What is the primary factor controlling trend of Glacier No. 1 runoff in the Tianshan Mountains: temperature or precipitation change?

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ABSTRACT

The internal relationship between summer temperature (ST), annual precipitation (AP), annual mass balance (AM) and annual runoff (AR) of Glacier No.1 from 1959 to 2006, a so-called 'summer accumulation type' glacier, was examined with several statistical methods including simple linear regression, the Mann–Kendall test and wavelet analysis. In total, ST, AP and AR increase with a rate of 0.02 °/year, 1.53 mm/year and 2.83×10^4 m^3/year, respectively, while AM decreases at a rate of −14.5 mm/year. A step change of ST, AP, AM and AR was identified to have occurred in the mid-1990s. After that, ST and AR increase significantly. Meanwhile, the period of coherence changes from 4–8 years to 2–4 years, implying that when temperature increases greatly, the period tends to be shorter due to the fast response of the glacier. The increase of AR is caused by the loss of AM. The rise of ST is found to be responsible for the loss of AM, although the rise of AP is beneficial to the glacier accumulation. Our results on the dominant effect of temperature (rather than precipitation) on runoff of Glacier No. 1 could be used as the input to models in hydrology, geomorphology, climatology and paleoclimatology.

Key words | climate change, Glacier No. 1, glacier river runoff, Mann–Kendall test, wavelet analysis

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INTRODUCTION

Increases in surface temperatures have significant consequences on the hydrological cycle, particularly in regions where the water supply is currently dominated by melting snow or ice (Barnett *et al.* 2005). It is believed that the retreat of glaciers and ice caps during the last hundred years has contributed to a global sea-level rise of several centimeters (Oerlemans 2001). Hence, it is necessary to examine the relationship between glacier runoff change and climate change, and to further assess the impact of climate change on water resources.

Glacier rivers in the Tianshan Mountains, the water tower of Central Asia, with limited disturbance from human activities, offer a good opportunity to study the impact of climate change on their runoff. The mechanism of response of Tianshan Glacier No. 1's runoff to climate change, as a representative of continental glaciers in the Tianshan Mountains, has great potential for the study of glaciology and hydrology as well as climatic change implications for Central Asia

(Mikhalenko 1997; Li *et al.* 2007). Furthermore, in these arid regions glacier melt water is vital to water resources management, as it may be a substantial contributor to a local potable and agricultural water source.

Glaciers in the Tianshan Mountains are considered to be 'summer-accumulation type', because they receive the main part of annual accumulation in summer (Ageta & Higuchi 1984; Li *et al.* 2010). In the Tianshan Mountains, the glacier rivers such as the headwaters of the Urumqi River are mainly recharged by seasonal glacier melt water and precipitation. Because temperature correlates with most terms of energy balance, it is always used as the index for melt (Li *et al.* 2010). So temperature and precipitation are always chosen as the climate factors affecting the recharge of the river. Previous studies investigated the variability of climate and runoff and discussed the relationship between them, showing that the runoff of Glacier

No. 1 hydrometric station has increased largely due to the rise of temperature and precipitation (Ye *et al.* 2005; Li *et al.* 2007, 2010; Xu *et al.* 2010). However, it is still not known which of these factors (precipitation or temperature) is more important to runoff, though this information is useful for runoff prediction and water resources management.

It is known that the hydroclimatic characteristics of a watershed have both long and short periods, and hydrological models are quite sensitive to these scales. Given various patterns of hydroclimatic change in different periods, analysis at different temporal scales may reveal some internal relationship between hydroclimatic time series. Thus, future investigations of the correlations between climate change and runoff will require research at different climatological scales (Kaser *et al.* 2004).

Recently, many statistical methods have been used to compare the seasonal and inter-annual variability in hydrological regimes and to study the trends, periods and the interrelationships among the key factors including air temperature, precipitation and stream discharges (Lafreniere & Sharp 2003; Labat *et al.* 2004; Chaouche *et al.* 2010; Ben Aissia *et al.* 2011). However, analysis of the variability of glacier runoff and its surrounding climate using time as well as frequency domain approaches is limited in the literature. Furthermore, to the authors' best knowledge, none of the studies have quantitatively determined the coherence between glacier river runoff and climate change (temperature and precipitation) at different time scales.

