will be employed in this study (Giannini *et al.*, 2001). The Wilcoxon-test statistic is given as follows,

$$Z_W = \frac{W - E(W)}{\sqrt{\operatorname{var}(W)}} \tag{10}$$

in which

$$W = \sum_{i=1}^{n} \operatorname{rank}(\text{ENSO}_i) \tag{11}$$

$$E(W) = \frac{n(n+m+1)}{2} \tag{12}$$

$$\operatorname{var}(W) = \frac{mn(n+m+1)}{12}. \tag{13}$$

Typically, $n < m$, so that n is the number of warm, or cold years, and m is the number of neutral years. The hydrological variable is ranked separately for warm and neutral, or cold and neutral conditions. A Wilcoxon two-sample sum statistic is applied to the ranks, and the hypothesis is stated as follows:

H_0: $\mu_{\mathrm{Nino}} = \mu_{\mathrm{Neutral}} = \mu_{\mathrm{Nina}}$
(No teleconnection between ENSO and hydrological process)

vs

H_1: At least two of the means are different (Teleconnection between ENSO and hydrological process)

in which μ_{Nino}, μ_{Neutral}, μ_{Nina} are the variable means for the periods of El Niño, neutral, and La Niña phases, respectively. Hydrological process is defined as being affected by El Niño (or La Niña) phase when μ_{Nino} is significantly different from μ_{Neutral} (or μ_{Nina} is significantly different from μ_{Neutral}).

3. Study Area and Data Description

The Tarim River basin with the area of 1 020 000 km^2, as given in Figure 1, covers the entire south Xinjiang Province in China. Its area is 1.4 times of the Yellow River basin and populated with 8 257 000. The mainstream catchment of

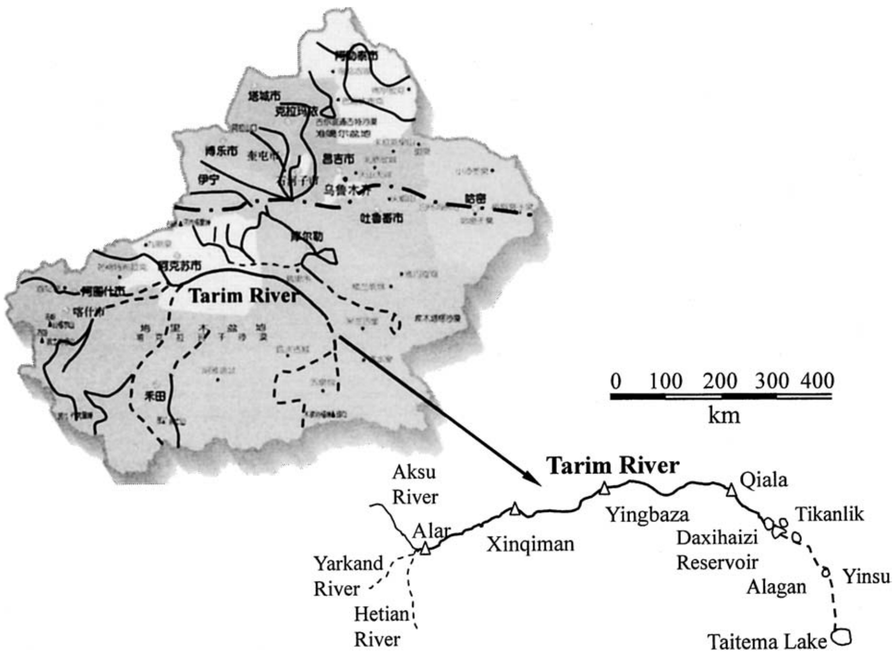


Figure 1. Map showing the study area.

the Tarim River basin, with the length of 1321 km, an area of 17 600 km^2 and a population of 120 100, is located in the extreme arid region receiving an annual rainfall of less than 50 mm with the potential evaporation of more than 2 000 mm. The available renewable resources of surface and groundwater are far below the demand. The average annual water consumption is 4.6 billion cubic meter (BCM). Hydrologically, the Tarim River basin represents a closed catchment, where several tributaries drain into its interior, the Tarim depression. The mainstream catchment of the Tarim River basin is located below the confluence of the Hetian River, Yarkand River, and Aksu River. It is a unique freshwater ecosystem located near one of the largest deserts—Tarim Desert in China. Depending on the river levels, water could feed the riparian landscape of the Tarim River basin that is characterized by a vast wetland, which is called "green corridor" before the 1970s.

