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Progress and prospects of climate change impacts on hydrology in the arid region of northwest China

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ABSTRACT

The arid region of Northwest China, located in the central Asia, responds sensitively to global climate change. Based on the newest research results, this paper analyzes the impacts of climate change on hydrology and the water cycle in the arid region of Northwest China. The analysis results show that: (1) In the northwest arid region, temperature and precipitation experienced "sharply" increasing in the past 50 years. The precipitation trend changed in 1987, and since then has been in a state of high volatility, during the 21st century, the increasing rate of precipitation was diminished. Temperature experienced a "sharply" increase in 1997; however, this sharp increasing trend has turned to an apparent hiatus since the 21st century. The dramatic rise in winter temperatures in the northwest arid region is an important reason for the rise in the average annual temperature, and substantial increases in extreme winter minimum temperature play an important role in the rising average winter temperature; (2) There was a significant turning point in the change of pan evaporation in the northwest arid area in 1993, i.e., in which a significant decline reversed to a significant upward trend. In the 21st century, the negative effects of global warming and increasing levels of evaporation on the ecology of the northwest arid region have been highlighted; (3) Glacier change has a significant impact on hydrology in the northwest arid area, and glacier inflection points have appeared in some rivers. The melting water supply of the Tarim River Basin possesses a large portion of water supplies (about 50%). In the future, the amount of surface water will probably remain at a high state of fluctuation.

1. Introduction

IPCC Fifth Assessment Report on Climate Change points out that: over the past half century, almost all regions of the world have experienced a heating process (IPCC, 2013), and the fastest warming region is the mid-latitudes of the northern hemisphere (Ji et al., 2014). The report further shows that global climate change is caused by both natural factors and human factors which work together. However, human activity is very likely the main reason for global warming since the mid-20th century, with the possibility being more than 95% (IPCC, 2013). Rising temperatures accelerate the global water cycle, exacerbate extreme hydrological events, and lead to the global redistribution of water resources in different scales. Determining exactly how global climate change impacts water systems has been an important research focus of the Intergovernmental Panel on Climate Change (IPCC), other international organizations (e.g., the American Institute of Architects, California Council (AIACC) project team), and research institutions.

The arid region of northwest China is located in the mid-latitudes of Eurasia, and is one of the areas in the world that responds most sensitively to global climate change (Y.N. Chen et al., 2012b). A variety of model simulation results show that if CO_2 incremental emission is at a rate of 1%/year, then the rising average temperature in the arid areas of Central Asia will exceed 40% of the global average temperature rise level (Aðalgeirsdóttir et al., 2005). In the context of global warming, the meltwater water-based system is very fragile in the northwest arid region. The water resources and changes in their spatial and temporal distribution due to climate change will cause the mismatched features of water resources and the spatial distribution of productivity to become increasingly dire. The growing population coupled with increasing irrational land and water resources development activities will finally lead to the water resources supply and demand contradiction of the oasis

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economy and desert ecology in the northwest arid regions to become more acute (Richard, 2008). Consequently, this will result in research on the impact of climate change on water systems vulnerability and security in the northwest arid area becoming the focus of the community's attention.

Water, largely originated from the mountain areas, has been a most critical factor to drive the energy and mass circulation in this region, which responds sensitively to the global climate change, thus, it plays a crucial role in future sustainable development. With the increasing concern of global environmental and ecological degradation, there has been an urgent need to investigate the related water cycle changes. This paper examines the major issues e.g. climate characteristics, the vulnerability water resources and the water system in the Northwest China, which has great significance to investigate the regional hydrological cycle under the content of climate change. Thus, it is necessary to plan ahead, and actively respond and adapt to the possible impacts brought by future climate change, especially the impacts on water resources, to ensure sustainable development of ecological safety in the northwest arid area. It is also noteworthy for water managers to cast attention to the spatial and temporal distribution of water resources caused by variation in water cycle, to secure informed policy-making in the layout, development, utilization, protection and management of water resources in a reasonable and sustainable way.

2. Data and methods

2.1. Data

Excluding several sites that have prolonged missing data, the data used in this study are collected from 74 ground-based meteorological stations in the region operated by the China Meteorological Administration, which have complete records of almost all the climatic factors from 1958–2012, and used the Cokriging and inverse distance weighted techniques to interpolate the several missing data. Grid data (HadCRUT4) during 1958–2012 used in this study developed by the Climatic Research Unit (University of East Anglia) in conjunction with the Hadley Centre (at the UK Met Office). In addition, 7 sites have complete observed monthly data of direct radiation and solar diffuse radiation. The observed pan evaporation data used for the calibration and validation of PenPan Model ranges from 1958 to 2001. The pans are made of copper with a diameter of 0.2 m and depth of 0.1 m. They are positioned on a frame of 0.7 m above the ground and have a rim to keep birds away from drinking.

The Normalized Difference Vegetation Index (NDVI) are collected from the Global Inventor Modeling and Mapping Studies (GIMMS). The length of the time series from 1982 to 2006. In order to obtain more time-series data, the MODIS data with the spatial resolution of 0.05° during 2001–2011 are also collected. In this study, two kinds of data sources in the overlap period 2001–2006 were corrected to maintain the consistency of data.

There were 29 sampling sites chosen within the Tizinafu River's principal course and its tributaries. Water samples including surface water, precipitation, pond, and ice-melt water were collected along Tizinafu River from June to October 2011, and at hydrology stations through 2011 and 2012. Precipitation was sampled from July 2011 to October 2011, and May 2012 to August 2012. A total of 31 samples of river water were collected at sites of interest, and 152 samples were collected at stations.

2.2. Methods

2.2.1. Trend analysis with Mann–Kendall non-parametric test

In this study, we used the Mann–Kendall test to detect trends in ET_0 and related meteorological factors. The Mann–Kendall test is often used to detect whether a time series has a significant trend or not (Gan, 1998).

2.2.2. Estimation of the 0 °C (freezing) layer height (FLH)

A linear interpolation method was used to calculate the FLH at each time (assumed the temperatures between two standard barospheres of 500 and 850 hPa to have uniform changes in the vertical direction). Subsequently, the mean of two times was calculated, so as to obtain daily FLH. Finally, daily values from June to August were averaged to obtain the summer FLH. The linear interpolation method was used to calculate the FLH with the following equation:

$$H_i = \frac{H_j - H_k}{T_j - T_k}(T_i - T_k) + H_k \tag{1}$$

where variable H represents the height (m), T represents the temperature (°C), subscript i is the identifier of FL, j and k are the identifiers of upper and lower standard barospheres of FL, respectively.

2.2.3. Estimation of pan evaporation using the PenPan model

A physically-based model is preferable to estimate E_p more accurately. Rotstayn et al. (2006) coupled the aerodynamic component developed by Thom et al. (1981) with the radiative component of Linacre (1994) to develop the PenPan model based on the mass and energy balance of the pan. These studies focused on the Class A pan with diameter of 1.21 m and depth of 0.254 m. However, the evaporative pan widely used in China is different from Class A pan with diameter of 0.2 m and depth of 0.1 m. Therefore, this study modifies the PenPan model for estimating the pan evaporation measured from Chinese micro-pan (Z. Li et al., 2013b).