In this paper, we use simple linear regression, the Mann–Kendall test and wavelet analysis to carry out statistical analyses of hydroclimatic time series in terms of the response of small continental glaciers' runoff to climate change with the following objectives: (1) to detect the trend and step change year of the time series for temperature, precipitation, mass balance and runoff; (2) to identify their co-variability; and (3) to identify which is more important in affecting the runoff of glacier rivers.

STUDY WATERSHED

Glacier No. 1 watershed in the Tianshan Mountains was selected to analyze the response of glacier runoff to climate change (Figure 1). It maintains a record of hydrological and
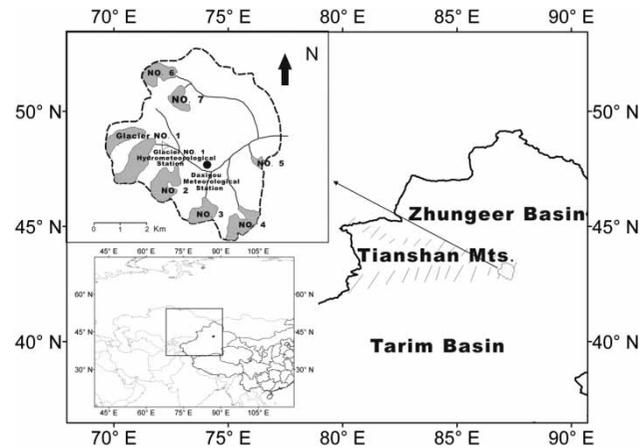
Figure 1 | Study area and locations of (hydro-)meteorological stations. No. 1 to No. 7 are the main glaciers in the area. The inset in the bottom left corner illustrates the location of the study area in the Euro-Asia continent.

climatic monitoring from 1959 to the present, which is the longest record of all the glacier observations in China. Previous studies have described its surrounding environments in detail (Li *et al.* 2007, 2010; Xu *et al.* 2010; Pang *et al.* 2011; Kong *et al.* 2013). Here we give a brief description of Glacier No. 1 watershed. Glacier No. 1 is located in the headwaters of the Urumqi River, Tianshan, China (43°01′N, 86°49′E) (Figure 1). There are seven glaciers at the headwaters of the Urumqi River. Among them, Glacier No. 1 is the largest. It has a catchment area of 3.34 km², of which 54% is covered by glaciers. The area of glaciers has retreated by 0.27 km² or 14% from 1962 to 2006, of which 8% took place from 1992 to 2006 (Li *et al.* 2010). Glacier No. 1 is composed of east and west tributaries. These two branches became separated into two small independent glaciers in 1994 due to continued glacier shrinkage (Ye *et al.* 2005).

The hydrometric station of Glacier No. 1 was established for runoff monitoring at the elevation of 3,693 metres above sea level (m.a.s.l.) in 1959. The Daxigou meteorological station at the elevation of 3,539 m.a.s.l., is located 3 km downstream of the Glacier No. 1 hydrometric station, which entered operation in 1958. The mean annual temperature from 1959 to 2006 in the Glacier No. 1 watershed was 5.1 °C, and the temperature was below 0 °C for 7–8 months of the year. The average annual precipitation (AP) is around 450 mm. Precipitation amount and frequency are both higher in summer than in winter. Most of the annual

runoff (AR) at Glacier No. 1 hydrometric station occurs from May to September.