The Tarim River is the largest continental river in China. Early in the 1960s, an ambitious plan for agricultural development in this arid region was put into effect, and vast reclamation projects in the study area were undertaken since the 1960s in conjunction with the construction of a series of dams. The settlement of population has resulted in the rapid development of various agricultural projects, and resulted in the diversion of the freshwater to the new reclamation land. Due to the poor management practice at the first stage of the development during the past several decades, the Tarim River basin and surrounding area are experiencing extensive environmental degradation with the development of economics. The runoff in the main channel of the Tarim River has been reduced greatly since the 1970s, and the runoff at Qiala station reduced by 80% in 40 yr, and decreased to 0.27 BCM in the 1990s from 1.24 BCM in the 1960s. The runoff into the Taitema Lake has dropped to zero since the 1970s and the lake dried up completely in 1974. Correspondingly, the area of forest decreased by 200 000 ha, the grassland decreased by 850 000 ha from the 1950s, and the area of desertification increased to 1494 km^2 in 1996 from 1371 km^2 in 1959 (Deng *et al.*, 2001). The irrigated area has increased to 2849 ha. Rapid development of the irrigated agriculture is the main reasons for the region's water resources problem. Associated with this environmental and land degradation are deforestation and salinization of high percent of irrigated land as well as the drying-up of the downstream of the Tarim River, causing considerable economic losses annually. The drying-up of the Taitema Lake was also associated with the construction and filling of the Daxihaizi reservoir, which has produced a range of changes of the ecosystem in the downstream of the Tarim River basin varying from well dominated vegetation types to dramatic declines of forests and great reduction of the groundwater level.

One of the tributaries affecting the Tarim River, the Yarkand River joins the Tarim River from the west. Since the 1960s, flow from its mountainous headwaters was captured and directly diverted to Xiaoxihaizi Reservoir, and with the filling of the Xiaoxihaizi Reservoir, the downstream of the Tarim River dried up since the 1970s. The drying-up including both the main channel of the downstream of the Tarim River and the Taitema Lake led to a rapid declination in forest in the green corridor.

Recently, both local and central government have paid significant concern on the altered hydrological regime of the Tarim River ecology. In an attempt to restore ecological system, releases from Boston Lake through the Daxihaizi Reservoir were carried out for several times. It was realized that these releases were beneficial to the potential restoration of the ecosystem. The flow release was a successful test of the remediation strategy designed to restore major riparian ecosystem in Tarim River basin.

Investigation on the relationship between climate change and the available water resources is beneficial for the efficient water resources management, and the precipitation, directly related to the soil moisture, water resources, ecosystem, has large impact on hydrological processes (Bordi and Sutera, 2001). Aiming at this objective, temperature, precipitation and streamflow data are employed in this study. Because the Tarim River basin covers more than two thirds of the area of Xinjiang Province and the impact of climate change usually involves large area, both temperature and precipitation data over Xinjiang Province will be employed. The temperature data from 77 climatological stations and the precipitation from 61 rain gauges are used in this investigation. Figure 2 exhibits the standardized average temperature and precipitation in the study area. It is obvious that both monotonic trend and jumps did occurr in both time series. On the other hand, streamflow represents an integrated response to hydrological inputs in the watershed and holds a good spatial coverage. Streamflow is essential in order to provide an indicator of the extent of impacts from climate change on water resources (Xu, 2000). To analyze the long-term trend of the streamflow, six time series of the streamflow runoff—three from mainstream of the Tarim River, three from the main tributaries: Hetian, Yarkand, and Aksu—are used. The basic statistics for these eight time series, including average, standard deviation, coefficient of variation, coefficient of skewness, minima, maxima, and range, are listed in Tables I–III.

4. Detection of Climate Change

Global climate change could have significant impacts on both natural and social systems. Water resources and ecosystems are particularly likely to be affected by climate change. In the case of large, complex, and heavily modified river systems, such as the Tarim River basin, the potential impacts of climate change can be understood by detecting the long-term trends of both climatological and hydrological processes. Climate change affects both the total volume and temporal pattern of runoff in the basin. This suggests that hydrological changes caused by any long-term climate change will have ecological and socioeconomic impacts that may affect the management of the water resources (Cohen *et al.*, 2000). Water resources could be altered with relatively small climate changes causing large water resource problems in drought-prone areas. Global warming can accelerate the hydrological cycle by increasing both precipitation and evapotranspiration rates. However, renewable water supplies are likely to decline under global warming (Abu-Taleb, 2000).