PenPan model is formulated at monthly basis, and calculates the pan evaporation rate (E_p, kg m^{-2} s^{-1}) as the sum of radiative ($E_{pan,R}$) and aerodynamic ($E_{pan,A}$) consumptions:

$$\mathrm{E}_p = E_p, R + E_p, A = \left(\frac{s}{s + a_\gamma}\frac{R_n}{\lambda}\right) + \left(\frac{a_\gamma}{s + a_\gamma} f_q(u) D\right) \tag{2}$$

where E_p is the pan evaporation rate (kg m^{-2} s^{-1}), s is the slope of saturation vapor pressure (e_s) curve (Pa K^{-1}) at air temperature T_a (K) measured at two meters above the ground, γ ($\approx$ 67 Pa K^{-1}) is the psychrometric constant, R_n (W m^{-2}) is the net irradiance of the pan, λ (J kg^{-1}) is the latent heat of vaporization, $D = e_s - e_a$ is the vapor pressure deficit at two meters and e_s is the saturation vapor pressure (P_a). $f_q(u)$ (kg m^{-2} s^{-1} Pa^{-1}) is an empirical vapor transfer function expressed as:

$$f_q(u) = 1.39 \times 10^{-8}(1 + 1.35u^2) \tag{3}$$

2.2.4. Attribution of the change in pan evaporation rate

For attribution, the change in pan evaporation rate is given by differentiating the equation of Roderick et al. (2007). The contribution of meteorological variables on evaporative demand is obtained from the partial derivatives multiplied by the annual average trend:

$$\frac{dE_p}{dt} = \frac{dE_{p,R}}{dt} + \frac{dE_{p,A}}{dt} \tag{4}$$

The term $dE_{p,A}/dt$ is then partitioned into three components representing the change of wind speed, vapor pressure deficit and temperature respectively.

$$\frac{dE_{p,A}}{dt} \approx \frac{\partial E_{p,A}}{\partial u}\frac{du}{dt} + \frac{\partial E_{p,A}}{\partial D}\frac{dD}{dt} + \frac{\partial E_{p,A}}{\partial s}\frac{ds}{dT_a}\frac{dT_a}{dt} \tag{5}$$

2.2.5. Measurement of $\delta^{18}O$ and δD

The measurement and analysis of water samples was completed using the Los Gatos Research liquid water isotope analyzer. The Analyzer uses LGR's patented Off-axis ICOS technology, a fourth-generation cavity ringdown spectroscopy (CRDS) technique, which employs an optical cavity to greatly enhance spectral absorption. As with all LGR analyzers, the IWA models provide users with measured high resolution absorption spectra for comprehensive performance validation and diagnostics in real time. The measured data use the LWIA Post software for data analysis. Accuracy of the measurements was 0.1% for $\delta^{18}O$ and 0.3% for δD. All $\delta^{18}O$ and δD values are expressed related to Vienna Standard Mean Ocean Water (V SMOW) in ‰. The final results were expressed by the relative value over SMOW:

$$\delta^{18}O = \left[({}^{18}O/{}^{16}O)_{sample} - ({}^{18}O/{}^{16}O)_{SMOW}\right]/({}^{18}O/{}^{16}O)_{SMOW} \times 10^3 \tag{6}$$

$$\delta D = \left[(D/H)_{sample} - (D/H)_{SMOW}\right]/(D/H)_{SMOW} \times 10^3 \tag{7}$$

3. Results and analysis

3.1. Climate change in the northwest arid region

3.1.1. Temperature and precipitation increased "sharply" in the northwest arid region

(1) Average temperature rise is above the global average

Over the past half century, the rate of temperature rise in the northwest arid area is up to 0.34 °C/10 a, which is significantly higher than the global average (0.12 °C/10 a) (IPCC, 2013). Analysis showed that a significant temperature rise occurred in the late 1980s. During 1960–1986, and the average temperature increased to a lesser extent. In 1987, the average annual temperature in the northwest arid area showed an abrupt change, and the elevated rate of 0.517 °C/10 years showed an increasing trend to accelerate. Using the Grid data (HadCRUT4) found that since 1997, although the temperature has been in a high and volatile state, the warming trend is not very clear (Fig. 1). The statistical analysis of 74 sites in the northwest arid area demonstrated that in the 1990s, about 96% of the stations had an increasing temperature trend; whereas, in the 21st century, over 92% of the stations had an increasing temperature trend, but the rise was weakened compared with the 1990s (Fig. 2). At the same time, extreme temperatures had a significant warming trend, abnormal warm extreme events increased significantly, and abnormal cold extreme events reduced significantly (H.J. Wang et al., 2013a).

(2) Precipitation rise showed a dynamic increase

In the past half century, precipitation exhibited similar changes in the northwest arid region. During 1960–1986, precipitation change remained in a relatively stable stage, and precipitation showed a "sharply" increase in 1987. The station statistics showed that approximately 80% of the stations had a decreasing trend in the 1970s, and then transformed into an increase of 75% in the late 1980s and 88% in the 1990s for the entire northwest arid region.

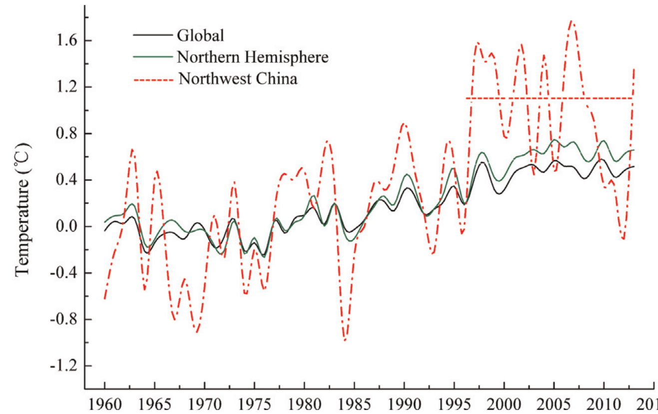

Fig. 1. Trends of temperature in the global, Northern Hemisphere, and arid region of Northwest China during 1960–2013.

The 1990s in the northwest arid area is the most humid 10 years in the past half century. It is worth mentioning that in the last 10 years, the increasing rate of precipitation reduced in the northwest arid area, and about 35% of the stations showed a more decreasing trend than they had in the 1990s (Fig. 3). According to the increasing temperatures and precipitation in the northwest arid region in the past 30 years, some scholars proposed that the west Tianshan region, which represented Xinjiang, showed a warm and humid climate change (Shi et al., 2003); whereas, some other academics suggested that it may due to climate fluctuations. Tree-ring studies showed that Tianshan Mountains and northern Xinjiang experienced eight warm phases, seven-to-eight cool phases, seven dry phases, and seven humid phases over the past 200–300 years (F. Chen et al., 2012a; Yang et al., 2012).