DATA AND METHODS

Data

Stream flow and meteorological parameters were measured at the Glacier No. 1 hydrometric station and at Daxigou meteorological station every year. In spite of the altitude difference of 100 m, the annual temperature and precipitation observed at Daxigou meteorological station can be used to characterize climate variability at Glacier No. 1 hydrometric station (Li *et al.* 2010), and can be compared with the runoff record of Glacier No. 1 hydrometric station. The observations of runoff have been carried out from May to September every year. Over 95% of the AR at the station occurs during the observation period, whereas for the rest of the year, the streams are mostly frozen. All the data are published in the annual reports of the Tianshan Glacier observatory station of the Chinese Academy of Sciences, with a delay from the observation by a few years. Up to now, data on annual mean temperature, summer temperature (ST) and AP at Daxigou meteorological station and AR at Glacier No. 1 hydrometric station from 1959 to 2006 have been reported by Li *et al.* (2010) and Jiao *et al.* (2011). The mass balance data of Glacier No. 1 has been reported by Li *et al.* (2007, 2010) and Jiao *et al.* (2011). Considering that melting of Glacier No. 1 mainly occurs in summer, the ST is used in this paper instead of annual temperature.

Methods

Two methods, namely simple linear regression and the Mann–Kendall test, are used to detect trends and the step change year. Each method has its own strength and weakness (Xu *et al.* 2003; Zhang *et al.* 2006; Chen *et al.* 2007). For instance, the simple linear regression method, which is a parametric t-test method, requires the data to be tested to see if it is normally distributed. However, the Mann–Kendall test, a non-parametric trend test, only requires the data to be independent and can tolerate outliers (Chen *et al.*

2007; Xu *et al.* 2011). The Mann–Kendall test is summarized as follows:

Let H_0 be the 'series is stationary' null hypothesis to be tested against alternative hypothesis H_1 'series displays change'. Let $X_1 \ldots X_N$ be variable X in dependent observations. The statistics S is calculated as in Equation (1):

$$S = \sum_{j=1}^{N-1} \sum_{k=j+1}^{N} \text{sign}(X_k - X_j) \tag{1}$$

where:

$$\text{Sign}(x) = \begin{cases} 1 & \text{if} \quad x > 0 \\ 0 & \text{if} \quad x = 0 \\ -1 & \text{if} \quad x < 0 \end{cases} \tag{2}$$

with the H_0 hypothesis, S approaches 0. Trends for an increase or a decrease result respectively in S being negative or positive. The expected value and variance of S are given by:

$$E(S) = 0 \tag{3}$$

$$V(S) = \frac{N(N-1)(2N+5)}{18} \tag{4}$$

The significance of trends is tested by comparing the standardized test statistic Z:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & \text{if} \quad S < 0 \end{cases} \tag{5}$$

when the time series has no trends, that is to say following the H_0 hypothesis, the value of S differs for each sample. The probability of rejecting H_0 when it is true is α. In this paper, the significance level (SL) 0.05 was chosen, that is to say α = 0.05.

To detect the step change point (the year when step change occurs), Goossens & Berger (1986) presented a graphical technique based on the Mann–Kendall method. For the time series $X_1, X_2, \ldots X_N$ shown above, it uses the intersection of two curves: UFK and UBK. This method is

based on the computation of all $U(d_i)$, $i = 1,2…N$:

$$U(d_i) = (d_i - E(d_i))/\sqrt{\text{var}(d_i)} \tag{6}$$

in which d_i is given as:

$$d_i = m_1 + m_2 + … + m_i \tag{7}$$

where, for each term X_i, the number m_i of terms X_j $(i > j)$ preceding it is calculated by

$$m_i = \begin{cases} 1 & \text{if} \quad X_i - X_j > 0'' i > j \\ 0 & \text{if} \quad X_i - X_j \leq 0'' i > j \end{cases} \tag{8}$$

For the statistic d_i, its expected value is given as:

$$E(d) = \frac{N(N-1)}{4} \tag{9}$$

and variance as:

$$var(d_i) = \frac{i(i-1)(2i+5)}{72} \tag{10}$$

The graphical presentation of this ensemble of all $U(d_i)$, $i = 1, 2 …N$, along the time series will be denoted as UFK. The sequential application to UFK of the rule issued for $U(d)$ allows us to detect a change in the time series as soon as $U(d_i)$ becomes larger than 1.96 (corresponding to $\alpha = 0.05$).

In order to localize the step change point, the same principle is applied to the retrograde time series (Let X_N be X_1, X_{N-1} be X_2 …X_1 be X_N), then recalculate the statistic UBK (we use UBK to replace UFK in order to differentiate it with the original time series). Plot the curve of UBK-Year and UFK-Year, respectively. If the point where the two lines cross is located between the critical lines of the 5% level of significance, it is just the step change point, because the point marks the significant change in both sequences (Goossens & Berger 1986; Kong & Pang 2014).