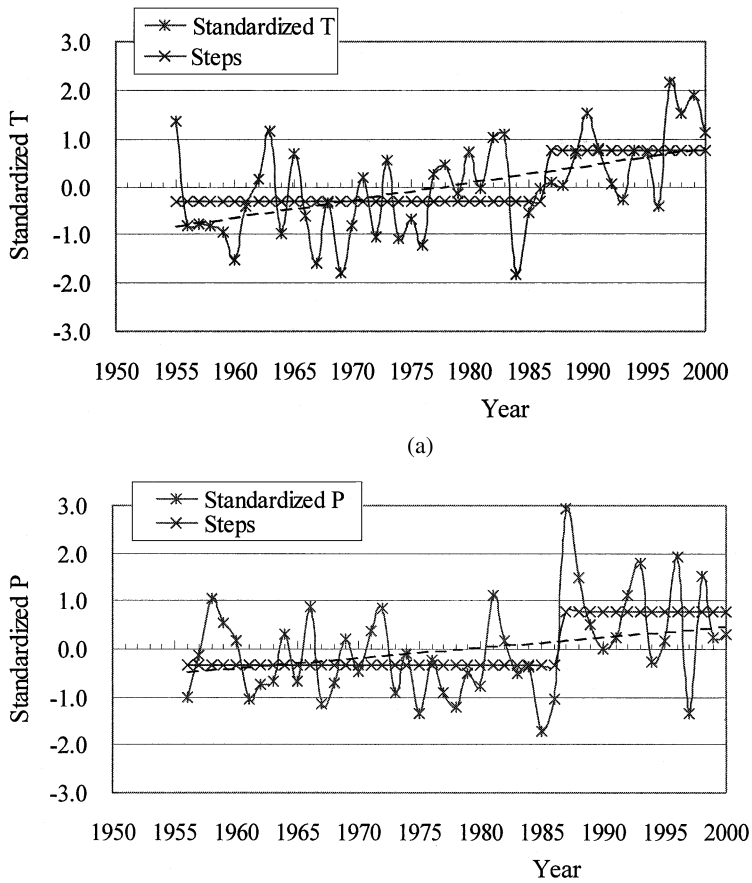


Figure 2. (a) Standardized average annual temperature in the study area. (b) Standardized average annual precipitation in the study area.

4.1. LONG-TERM TRENDS OF THE TEMPERATURE, PRECIPITATION AND RUNOFF TIME SERIES

The impacts of climate change on hydrology and water resources have been investigated by many hydrologists during the past decades. For example, Muttiah and Wurbs (2002) concluded that the average temperature of the United States has risen by about 0.6°C, and precipitation has increased by about 5 to 10 percent throughout the 20th century, mostly due to the increases in intense rainstorms. The author of this paper once investigated the plausible long-term trend of precipitation in China, and concluded that a great number of decreasing trends are observed than are expected to occur by chance. Geographically, the decreasing trends were concentrated in the northern part of China including Songliao River, Hai River, Huai River, and Yellow River basins, while the increasing trends appeared primarily in southern

Table I. Statistics for the temperature and precipitation time series

Statistics	Temperature (°C)	Precipitation (mm)
Mean	6.86	156.65
Standard deviation	0.63	30.34
Coefficient of variation	0.09	0.19
Coefficient of skewness	0.13	0.69
Maximum value	8.23	245.58
Minimum value	5.71	104.36
Range	2.52	141.21

Table II. Statistics for three streamflow runoff time series along the mainstream of the Tarim River (10^8 m^3)

Statistics	Alar	Xinqiman	Qiala
Mean	46.0	37.52	7.04
Standard deviation	10.55	9.88	4.42
Coefficient of variation	0.23	0.26	0.63
Coefficient of skewness	0.20	0.11	0.71
Maximum value	69.59	57.90	17.50
Minimum value	25.58	16.49	1.83
Range	44.01	41.41	15.67

Table III. Statistics for the inflow runoff time series from three tributaries (10^8 m^3)

Statistics	Aksu	Yarkand	Hetian
Mean	74.21	73.17	43.59
Standard deviation	10.03	12.41	8.90
Coefficient of variation	0.14	0.17	0.20
Coefficient of skewness	1.09	0.33	0.60
Maximum value	101.54	105.14	68.92
Minimum value	58.21	50.53	24.49
Range	43.33	54.61	44.43

part of China including Yangtze River, Zhujiang River basins, and the Southeastern Region. Due to the limited data in west China, it was not clear which kind of long-term trend—increasing or decreasing—dominated Xinjiang and Tarim River basin.

The long-term trend of annual temperatures over Xinjiang Province is detected by using both parametric and nonparametric techniques in this study. The result is given in Table IV, where β_0 and β_1 are base level and trend magnitude, and T_c is the t-test statistic. It is noted that both parametric t-test and the nonparametric

Table IV. Monotonic trend test for temperature and precipitation time series

	t-test				Mann-Kendall test		
	β_0	β_1	T_c	H_0	Z_0	β	H_0
Temperature	6.313	0.0233	15.38	R	3.428	0.0252	R
Precipitation	141.22	0.6706	23.61	R	1.702	0.6883	A

Note: R–rejected, A–accepted. Significant level $\alpha = 0.05$.