3.1.2. Increases in winter temperatures effectively raised the average annual temperature

The increasing winter temperature has found in the northwest arid region over the past 50 years (Li et al., 2012). Specifically, the study of different seasonal temperature variation showed that the winter average temperature contributed 57.01% to the temperature increase rate of annual temperature (Fig. 4); thus, these greatly increased winter temperatures in the northwest arid area may be an important reason for raising the average annual temperature.

Detailed analysis of winter temperature changes also found the increase in the winter extreme minimum temperature to be very intense in the northwest arid region. In the past 50 years, the winter extreme minimum temperature increased observably, which is from −15.08 °C in the 1980s to −13.01 °C in the 1990s, and rise to −12.97 °C in the 2000s (2000–2010) (B.F. Li et al., 2013a). The increasing of winter extreme minimum temperature dramatically boosted the average winter temperatures. In order to explore the reasons behind this faster rising rate of winter temperatures, selected seven atmospheric circulations, including the Siberian High (SH), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Pacific North Oscillation (PNA), the Antarctic Oscillation (AAO), the Southern Oscillation (SO) and the Westerly Index (WCI), and compared the effects of them on climate system in the arid areas of the northwest according to elasticity theory. The results show that the SH activity and carbon dioxide emissions are the main factors behind the changes in winter temperature in the northwest arid region. Furthermore, a high correlation between winter temperature and the Siberian High Index ($R = -0.715$, $P < 0.001$) is found in the northwest arid region, which is significantly higher than the correlation with carbon dioxide ($R = 0.51$, $P < 0.001$). During the mid-1980s to the 1990s, the SH exhibited an apparent weakening trend, while the winter

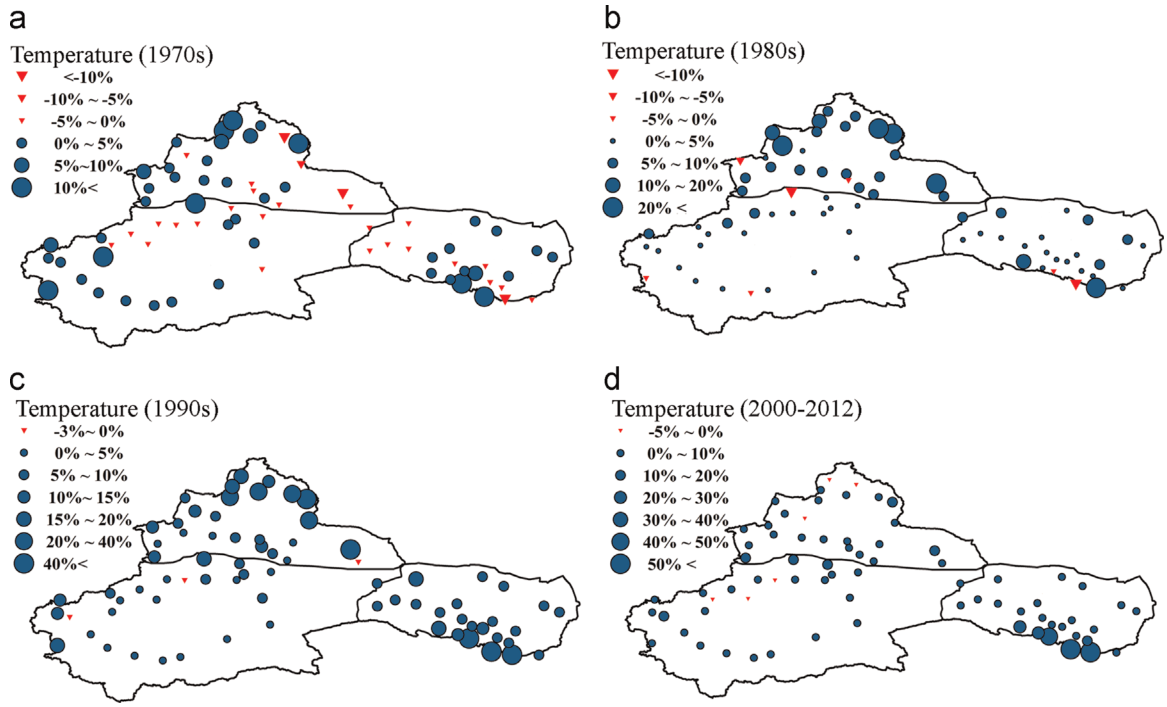

Fig. 2. Trends of temperature in the arid region in the (a) 1970s compared 1960s, (b) 1980s compared 1970s; (c) 1990s compared 1980s, and (d) 2000–2012 compared 1990s.

temperatures rose during this period. Meanwhile, in the past five years (2005–2010) SH pressure rose slightly, while winter temperatures subsequently decreased slightly; the two changes demonstrate synchronization (Fig. 5). Why the temperature and precipitation showed sharp incremental changes in 1987? There has not had an ultimate explanation (Chen and Xu, 2004).

Atmospheric circulation is a major factor in the impact of climate change, and the use of a remote-related index is a reliable method to study climate change (Mishra and Singh, 2010). In the study of climate and water resources changing trend in the northern region during nearly 50 years, the results showed that: (1) the winter NAO index has a significant positive correlation with average annual temperature and winter temperature; (2) the AO index was positively correlated with average annual temperature; (3) the summer AO index and the spring and summer temperature have a positive correlation; and (4) the winter AO index is positively correlated with winter temperatures. The NAO and AO index has a certain influence on precipitation, but according to temperature; however, the main factor affecting the west of northern Xinjiang precipitation is the spring NAO index (Yang et al., 2010). The analysis of the 0 °C layer height (Eq. (1)) and summer runoff in Southern Tianshan, North Tianshan, Northern Kunlun Mountains,