In order to identify the relationship between temperature and runoff and between precipitation and runoff, the wavelet method is employed. It can reveal the localized time and frequency information without requiring the time series to be

stationary (Torrence & Compo 1998). Wavelet coherence is defined as (Grinsted et al. 2004):

$$R_N^2(a) = \frac{\left|SO(a^{-1}W_{XY}(a))\right|^2}{SO(a^{-1}|W_X(a)|^2)gSO(a^{-1}|W_Y(a)|^2)} \tag{11}$$

where W_{XY} is the cross wavelet transform; SO is a smoothing operator. They can be written as:

$$W_{XY} = W_X W_Y^* \tag{12}$$

where * denotes complex conjugation.

The wavelet coherence is done to show the correlation between the variants mentioned above in the time–frequency domain (Grinsted et al. 2004). Wavelet coherence analysis can be used to identify the correlations between two signals, especially for highlighting the time and frequency intervals between them (Torrence & Compo 1998; Grinsted et al. 2004; Valdés-Galicia & Velasco 2008). If the two series are physically related, one would expect a consistent or slowly varying phase lag that can be tested against mechanistic models of the physical processes (Grinsted et al. 2004). All of the three methods are used comparatively to check the interrelationships among the key factors of temperature, precipitation and runoff time series.

RESULTS AND DISCUSSION

Variability in temperature, precipitation, mass balance and runoff

The statistics for ST, AP, annual mass balance (AM) and AR time series are given in Table 1. For visualization purposes, the 5-year moving averages are also presented in Figure 2. A simple linear regression method is used to test the

Table 1 │ Statistics for ST, AP, AM and AR time series of Glacier No. 1 watershed

| Item	Mean	Max.	Min.	Variance	Standard dev.
AM (mm)	−250.1	372.0	−893.8	133,848.8	365.9
AR (10^4 m^3)	134.3	304.5	22.8	4596.4	67.8
ST (°C)	4.2	5.7	3.0	0.3	0.5
AP (mm)	456.7	644.0	287.3	5180.7	72.0
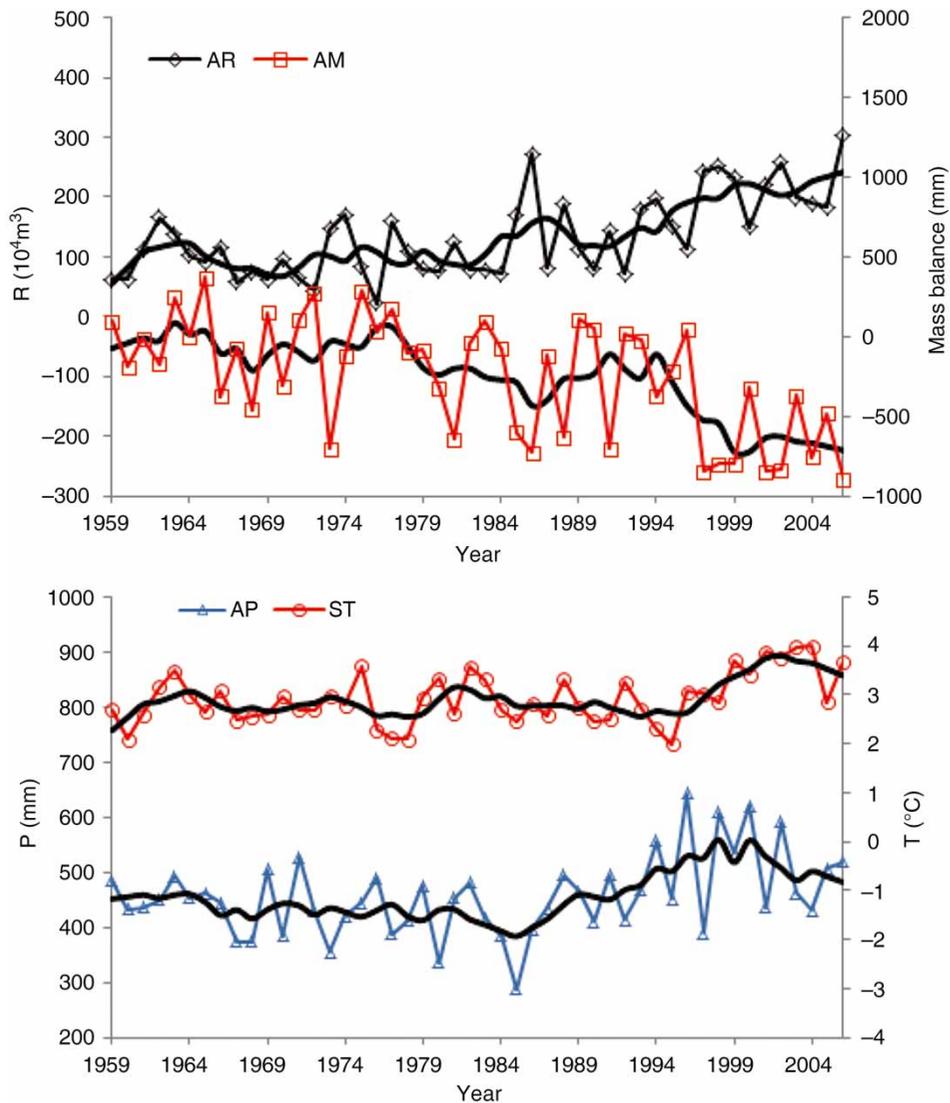
Figure 2 | Variability of ST and AP at Daxigou meteorological station (3,539 m.a.s.l.), AR at Glacier No. 1 hydrometric station (3,693 m.a.s.l.) and AM of Glacier No. 1 from 1959 to 2006. The black curves are the 5-year moving averages of ST, AP, AM and AR time series.