Mann-Kendall test are all reject hypothesis H_0. In other words, the increasing tendency of the temperature is significant at the 5% level of significance. Together with the plot of mean annual temperatures of the 77 synoptic stations in the study area from 1955 to 2000 given in Figure 2, it shows nearly a 1 °C rise in temperature over the past 50 yr. The rise of 1 °C degree in temperature means that the capacity of the air for water vapor increases by about 5 or 6% (Philip and Biney, 2002). There is, therefore, a corresponding increase in evaporation due to the rise in temperature. This means that considerable amount of freshwater may be lost through evaporation as a result of the increasing temperature in the study area during the past several decades.

The test result for the long-term trend of the precipitation is also shown in Table IV. It is interesting to note that although the *t*-test rejects the hypothesis H_0, the Mann-Kendall test accepts the H_0 at the 5% level of significance. In other words, both parametric and nonparametric tests show a tendency of increasing in precipitation, but it can not identify whether this kind of increasing tendency is attributed to climate change or resulted from noises. Anyhow, the increased precipitation may partly weaken the effect from the increased temperatures, which may increase evaporation and thereby resulted in the reduction in the river runoff and water supply. The increased temperatures may be attributed to the global warming, but the increase in precipitation may be attributed mainly to the local activities such as the deforestation and the increase of water surface due to the construction of reservoirs, both resulted in the increase of evaporation and strengthened the hydrological cycles during the past several decades.

Since precipitation is a primary factor in the generation of river runoff, the precipitation in the study area and its pattern are thus further analyzed. The precipitation in the study area is not uniformly distributed over time and space. During the wet season, precipitation is available, whereas there is scarcity in the dry season. The study area experiences a precipitation regime in a year from May to September with a peak in July. However, nearly half of the total annual rainfall is recorded in just 2 months—July and August. During the dry season from November to March next year, there is very little or no rainfall at all. Figure 3 gives an example for the temporal distribution of the precipitation at Aksu gauging station. For the purpose to further investigate the spatial distribution of the precipitation in the study area, and note the fact that the serious water scarcity in the study area began to appear

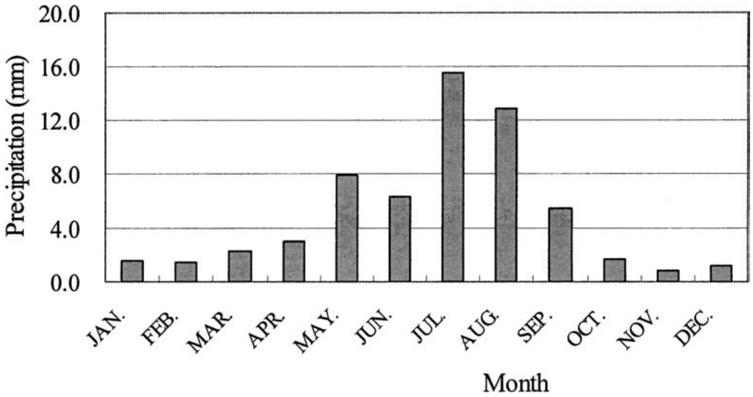
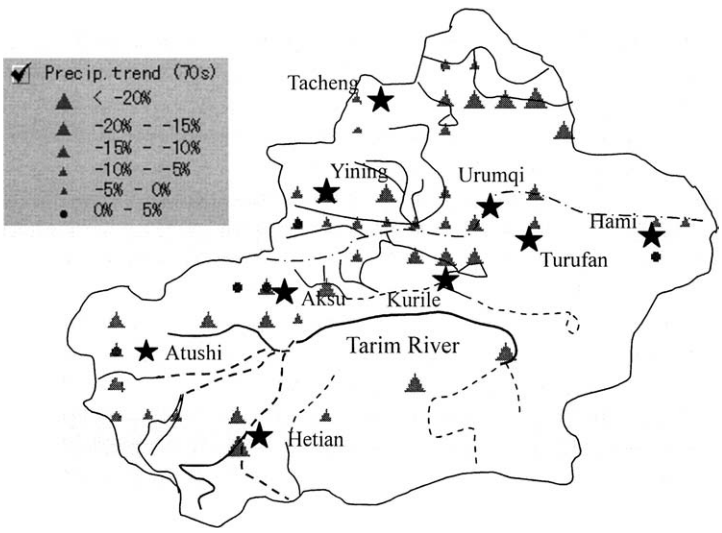


Figure 3. Temporal distribution of the precipitation at Aksu gauging station.

in the 1970s, several distinct periods for the record from 1950 to 2000 is further examined: 1970s, 1980s, and 1990s. The spatial distribution of the precipitation over major gauging stations during these three periods is shown in Figure 4. In these maps, the ratio (%) of the difference between the average annual precipitation from 1950 to 2000 and that over the distinct period (1970s, 1980s, or 1990s) to the average annual precipitation from 1950 to 2000 ($\Delta P/P$) is shown. The star symbols give the site of major cities and towns. The triangle implies decrease and



(a)

Figure 4. Changes of average precipitation over different periods: (a) 1970s, (b) 1980s, (c) 1990s.