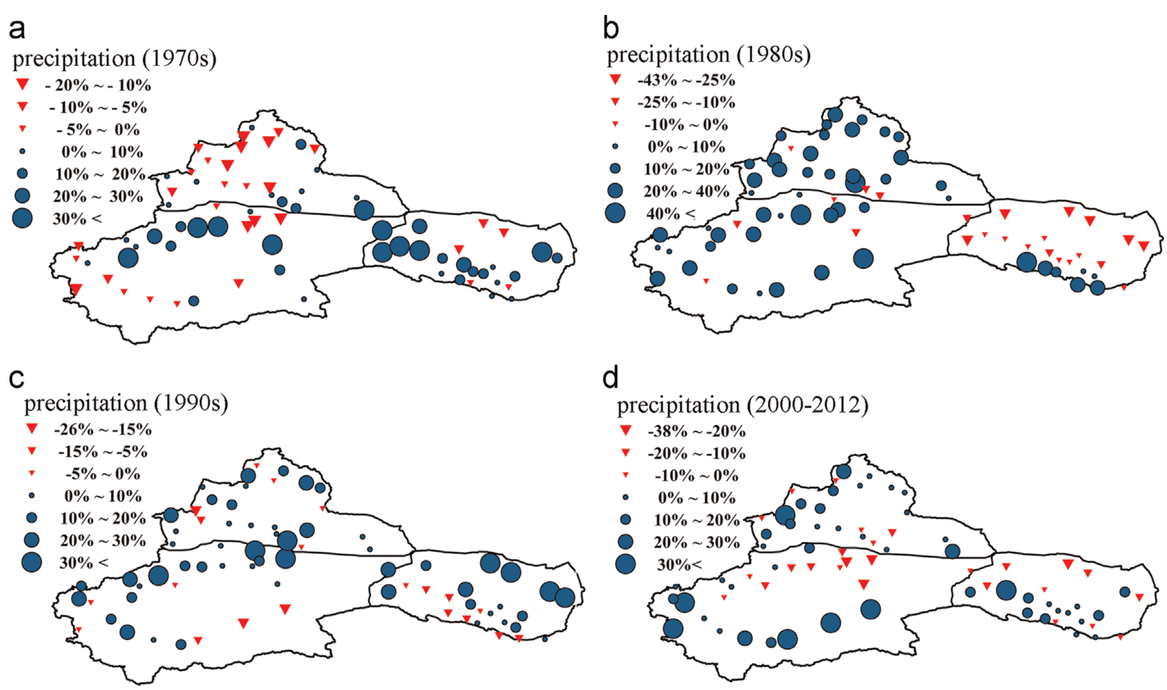

Fig. 3. Trends of precipitation in the arid region in the (a) 1970s compared 1960s, (b) 1980s compared 1970s; (c) 1990s compared 1980s, and (d) 2000–2012 compared 1990s.

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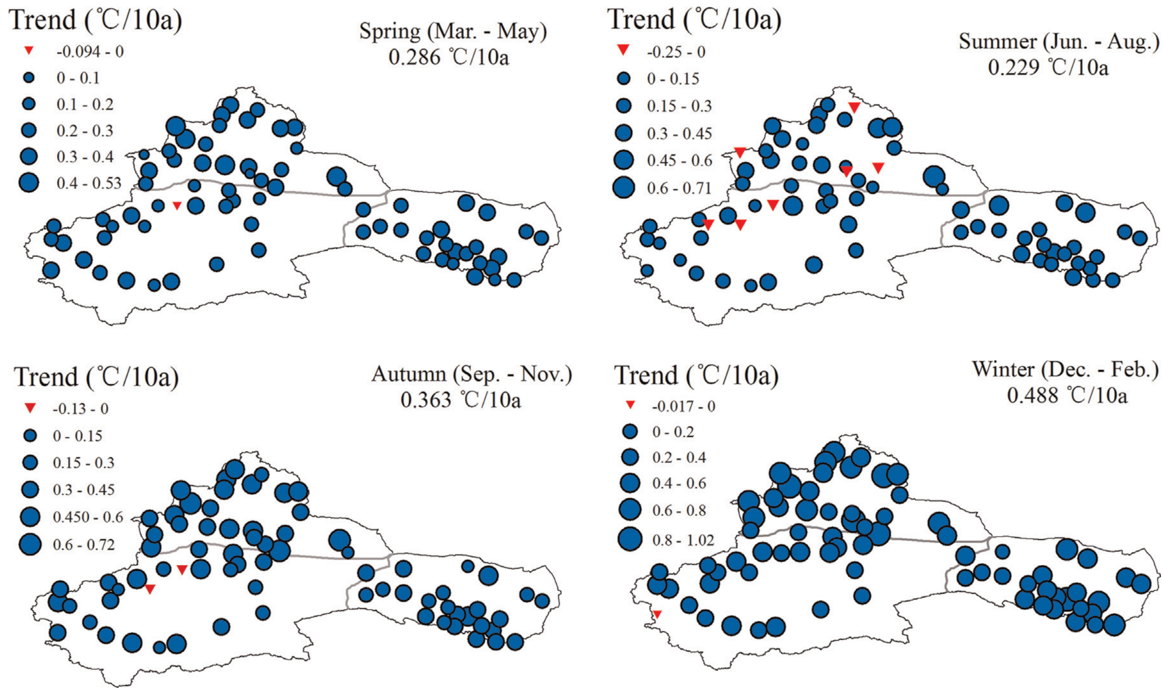

Fig. 4. Different seasonal temperature variation in northwest China.

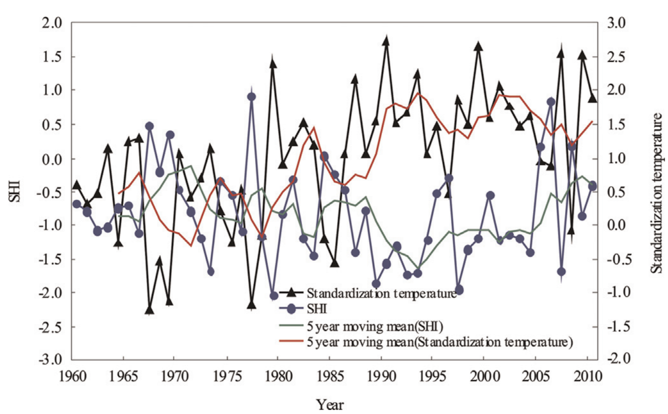

Fig. 5. The Siberian High Intensity and the winter temperature in the arid region of northwest China (Li, et al., 2012).

and Northern Qilian Mountains over the past 50 years found that the 0 °C layer height variations in different regions are inconsistent, and changes in river runoff and 0 °C layer height are closely related (Z.S. Chen et al., 2012c).

3.1.3. Pan evaporation reversed to an upward from a downward trend

Traditionally, measurements of evaporation from pans have been used to represent the evaporative demands of the atmosphere, and often represent potential evaporation, which plays a key role in global and regional hydrological processes, and experiences the most direct impact of climate change. Over the past half century, despite the rise in air temperature, a decrease of pan or potential evaporation has been commonly found worldwide, especially in the Northern Hemisphere (Peterson et al., 1995; Brutsaert and Parlange, 1998; Roderick and Farquhar, 2002; Gong et al., 2006; Burn and Hesch, 2007; Roderick et al., 2007; Szilagyi, 2001, 2007; Cong et al., 2009; Yang and Yang, 2011). This results in controversy regarding changes to the hydrological cycle expected by using Penman's proportional hypothesis (1948) (Penman, 1948) and Bouchet's complementary relationship (1963) hypothesis (Bouchet, 1963). Most of the pan-evaporation measurements in China ended in 2001. PenPan model is preferable to estimate E_p more accurately. A recent study based on the pan evaporation dynamics in the hyper-arid region of China during the period of 1958–2010 using a generic physical model based on long-term meteorological data collected at 81 ground-based meteorological stations, has some new explanation. The monthly pan evaporation data observed at the 81 ground-based meteorological stations of the China Meteorological Administration from 1958 to 2001 was used, at first, we took 50 stations in the entire Xinjiang Uyghur Autonomous during 1958–2001 in the western part of the study area to calibrate the PenPan model, and then took 31 stations during 1958–2001 in the Hexi Corridor in the eastern part of the study area to validate the model. The comparison with pan evaporation observations was excellent. And then the study reconstructed the data from 1958 to 2010 with the PenPan model (Eq. (2)) for the statistical analysis. (Z. Li et al., 2013b). Therefore, the statistical analysis of pan evaporation data in this paper is consistent. The results showed that pan evaporation in the region