long-term linear trend. Results show that ST, AP and AR have a mean value of 4.2 °C, 456.7 mm and $134.3 \times 10^4 \, m^3$, and they all present an increasing trend while AM has an average of -250.1 mm and a trend of decreasing.

Trend analysis of temperature, precipitation, mass balance and runoff

Time series of ST, AP, AM and AR are analyzed with the Mann–Kendall test. In this work, two statistics named UFK and UBK are introduced to test the significance of each time series. Take the time series of runoff for example, the UFK refers to the runoff series from 1959 to 2006. When the values of UFK are above 1.96 (the dotted line in Figure 3), it illustrates a significant rising trend, and when they are below -1.96, it means a significant declining trend. The UBK refers to the retrograde runoff series from 2006 to 1959. The crossing of UFK and UBK between the two dotted lines is the step change point (year) when the record changes profoundly.
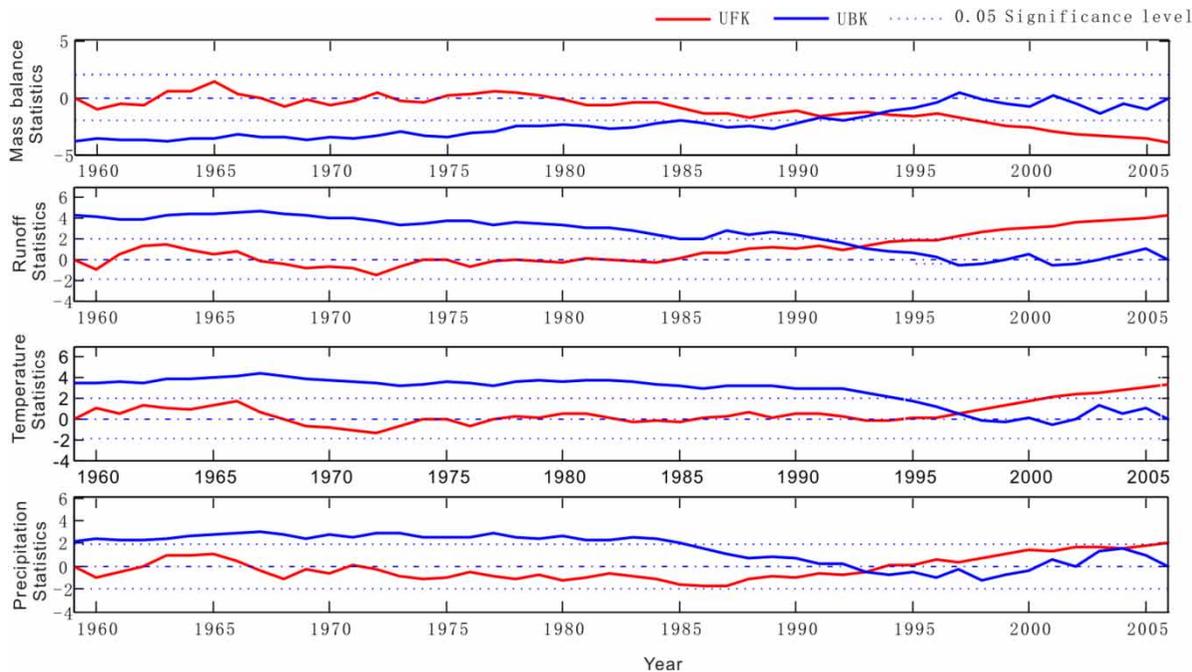
Figure 3 │ Trend test and step change detection of AM, AR, ST and AP change. The red line above (>1.96) or below (<− 1.96) the dotted lines (SL 5%) illustrates a statistical significant rising or decreasing trend. The crossing point of the red and blue lines is the year when step change occurs. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/nh.2016.190.