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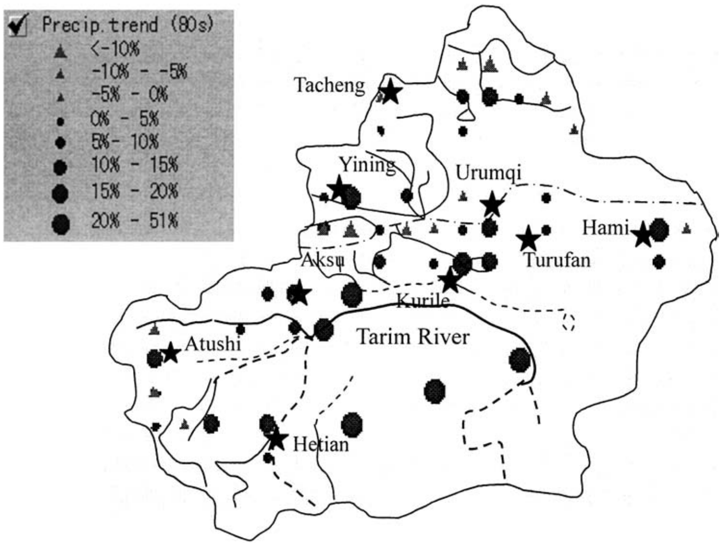

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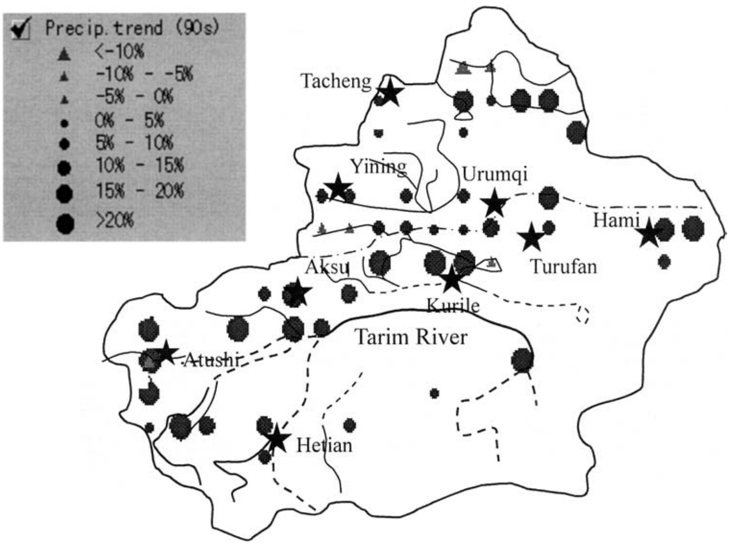


(c)

Figure 4. (*Continued*)

the circle implies increase of the annual precipitation, and the magnitude of the triangle or circle exhibits the strength of the change. The comparison shows that there is a significant decrease in the 1970s and a significant increase in the latter two decades. It dictated that the drying-up of the downstream mainstream of the Tarim River occurred in the 1970s may result from not only anthropologic activities but also climate change. However, the continuous channel desiccation during the 1980s and 1990s may mainly result from the speedy increase of water diversion from the river as well as the filling of the upstream reservoirs. At this stage of the study, the physical mechanism of this trend remains not clear. Nevertheless, two different interpretations may be offered: either the study area was affected by an increase in precipitation during the past several decades, or the trend was only the ascending part of a periodic behavior, which was not observed due to the small size of the record sampled. It seems that the temperature trends detected are more likely linked to greenhouse warming than to natural climate variability. Apparently, there is no clear significant change in precipitation, which implies that the statistical evidence of change in meteorological drought has not yet to be detected, and more thorough investigation is needed before the definite causes behind the increase of precipitation is able to be concluded. The result shows that the study area has become warmer and somewhat wetter in the last four to five decades.

In the detection of long-term trend for both temperature and precipitation time series, it is noted that two records all exhibit a jump around 1986, as shown in Figure 3. For the purpose to detect whether there is indeed a jump for these two time series, both records are divided into two samples, as given in Tables V and VI, in which the major statistics for these two time series are also listed. From the changes of the means for the two subrecords, it is noted that there seems indeed a jump for these two short records. The results of the Mann-Whitney test are given

Table V. Partitions of the temperature time series

No.	Time series	Length of record	Mean value	Standard deviation	Coefficient of variation
1	1955–1986	32	6.65	0.56	0.08
2	1987–2000	14	7.34	0.51	0.07

Table VI. Partitions of the precipitation time series

No.	Time series	Length of record	Mean value	Standard deviation	Coefficient of variation
1	1956–1986	31	146.2	22.63	0.15
2	1987–2000	14	179.7	33.20	0.18

Table VII. Mann-Whitney test results of step trend for temperature and precipitation time series

Temperature				Precipitation			
Series		Test		Series		Test	
n_1	n_2	Z_c	H_0	n_1	n_2	Z_c	H_0
32	14	3.342	R	31	14	2.550	R

in Table VII. It is interesting to note that the hypothesis H_0 is rejected at the 5% level of significance for both time series. In other words, significant jumps around 1986 did have occurred for both temperature and precipitation time series. Similar changes have been found in Europe by Franks (2002) and in Japan by Xu *et al.* (2003). The physical mechanism producing this kind of jump still needs further investigation.