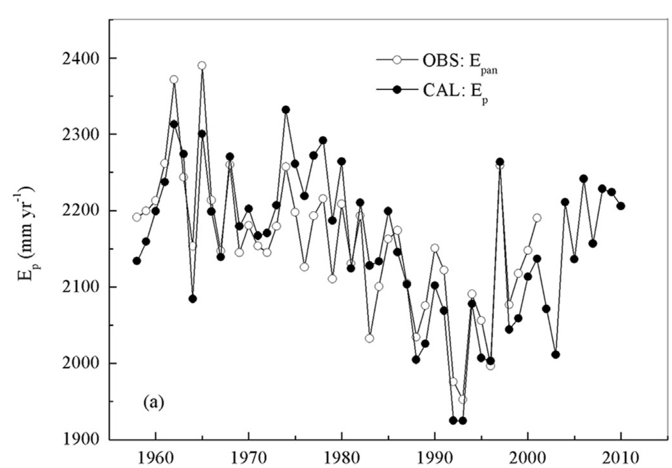

Fig. 6. Change of annual E_p in the arid region of Northwest China from 1958 to 2010 (Z. Li et al., 2013b).

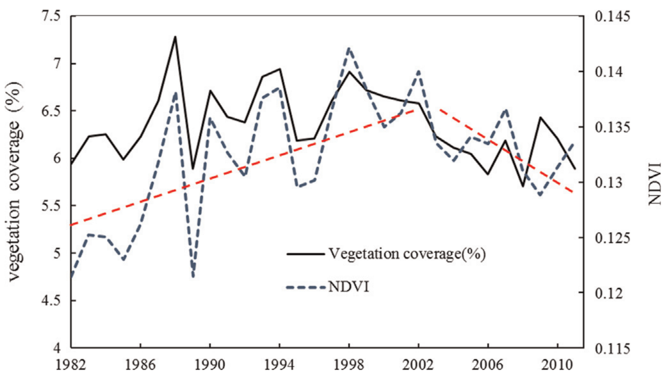

Fig. 7. Dynamic changes of vegetation area and NDVI in the Northwest China.

exhibited an obvious decreasing trend until the early 1990s (1993), at a rate of $-6.0\ \text{mm yr}^{-2}$. However, the downward trend reversed in 1993, and the rate of increase after that was $10.7\ \text{mm yr}^{-2}$ (Fig. 6) (Z. Li et al., 2013b). This is consistent with nationwide findings (Liu et al., 2011). assessed the sensitivity of rates of evaporative demand to changes in aerodynamic and radiative components (Eqs. (4) and (5)), and found that pan evaporation could be mostly attributed to changes in the aerodynamic component, with some regional contributions from solar irradiance. The aerodynamic component at 77% of the 81 observation stations involved in this study decreased during 1958–1993, leading to a decrease of E_p at a rate of $-5.6\ \text{mm yr}^{-2}$; the component at 79% of the stations increased during 1994–2010, leading to an increase of E_p at a rate of $8.6\ \text{mm yr}^{-2}$. The near-surface wind speed is the primary factor for the decline of pan evaporation during 1958–1993, while both wind speed and vapor pressure are the primary factors responsible for the increase of pan evaporation from 1994–2010 (Z. Li et al., 2013b).

The increases of temperature and pan evaporation may bring some adverse ecological effects. Recent research results show that the vegetation coverage and NDVI in the arid region of Northwest China exhibit an increased trend before 2000; however, the trends reversed to decrease since 2000 (Fig. 7) (Zhao et al., 2011; Y.F. Wang et al., 2013b; Li and Chen, 2014). Terrestrial vegetation dynamics are closely influenced by both climate and land use/cover change caused by human activities. Vegetation dynamics in arid areas have been shown to be more sensitive to climate change when compared with those in other regions. The decrease of the vegetation coverage and NDVI may be related to the temperature, precipitation, and evaporation during the past 30 years. The increases of temperature, pan evaporation and decreases of precipitation may conjointly cause a heavy loss of soil moisture, which leads the shallow roots of desert plants to weaken and die, thereby reducing species diversity and vegetation cover. The influence of human activities on vegetation is the opened up and abandoned of the wasteland. The rapid growth of population and expansion of cultivated land by human was mainly sourced from reclamations of wasteland and natural grassland. Oasis mainly produces the agricultural economy, because of the limitation of the condition and the law, the distribution of the vegetation/crops has not only the spatial distribution law, but also has the part variation, showing the random variety characters (Wang et al., 2014).

3.2. The vulnerability water resources and the water system in the northwest China

The characteristics of water formation, spatial and temporal distribution, and the water supply in the northwest arid region are very distinct. The unique water cycle has a strong representation in the world arid area. Northwest arid area rivers originate from mountains, and there is ice–snow meltwater on the high mountains, precipitation in the mid-mountain forest, and fissure water in the low mountain areas. It also has complex multi-components that converge in the mountains and constitute the surface water resources in arid areas. For a long time, the water resources relied on natural water resources in the northwest arid area, which maintain the fragile balance in the water cycle. Under the impact of global warming, the vulnerability of water systems and uncertainty of water resources are increasing.

3.2.1. Changes in hydrology and water resources under the effect of a weak exchange in water vapor

Climate change under the effects of weak exchange of vapor has an important impact on water resources formation, and spatial and temporal variations in the northwest arid region. The water system is clearly vulnerable in the northwest arid region; as global warming increases the frequency and intensity of extreme hydrological events, the uncertainty of volatile hydrology and water resources in arid inland river basins in the northwest region is also exacerbated.

The latest research results of water resources show that: (1) The runoff showed a "sharply" increase. From runoff prolonged sequence detection, some larger rivers that are supplied by glacier melt water have experienced a widespread "sharply" increase in 1994. For example, the Kaidu River runoff increased 26.5% from 1994–2010 to 1960–1993, but the mutation time is later than temperature and precipitation in 1987 (Y.N. Chen et al., 2013b). (2) Runoff increased in the flood periods. The analysis of the changes of runoff during the year in the northwest arid area found that some rivers with large glaciers and snow melt water supply occur in earlier periods of glaciers and snow melt, and the phenomenon of increased flood ablation appears, which is mostly prominent in the early 1990s. For example, in the Tarim Basin, the proportion of glacial melt water runoff during 1991–2006 increased from 41.5% in 1961–1990 to 46.5% (Gao et al., 2010). (3) The abundance of runoff is intensified. Climate change has exacerbated hydrology fluctuations and water uncertainty of the inland river basins. For example, statistical analysis of the Tarim River Basin over the past 50 years showed that upstream's (Aksu River, Yarkand River, Hotan River) water import into mainstream (Alar hydrological station) in 2009 and 2010 were $14.02 \times 10^8\ \text{m}^3$ and $72 \times 10^8\ \text{m}^3$, the ratio of the minimum (2009) and maximum (2010) is more than five times.