Figure 3 gives the graphical representation of AM, AR, ST and AP time series from 1959 to 2006. Under the SL 5%, ST, AP and AR all reveal a rising trend while AM decreases, which confirms the findings of visual observation. Using Sen's non-parametric trend estimator (Sen 1968), we find the temperature, precipitation, mass balance and runoff rise at a rate of 0.02 °C/year, 1.53 mm/year, −14.5 mm/year and 2.83×10^4 m³/year, respectively (see Table 2).

The step change years for ST, AP, AM and AR are different but close to each other (Figure 3 and Table 2). For the annual average temperature series, the step change towards

Table 2 │ Mann–Kendall trend test for ST, AP, AM and AR time series of Glacier No. 1 watershed

Item	Time series	Z	K (/year)	Step change year	H0
AM (mm)	1959–2006	−3.9	−14.5	1991	R
AR (10^4 m³)	1959–2006	4.293	2.83	1993	R
ST (°C)	1959–2006	3.4	0.02	1997	R
AP (mm)	1959–2006	2.044	1.53	1993	R

Notes: R: Reject the assumption H0; SL = 5%; K is calculated by Sen's non-parametric trend estimator; Z is the statistics of the Mann–Kendall test.

warming is located in 1997. Before and after the step-change year 1997, the temperature rises from 4.0 to 4.9 °C, the increment of which is close to that of the whole Xinjiang Province (from 8.8 to 9.8 °C (Kong & Pang 2012)), but rises more rapidly than the global average in the past century (0.74 °C/100 years (IPCC 2007)). The step change year for precipitation is 1993. Around the step year 1993, precipitation increased about 83.4 mm or 19% in one of the regions that changes most rapidly in Xinjiang (Kong & Pang 2012). The step change year for mass balance is 1991, before which mass balance changed little, and after which it decreased significantly. The step year for runoff is 1993, which is same as that of precipitation and close to that of temperature (Table 2), suggesting that significant climate and runoff changes exist in Glacier No. 1 around the middle 1990s.
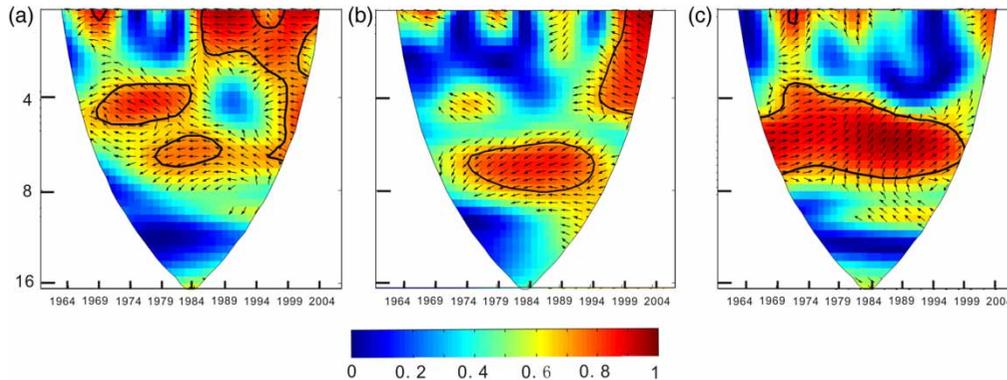
Wavelet coherence between mass balance, runoff, precipitation and temperature