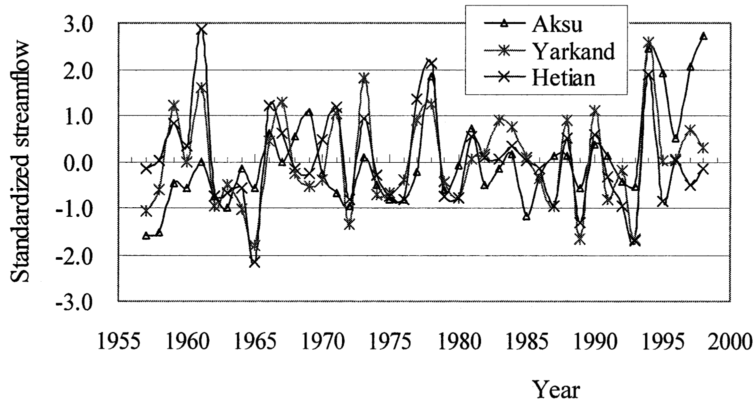
Chiew *et al.* (1995) have pointed out that changes in precipitation are amplified in streamflow, and as such, it may be easier to detect variability or climate change in streamflow rather than in precipitation or other climatic variables. River flows are a synthesis of what happens to precipitation, evapotranspiration and other components of the hydrological cycle. In response to the precipitation pattern in the study area, some of the small rivers are characterized with perennial streams. The detection of the long-term trend on streamflow may be problematic due to the large number of zero values. The detection is, therefore, undertaken on average annual runoffs in this study. The annual runoff time series in several tributaries and along the mainstream of the Tarim River over 1950 to 2000 are used. The standardized streamflow runoff from three major tributaries—Aksu, Yarkand, and Hetian rivers—are shown in Figure 5a. It is observed that the streamflow in both Aksu River and Yarkand rivers show an increase tendency, but there is a subtle reduction on the Hetian River. The results of both t-test and the Mann-Kendall test are given in Table VIII. It is interesting to note that only the Aksu River showed a significant tendency of increase at the 95% level of confidence. The streamflow on Yarkand River exhibits increase trend and the streamflow on Hetian River shows a downward trend, and both do not show significant trend. Figure 5b shows the

Table VIII. Monotonic shift test for three streamflow time series on tributaries

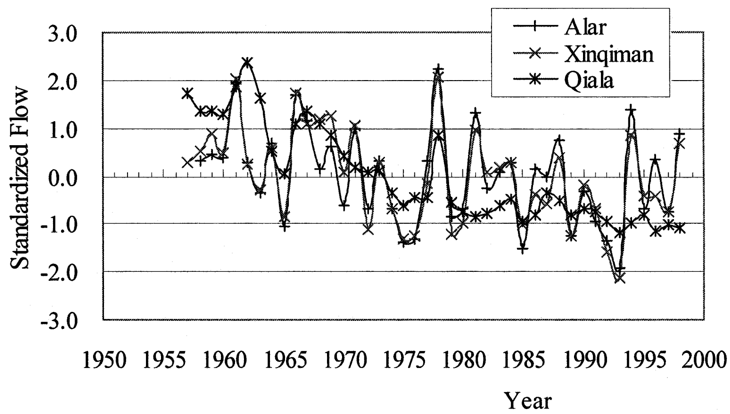
	t-test				Mann-Kendall test		
	β_0	β_1	T_c	H_0	Z_0	β	H_0
Aksu	64.868	0.4344	14.049	R	3.327	0.3700	R
Yarkand	71.072	0.0954	66.654	R	0.649	0.1113	A
Hetian	46.238	−0.1230	37.840	R	−1.301	−0.1123	A

Table IX. Monotonic shift test for three streamflow time series along the mainstream of the Tarim River

	t-test				Mann-Kendall test		
	β_0	β_1	T_c	H_0	Z_0	β	H_0
Alar	51.286	−0.2519	22.791	R	−1.887	−0.2820	A
Xinqiman	44.830	−0.3399	16.530	R	−2.601	−0.3339	R
Qiala	13.918	−0.3198	15.422	R	−7.099	−0.3019	R



(a)



(b)