In the northwest arid area, various aspects of the water cycle are significantly affected by climate and land patterns. Furthermore, the water resources are complex, and water runoff has variable and large elasticity; thus, small changes in precipitation and temperature due to climate change will lead to more substantial runoff changes, and have a significant impact on the eco-hydrological processes in arid areas. The effects of climate change on mountain water cycle elements have exacerbated the instability of the water system. Under the background of global warming, the precipitation and snow melt water supply of water-based systems are more fragile, and human activity is changing the natural water cycle basin.

3.2.2. Glacier water resources and glacier inflection points

The runoff of the northwest arid area strongly depends on glaciers (snow). Specifically, with the intensification of warming and extreme hydrological events, changes in glacier water resources will become increasingly complicated. The mountain glaciers melt and retreat has been accelerated by climate change, particularly by the impact of winter temperatures, which change the share of the different sources of water. Some rivers with large glaciers and snow melt water supply occur in earlier periods of glaciers and snow melt, with a resulting phenomenon of increased flood ablation. However, in the long term, with further increases in temperature, the rivers mainly recharged by meltwater rivers will appear as inflection points of glaciers melting due to glacial retreat and reduce the storage capacity of glaciers; then, the amount of water in the summer would reduce, and the surface availability of water would decrease sharply, or variability would increase because of the influence of abnormal rainfall.

The results demonstrate that in the past 50 years, 82.2% of glaciers in western China are retreating, and glacier area has decreased by 4.5% (Liu et al., 2006). Especially since the 1990s, glacial retreating trends are exacerbated in the northwest arid area, with the largest number and magnitude of glacier retreat since the 20th century, and being in a period of an accelerating process of withdrawal and strong ablation (Li et al., 2010). It is worth noting that, since these glacier areas are relatively small, the impact of the meltwater change on runoff is limited. However, even though the increase in runoff is not very obvious when the temperature increases, the impact of the turning point of glaciers shrinking with glacier retreat or the disappearance of glaciers should not be ignored. For example, the ratio of glacier areas reduction were 25% and 11% in the west and east of eastern basin in Xinjiang (Li et al., 2010), glaciers in here already been in a strong ablation, even appeared glaciers inflection point. Another example is the Heihe River Basin located in the middle of the Qilian Mountains; there, the glaciers shrink rate is 29.6% over the past 50 years (H. Chen et al., 2013a), and the number of glaciers was reduced from 967 in the 1960s to about 800 in 2010 (Huai et al., 2014). Moreover, in the Shiyang River Basin located in the eastern section of the Qilian Mountains, the glacier reduction ratio is 30% (Wang et al., 2012) and the retreat of glaciers melting is in a strong state. In particular, in the Shiyang River Basin of the eastern section of the Hexi Corridor, the rivers' hydrological process and water resources will become more complex due to the sharp ablation in glaciers.

Some rivers have a large share of glacier meltwater in the northwest arid region. Increased glacial melt water will make the annual runoff remain highly volatile over a long period. These rivers, such as the Aksu River, Yarkand River, Hotan River of the Tarim River Basin, the Shule River of Hexi Corridor, etc., are largely regulated by glacial melt water. With the recent warming trend, runoff is also increasing quite obviously. This can be seen in the main tributaries of the Aksu River and the Kumalake River, which have a high glacial meltwater runoff component of 47%. Moreover, in the past 30 years, the mountains' water increased by about 31.2% (Shen et al., 2009).

3.2.3. Composition and glacial runoff water partition

Water formation and the transformation of the northwest arid region have distinct characteristics, especially in the composition of runoff and water components, which have a strong representation in the world arid region. The rivers originated entirely from mountains. There is ice–snow meltwater on the high mountains, precipitation in the mid-mountain forest and fissure water in the low mountain areas, which converge in the mountains and constitute the surface water resources in arid areas. Global warming exacerbates the uncertainty of water resources, accelerates the glaciers melting and retreat, and changes the share of the different sources of water in the constitution. Therefore, quantitative segmentation of the runoff component and distinguishing the proportion of mountain glaciers–snow melt water and precipitation in the water resources, is important to obtain reference scenarios of water resource prediction under future different changing situations.

According to the latest research about the Tarim River Basin in the northwest arid region, mountain glacier–snow meltwater and precipitation are the main sources of recharge for the four Tarim River headstreams (Aksu River, Hotan River, Yarkand, Kaidu River). Moreover, the fissure water in the low mountains is also mainly formed by the former supplies. The proportional contribution of meltwater from April to July showed a larger proportion of more than 55% in a whole year, especially in June (Table 1) (Fan et al., 2014). A higher proportion during 4–5 months is due to the rising temperature in the mountains, with a large amount of seasonal shallow mountain snow melting during the replenishment period.

The highest average temperature is in July, followed by August in a whole year, however, the proportional of meltwater in June and August are less than June. The possible reasons for this are: (1) during this period, seasonal snow has been melting and exhausted, and snowmelt water reduced significantly; and (2) heavy precipitation occurs in July and August in mountainous area, thereby reducing the proportion of meltwater. Composition analysis of different altitudes from runoff revealed that the glacial melt water ratio showed a decreasing trend with decreasing altitude. In the upstream mountainous basin, meltwater rate is close to 70%, midstream is about 45%, and downstream of the river at low altitude is 38% (Fan et al., 2014).

The Aksu River that originates from the southern slope of the Tianshan mountains has a proportion of meltwater that is about 59.3%; the Yarkand River that originates from the Karakoram mountain has a rate of approximately 54.0%; and the Hotan River that originates from the northern slope of the Kunlun Mountains has a rate of about 59.5%. Meanwhile, baseflow analysis of the different rivers showed that the Kaidu River has a large baseflow index (32.1%), and the remaining three headstreams are small, i.e., the Aksu River is 14.4%, the Hotan River is 9.3%, and the Yarkand River is 20.5% (Fan et al., 2013). Moreover, the years with more precipitation have a relatively large baseflow index compared to years with less precipitation; thus, the results of this study contradict Wittenberg's theory (Wittenberg and Sivapalan, 1999; Luo et al., 2012). In the northwest arid inland river basin, glacier–snow meltwater occupies an important share of the constitution in runoff, and, therefore, the baseflow component has a somewhat complex composition in different periods.

4. Discussion

The climate change of the northwest arid region is certainly complex. It is difficult to accurately reveal the process of change

Table 1
Temporal characteristics of ice–snow melt in the Tizinafu River streamflow.

Months	Cp (%)	Cr (%)	Ci (%)	Estimated fractions (%)	Months	Cp (%)	Cr (%)	Ci (%)	Estimated fractions (%)
January	−3.34	−7.18	−13.01	39.74	July	−3.34	−9.06	−13.01	59.18
February		−6.91		36.95	August		−6.98		37.63
March		−6.81		35.89	September		−7.21		40.00
April		−8.87		57.22	October		−6.97		37.51
May		−8.77		56.18	November		−6.08		28.31
June		−9.67		65.43	December		−6.46		32.24
Mean of the ice-snow melt percentage (%)					43.86%				

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and trends only from the short-term, individual point of view. Many domestic and international researches mainly focused on the analysis of climate characteristics on different time scales in regional scale. However, these studies are mostly qualitative descriptions and lack quantitative data; none elucidate historical centennial-scale climate variation, how the mechanism of climate change affects the water cycle and water systems, or emphasize that the understanding of different temporal scales of the climate system evolution and its interaction law needs to be improved.