The squared wavelet coherence between ST, AP and AM is shown in Figure 4, which reveals the localized correlation in

Figure 4 | Squared wavelet coherence between AM and AR (a), ST (b) and AP (c). The thick black contour designated the 5% SL against red noise. The arc line is the cone of influence (COI), below which edge effects become important. The X axis corresponds to the physical time and the Y axis corresponds to scales in years. The vectors indicate the phase difference (a horizontal arrow pointing from left to right signifies in-phase and an arrow pointing vertically upward means the second series lags the first by 90°).

time and frequency space. The directions of arrows and significance of the results show how the two time series are correlated. Arrows pointing straight right/left in phase denote linear positive/negative relationships, while arrows pointing up/down (out of phase) denote nonlinear relationships (Grinsted et al. 2004).

Figure 4(a) illustrates that AM and AR share a cycle with a period of about 4–8 years over much of the instrumental record, but becoming clearer and stronger starting in the 1990s in 2–4 year scale. Most of the arrows in the regions with high coherence point to about −90° in all the 4–8 and 2–4 year periods. Such an anti-phase relationship shows that the rise of AR is caused by the loss of AM.

Figure 4(b) reveals that there is remarkable negative correlation between AM and ST in the periods of 6–8 years from 1976 to 1994. And the negative correlation remains but the period tends to be 2–4 years after 1995. The negative correlation indicates that glacier ablation is caused by the rising temperature. The shift of period is just echoed by the step change years found with the method of the Mann–Kendall test. Such a shift implies that when temperature increases significantly, the period of coherence tends to be shorter. This seems reasonable due to the rapid response of the glacier to rising temperature.

Figure 4(c) shows that the hydroclimatic coherence between AM and AP is concentrated on the 4–8 year scale, starting from 1966. In the regions of 4–8 year periods with high coherence, AM and AP change in phase, implying that a strong positive correlation exists between them. This is reasonable, because the accumulation of Glacier No. 1

mainly comes from summer precipitation, which is composed of more than 80% solid precipitation (Ye et al. 2005).

It is very difficult to identify which (temperature or precipitation) is more important in controlling the runoff of Glacier No. 1, because both temperature and precipitation increase. The rise of temperature causes more melted water and thus increases the runoff, and the increase of precipitation directly causes the increase in runoff. However, we find significant correlation between AR and ST ($R^2 = 0.44$, $n = 48$), while there is no correlation between AR and AP. From the analysis of Figure 4, we know that a strong linear correlation exists between the loss of AM and the increase of AR. This indicates that the increase of runoff is primary attributed to the loss of AM and thus to the increase in temperature. Such a result is bolstered by the calculation of the water budget. As we mentioned above, Glacier No. 1 has a catchment area of 3.34 km², of which 54% is covered by glaciers. Weighted by the catchment area, we can transfer the rising rate of AP and AR into 0.51×10^4 m³/year and 2.83×10^4 m³/year, and the decreasing rate of AM into 2.62×10^4 m³/year. Thus the increase in AP is about 1/5 of the increase in AR, and the AP is not the primary factor in the controlling trend of Glacier No. 1 runoff. The loss of AM, caused by temperature rising, is slightly lower than the increase in AR, showing that the increase in AR is caused by the loss of AM.