Figure 5. (a) Standardized streamflow runoff on three major tributaries of the Tarim River. (b) Standardized streamflow runoff on three gauging stations along the mainstream of the Tarim River.

standardized annual runoff at three stations located in the up-, middle-, and downstream of the mainstream of the Tarim River. Similar results for the streamflows on the mainstream of the Tarim River—Alar, Xinqiman, and Qiala—are given in Table IX. It is obvious that three streamflow time series show downward trend. The decrease trends for the streamflow on both Xinqiman and Qiala are significant at 5% level of significance. The increase in precipitation and decreases in runoff in the Tarim River basin may have been attributed to both global natural climate change and anthropogenic activities that lead to environmental degradation, desertification, and overdepletion on surface and groundwater. The increase of water surface due to the construction of reservoirs greatly increases the loss of water through evaporation. The removal of vegetation cover in the watershed has the effect of exposing the water bodies to the elements of weather and thereby constitutes one of the factors that precipitated the drying-up of the Tarim River. A similar example was also found in the Tano River, where the removal of vegetation cover at its headwaters and along the river is currently causing seasonal drying-up of the hitherto perennial river (Philip and Biney, 2002).

4.2. ASSOCIATION BETWEEN TEMPERATURE/PRECIPITATION AND ENSO

Kane (1999) showed that the precipitation inside China is highly variable from one region to another, and the relationship between El Niño onsets and drought was not obvious. As described in the previous section, both spatial and temporal distributions of the precipitation in the study area are considerably uneven. For example, the annual precipitation varies from about 42.4 mm (Alar) in the upstream to about 17.4 mm (Luoqiang) in the downstream of the Tarim River basin. The inter- and intraannual changes of the precipitation are also dramatic. The ENSO is a major forcing mechanism of climatic and hydrological anomalies, and there usually are some kinds of association between ENSO and hydrological variables. For example, Mechoso and Iribarren (1992) have found a relationship between the ENSO phase and streamflow in the Negro and Uruguay Rivers. Generally, negative streamflow anomalies are associated with the cold phase, and positive anomalies with the warm phase in the Equatorial Pacific. Similar teleconnection was also found by Bordi and Sutera (2001). The possible relationship between the ENSO and the hydrological processes in the study area is also investigated in this paper. Table X shows both the Pearson correlation coefficients and the Kendall's tau between SOI and the precipitation/temperature time series. It shows that both parametric and nonparametric tests all accept the hypothesis H_0. In other words, there is no any significant association between SOI and precipitation/temperature time series. Similar results for the six streamflow time series on three tributaries and along the mainstream of the Tarim River are also given in Tables XI and XII. All these six streamflow do not show any significant correlation with the SOI time series as well. This suggests that the changes in temperature, precipitation, and streamflows in the study area may be a result of a complex linkage between ENSO phase and local climatic factors.

In an attempt to detect possible association between hydrological processes and the occurrence of warm, neutral and cold phases of ENSO, the hydrological time

Table X. Pearson cross-correlation coefficient and Mann-Kendall τ_a/τ_b between SOI and precipitation/temperature

	Pearson		Kendall		
	r_c	H_0	τ_a/τ_b	Z_c	H_0
Temperature	−0.191	A	−0.122	−1.184	A
Precipitation	−0.163	A	−0.068	−0.646	A

Table XI. Pearson cross-correlation coefficient and Mann-Kendall τ_a/τ_b between SOI and streamflow from three tributaries

	Pearson		Kendall		
	r_c	H_0	τ_a/τ_b	Z_c	H_0
Aksu	−0.208	A	−0.116	−1.073	A
Yarkand	0.041	A	0.083	0.774	A
Hetian	0.125	A	0.134	1.235	A

Table XII. Pearson cross-correlation coefficient and Mann-Kendall τ_a/τ_b between SOI and streamflow along the mainstream of the Tarim River

	Pearson		Kendall		
	r_c	H_0	τ_a/τ_b	Z_c	H_0
Alar	0.122	A	0.123	1.123	A
Xinqiman	0.165	A	0.106	0.975	A
Qiala	0.223	A	0.163	1.506	A

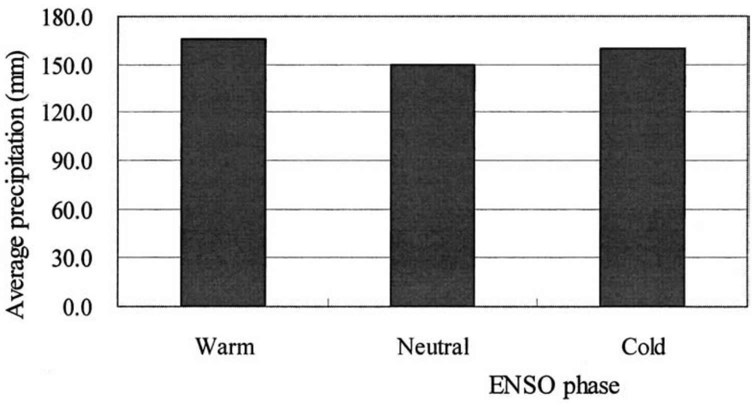


Figure 6. Average precipitation over different ENSO phases.