The rate and intensity of soil evaporation in the arid desert area will fluctuate with the change of weather conditions. Since evapotranspiration is hard to measure directly, it is greatly difficult to quantify the effect of evapotranspiration on soil water consumption, also, it is difficult to quantitatively distinguish the climate change and human activities. Under the influence of climate warming, evaporation levels, rainfall patterns and surface runoff will change, as will soil water, groundwater, and surface water resources. However, there is still a lack of systematic analysis and research on these issues.

The mountain glaciers melt and retreat has been accelerated by climate change, particularly by the impact of winter temperatures. In the northwest arid area, glacier runoff is dependent on glaciers. Moreover, since changes in glaciers have a significant impact on water resources and their annual portion of water supplies, glacier inflection points have appeared in some rivers. Rivers with comparative development of glaciers and more glacial melt water supply may have runoff of high volatility for a long period of time. In addition, glacier inflection points will appear, glacial melt water will reduce, glaciers' swap function will decline, and runoff variability will increase due to the impact of precipitation anomalies, glaciers' swap function will decline, and runoff variability will increase due to the impact of precipitation anomalies. In the context of global climate change, the frequency and intensity of extreme hydrological events in the northwest arid region are increasing, which affect the safety of the water system, and increase water resource vulnerability and uncertainty.

5. Conclusion

(1) In the northwest arid region, temperature and precipitation experienced "sharply" increasing in the past 50 years. The precipitation trend changed in 1987, and since then has been in a state of high volatility. Temperature experienced a "sharply" increase in 1997; since then, it has remained highly volatile, and the increasing trend became slow. The dramatic rise in winter temperatures in the northwest arid region is an important reason for the rise in the average annual temperature, and substantial increases in extreme winter minimum temperature play an important role in the rising average winter temperature.
(2) There was a significant turning point in the change of pan evaporation in the northwest arid area in 1993, i.e., in which a significant decline reversed to a significant upward trend. In the 21st century, the negative effects of global warming and increasing levels of evaporation on the ecology of the northwest arid region have been highlighted.
(3) Glacier change has a significant impact on water resources in the northwest arid area, and glacier inflection points have appeared in some rivers. The melting water supply of the Aksu River, Tarim Basin, Yarkand River, Hotan River possess a large portion of water supplies (about 50%). In the future, the amount of surface water will probably remain at a high state of fluctuation.

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References

Aðalgeirsdóttir, G., Guðmundsson, G.H., jörnsson, H.B., 2005. Volume sensitivity of Vatnajökull Ice Cap, Iceland, to perturbations in equilibrium line altitude. J. Geophys. Res. 110, F04001. http://dx.doi.org/10.1029/2005JF000289.
Bouchet, R.J., 1963. Evapotranspiration reele et potentielle, signification climatique. General Assembly of Berkeley. Red Book 62, 134–142 (IAHS, Gentbrugge, Belgium).
Brutsaert, W., Parlange, M.B., 1998. Hydrologic cycle explains the evaporation paradox. Nature 396, 29–30. http://dx.doi.org/10.1038/23845.
Burn, D.H., Hesch, N.M., 2007. Trends in evaporation for the Canadian Prairies. J. Hydrol. 336 (1–2), 61–73. http://dx.doi.org/10.1016/j.jhydrol.2006.12.011.
Chen, F., Yuan, Y., Wen, W., et al., 2012a. Tree-ring-based reconstruction of precipitation in the Changling Mountains, China, since AD 1691. Int. J. Biometeorol. 56 (4), 765–774. http://dx.doi.org/10.1007/s00484-011-0431-8.
Chen, H., Li, Z.Q., Wang, P.Y., et al., 2013a. Change of glaciers in the central Qilian Mountain. Arid Zone Res. 30 (4), 588–593 (in Chinese).
Chen, Y.N., Xu, Z.X., 2004. The possible impact of global climate change on water resources in the Tarim River Basin. Sci. China Ser. D 34 (11), 1047–1053.
Chen, Y.N., Yang, Q., Luo, Y., et al., 2012b. Ponder on the issue of water resources in the arid region of northwest China. Arid Land Geogr. 35 (1), 1–9.
Chen, Y.N., Du, Q., Chen, Y.B., et al., 2013b. Sustainable Water Resources Utilization in Bosten Lake Basin. Science Press, Beijing, pp. 45–74.
Chen, Z.S., Chen, Y.N., Li, W.H., 2012c. Response of runoff to change of atmospheric 0 °C level height in summer in arid region of Northwest China. Sci. China-Earth Sci. 55 (9), 1533–1544. http://dx.doi.org/10.1007/s11430-012-4472-6.
Cong, Z.T., Yang, D.W., Ni, G.H., 2009. Does evaporation paradox exist in China? Hydrol. Earth Syst. Sci. 13, 357–366. http://dx.doi.org/10.5194/hess-13-357-2009.
Fan, Y.T., Chen, Y.N., Li, X.G., et al., 2014. Characteristics of water isotopes and ice-snowmelt quantification in the Tizinafu River, North Kunlun Mountains, Central Asia. Quat. Int. . http://dx.doi.org/10.1016/j.quaint.2014.05.020
Fan, Y.T., Chen, Y.N., Liu, Y.B., 2013. Variation of baseflows in the headstreams of the Tarim River Basin during 1960–2007. J. Hydrol. 487, 98–108. http://dx.doi.org/10.1016/j.jhydrol. 2013.02.037.
Gao, X., Ye, B.S., Zhang, S.Q., et al., 2010. Glacier runoff variation and its influence on river runoff during 1961–2006 in the Tarim River Basin, China. Sci. China Ser. D Earth Sci. 40 (5), 654–665.
Gan, T.Y., 1998. Hydroclimatic trends and possible climatic warming in the Canadian Prairies. Wat. Resour. Res. 34 (11), 3009–3015. http://dx.doi.org/10.1029/98WR01265.
Gong, L.B., Xu, C.Y., Chen, D.L., et al., 2006. Sensitivity of the Penman-Monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) Basin. J. Hydrol. 329, 620–629. http://dx.doi.org/10.1007/s11769-008-0340-x.
Huai, B.J., Li, Z.Q., Sun, M.P., et al., 2014. RS analysis of glaciers change in the Heihe River Basin in the last 50 years. Acta Geogr. Sin. 69 (3), 365–377.
IPCC, 2013. Working Group Contribution to the IPCC Fifth Assessment Report. Clim. Change, The Physical Science Basis, Summary for Policymakers.
Ji, F., Wu, Z.H., Huang, J.P., et al., 2014. Evolution of land surface air temperature trend. Nat. Clim. Ch. . http://dx.doi.org/10.1038/NCLIMATE2223
Linacre, E.T., 1994. Estimating U.S. Class A pan evaporation from few climate data. Water Int. 19, 5–14. http://dx.doi.org/10.1080/02508069408686189.
Li, B.F., Chen, Y.N., Li, W.H., et al., 2013a. Spatial and temporal characteristics of temperature and precipitation in the arid region of China from 1960–2010. Fresen. Environ. Bull. 22 (2), 362–371.
Li, B.F., Chen, Y.N., Shi, X., 2012. Why does the temperature rise faster in the arid region of northwest China? J. Geophys. Res. 117, D16115. http://dx.doi.org/10.1029/2012JD017953.
Li, Q.H., Chen, Y.N., 2014. Response of spatial and temporal distribution of NDVI to hydrothermal condition variation in arid regions of Northwest China during 1981–2006. J. Glaciol. Geocryol. 36 (2), 327–334.
Li, Z., Chen, Y.N., Shen, Y.J., et al., 2013b. Analysis of changing pan evaporation in the arid region of Northwest China. Water Resour. Res. 49, 2205–2212. http://dx.doi.org/10.1002/wrcr.20202.
Li, Z.Q., Li, K.M., Wang, Lin, 2010. Study on resect glacier changes and their impact on water resources in Xinjiang, North western China. Quaternary Sciences 30 (1), 96–106.
Liu, S.Y., Ding, Y.J., Li, J., et al., 2006. Glaciers in response to recent climate warming in western china. Quat. Sci. 26 (5), 762–771.
Liu, X.M., Luo, Y.Z., Zhang, D., et al., 2011. Recent changes in pan-evaporation dynamics in China. Geophys. Res. Lett. 38, L13404. http://dx.doi.org/10.1029/2011GL047929.
Luo, Y., Arnold, J., Allen, P., et al., 2012. Baseflow simulation using SWAT model in an inland river basin in Tianshan Mountains, Northwest China. Hydrol. Earth Syst. Sci. 16 (4), 1259–1267. http://dx.doi.org/10.5194/hess-16-1259-2012.

Mishra, A.K., Singh, V.P., 2010. A review of drought concepts. J. Hydrol. 391, 204–216. http://dx.doi.org/10.1016/j.jhydrol.2010.07.012.
Penman, H.L., 1948. Natural evaporation from open water, bare and grass. Proc. R. Soc. Lond. 193, 120–145. http://dx.doi.org/10.1098/rspa.1948.0037.
Peterson, T., Golubev, V., Groisman, P., 1995. Evaporation losing its strength. Nature 393, 687–688.
Richard, S., 2008. Chinese probe unmasks high-tech adulteration with melamine. Science 320 (4), 34. http://dx.doi.org/10.1126/science.322.5906.1310.
Roderick, M.L., Farquhar, G.D., 2002. The cause of decreased pan evaporation over the past 50 years. Science 298, 1410–1411. http://dx.doi.org/10.1126/science.1075390-a.
Roderick, M.L., Rotstayn, L.D., Farquhar, G.D., et al., 2007. On the attribution of changing pan evaporation. Geophys. Res. Lett. 34, L17403. http://dx.doi.org/10.1029/2007GL031166.
Rotstayn, L.D., Roderick, M.L., Farquhar, G.D., 2006. A simple pan-evaporation model for analysis of climate simulations: evaluation over Australia. Geophys. Res. Lett. 33, L17715. http://dx.doi.org/10.1029/2006GL027114.
Shen, Y.P., Wang, G.Y., Ding, Y.J., 2009. Changes in glacier mass balance in watershed of SaryJaz-Kumarik Rivers of Tianshan Mountains in 1957–2006 and their impact on water resources and trend to end of the 21th Century. J. Glaciol. Geocryol. 31 (5), 792–800.
Shi, Y.F., Shen, Y.P., Li, D.L., et al., 2003. Discussion on the present climate change from warm–dry to warm–wet in Northwest China. Quat. Sci. 23 (2), 152–164.
Szilagyi, J., 2001. On Bouchet' s complementary hypothesis. J. Hydrol. 246, 155–158. http://dx.doi.org/10.1016/S0022-1694(01)00367-5.
Szilagyi, J., 2007. On the inherent asymmetric nature of the complementary relationship of evaporation. Geophys. Res. Lett. 34, L02405. http://dx.doi.org/10.1029/2006GL028708.
Thom, A.S., Thony, J.L., Vauclin, M., 1981. On the proper employment of evaporation pans and atmometers in estimating potential transpiration. Q. J. R. Meteorol. Soc. 107 (453), 711–736. http://dx.doi.org/10.1002/qj.49710745316.
Wang, H.J., Chen, Y.N., Shi, X., et al., 2013a. Changes in daily climate extremes in the arid area of northwestern China. Theor. Appl. Climatol. 112 (1–2), 15–28. http://dx.doi.org/10.1007/s00704-012-0698-7.
Wang, Y., Chen, Y.N., Ding, J.L., 2014. Land-Use coversion and its attribution in the Kaidu-Kongqi River Basin, China. Quat. Int. . http://dx.doi.org/10.1016/j.quaint.2014.10.010.
Wang, Y.F., Shen, Y.J., Chen, Y.N., et al., 2013b. Vegetation dynamics and their response to hydroclimatic factors in the Tarim River Basin, China. Ecohydrology 6, 927–936. http://dx.doi.org/10.1002/eco.1255.
Wang, Y.K., Jia, W.X., Liu, C.H., et al., 2012. Ecological environment change in north Slope of the Qilianshan Mountains. Sci. Silvae Sin. 48 (4), 21–26.
Wittenberg, H., Sivapalan, M., 1999. Watershed groundwater balance estimation using streamflow recession analysis and baseflow separation. J. Hydrol. 219 (1), 20–33. http://dx.doi.org/10.1016/S0022-1694(99)00040-2.
Yang, H.B., Yang, D.W., 2011. Climatic factors influencing changing pan evaporation across China from 1961 to 2001. J. Hydrol. 414–415, 184–193. http://dx.doi.org/10.1016/j.jhydrol. 2011.10.043.
Yang, Y.H., Chen, Y.N., Li, W.H., et al., 2010. Impacts of climatic change on river runoff in Northern Xinjiang of China over last fifty years. Chin. Geogr. Sci. 20 (3), 193–201. http://dx.doi.org/10.1007/s11769-010-0193-y.
Yang, Y.H., Chen, Y.N., Li, W.H., et al., 2012. Climatic change of inland river basin in arid area, a case study in northern Xinjiang, China. Theor. Appl. Climatol. 107, 143–154. http://dx.doi.org/10.1007/s00704-011-0467-z.
Zhao, X., Tan, K., Zhao, S., et al., 2011. Changing climate affects vegetation growth in the arid region of the northwestern China. J. Arid Environ. 75 (10), 946–952. http://dx.doi.org/10.1016/j.jaridenv.2011.05.007.

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