series is further divided into three samples, each one corresponding to the warm, neutral, and cold years. Figure 6 shows the mean annual precipitation over ENSO warm, cold, and neutral years in the study area. It shows that there are no substantial differences in the results. When a warm event occurs in the Equatorial Pacific, the precipitation in the study area does not show any tendency to be above or below the average. During cold phases, the flows also do not show any significant tendency to be different from those in other two phases. In other words, the differences between neutral and cold/warm phases may be negligible. Tables XIII–XV give the Wilcoxon test results for precipitation, temperature, and six streamflow time series. It is obvious that nearly all time series accept the hypothesis H_0, but the

Table XIII. Wilcoxon test for precipitation/temperature time series

	El Niño		La Niña	
	W^*	H_0	W^*	H_0
Temperature	1.684	A	1.045	A
Precipitation	1.198	A	0.936	A

Table XIV. Wilcoxon test for streamflow from three tributaries

	El Niño		La Niña	
	W^*	H_0	W^*	H_0
Aksu	0.412	A	−0.656	A
Yarkand	−1.160	A	−0.930	A
Hetian	−1.871	A	−0.701	A

Table XV. Wilcoxon test for streamflow along the mainstream of the Tarim River

	El Niño		La Niña	
	W^*	H_0	W^*	H_0
Alar	−1.596	A	−0.283	A
Xinqiman	−1.909	A	−1.199	A
Qiala	−1.966	R	−0.611	A

streamflow at Qiala shows a significant association with the ENSO warm phase. Whether this association is resulted from climate change needs further investigation, the ENSO events seemed to marginally affect the climate and hydrologic cycles in the study area.

5. Conclusions

For the purpose to estimate the impact of climate change on the hydrological processes at Tarim River basin, both parametric and nonparametric tests are used to detect the plausible long-term trend of the temperature, precipitation, and streamflow time series in the study area. Result shows that significant monotonic trend did occur for the temperature time series at the 5% level of significance. Similar trends have also been detected for the streamflow time series at two gauging stations along the mainstream of the Tarim River—Xinqiman and Qiala. The streamflow at Aksu show a significant increasing monotonic trend. The average annual precipitation exhibited an increasing trend with the magnitude of 6.8 mm per decade, but this is not statistically significant. It is interesting to note that except the Hetian River, other two tributaries all exhibited an increasing trend of the annual streamflow. On the contrary, the streamflows at three gauging stations along the mainstream of the

Tarim River showed a decreasing trend. In other words, increase of the streamflow at the headwater of the Tarim River was resulted from the increase of precipitation due to, possibly climate change, but the anthropogenic activities such as overdepletion of the surface water resulted in the decrease of the streamflow in the mainstream of the Tarim River. It is interesting to note that a jump occurred in both temperature and precipitation time series around 1986. Whether this resulted from climate change needs further study with the combination of climatological analysis. Correlation analysis between the hydrological time series and SOI showed that there is no significant association between these time series and the ENSO. In order to further investigate the influence of warm, neutral and cold phases of ENSO in the Equatorial Pacific on the Tarim River basin, the hydrological time series were divided into three samples, one for each of the warm, neutral, and cold phases. The results show that there is no difference for the temperature, precipitation, and streamflow in different ENSO phases. In other words, the relationship between the ENSO and the precipitation in the study area is not yet clearly understood. Future efforts will be planned to investigate whether the trend (monotonic and step changes) is related to some multidecadal variability of the climatic system. The result shows that the study area has become warmer and wetter in the last few decades, but positive trend in precipitation is not statistically significant. The negative trends in streamflow have mainly resulted from anthropogenic activities. The potential impact of ENSO on local climate is likely marginal.

Although the result obtained in this investigation is preliminary due to the fact that only very limited number of gauge stations were available in the study area, the conclusions would be helpful for the further examination in the ongoing study. From the analysis made in this paper, it is clear that the plausible climate change resulted in the increase of both precipitation and streamflow. But the positive effect on streamflow from climate change may be upset by the increase of evaporation due to the increase of temperature. The anthropogenic activities such as overexploitation of the surface water resulted in the decrease of the streamflow in the mainstream of the Tarim River. Considering the fact that the risk of water shortage from warmer conditions may occur in the future, an innovative scenario to incorporate climate change study into regional water resources planning and to implement precautionary measures need to be investigated. Leaving natural ecosystems with sufficient water may be an important driver for water resources planning and management in the study area.

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