The dominant effect of temperature on runoff in the study region is also supported by the finding that runoff in the Glacier No. 1 is composed of more than 90% glacier-melt water (Kong & Pang 2012). Kong & Pang (2012) further claimed

that the sensitivity of glacier river runoff to climate change is dependent on their replenishment type: the more glacier-melt water is incorporated, the more sensitive it is to temperature change. To prevent flood hazards, managers of water resources should be clear about the controlling factors for glacier river runoff. For small glaciers like Glacier No. 1, more attention should be paid to their melt water because of their sensitivity to temperature. In order to prevent water loss through evaporation in the arid regions, major adaptive strategies to utilize melt water, such as groundwater reservoirs, should be constructed for water resources management.

CONCLUSIONS

Using simple linear regression, the Mann–Kendall test and wavelet analysis, we have identified the trends and periods of runoff and climate change at Glacier No.1 hydrometric station in the Tianshan Mountains, and compared the relative significance of temperature and precipitation to the change in continental glacier river runoff. The main findings of the study can be summarized as follows:

1. In the time series of 48 years (1959–2006), ST, AP and AR exhibit an increasing trend with a slope of $0.02\,°C$/year, $1.53\,mm$/year and $2.83\times10^4\,m^3$/year, respectively; while AM decreases with a gradient of $-14.5\,mm$/year.
2. There is a step change in the trends of ST, AP, AM and AR. The turning point is the middle 1990s.
3. There is a clear negative correlation between AR and AM, which shows that the rise in runoff is caused by glacier ablation.

From a new perspective, we show that temperature has a primary effect on the mass balance and runoff as compared to precipitation throughout the instrumental records. Furthermore, when the temperature began to rise significantly after 1993, the period became shorter and changed to 2–4 years. This implies that temperature rise can dominate the runoff change in such a small continental glacier watershed under climate change conditions. Nevertheless, the effect of temperature and precipitation on runoff is even more complicated, which should be analyzed on short-wave radiation, sensible heat and local geometric characteristics of glaciers. Therefore, long-term monitoring of hydroclimatic parameters is needed in order to identify the cause of variations and interaction between climate change and runoff.

REFERENCES

Ageta, Y. & Higuchi, K. 1984 Estimation of mass balance components of a summer-accumulation type glacier in the Nepal Himalaya. Geog. Ann. 66A (3), 249–255.

Barnett, T., Adam, J. & Lettenmaier, D. 2005 Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309.

Ben Aissia, M., Chebana, F., Quarda, T., Roy, L., Desrochers, G., Chartier, I. & Robichaud, E. 2011 Multivariate analysis of flood characteristics in a climate change context of the watershed of the Baskatong reservoir, Province of Quebec, Canada. Hydrol. Process. 26 (1), 130–142.

Chaouche, K., Neppel, L., Dieulin, C., Pujol, N., Ladouche, B., Martin, E., Salas, D. & Caballero, Y. 2010 Analyses of precipitation, temperature and evapotranspiration in a French Mediterranean region in the context of climate change. Compt. Rend. Geosci. 342, 234–243.

Chen, H., Guo, S., Xu, C. & Singh, V. 2007 Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. J. Hydrol. 344, 178–184.

Goossens, C. & Berger, A. 1986 Annual and seasonal climatic variations over the northern hemisphere and Europe during the last century. Ann. Geophys. 4, 385–400.

Grinsted, A., Moore, J. & Jevrejeva, S. 2004 Application of the cross wavelet transform and wavelet coherence to

geophysical time series. *Nonlinear Process. Geophys.* **11** (5/6), 561–566.

IPCC 2007 *Climate Change 2007: the Physical Science Basis. Report of Working Group I of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Jiao, K., Ye, B., Han, T., Jing, Z. & Yang, H. 2011 Response of runoff to climate change in the Glacier No. 1 at the headwater of Urumqi River, Tianshan mountains during 1980–2006. *J. Glaciol. Geocryol.* **33**, 606–611.

Kaser, G., Hardy, D., Molg, T., Bradley, R. & Hyera, T. 2004 Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts. *Int. J. Climatol.* **24**, 329–339.

Kong, Y. & Pang, Z. 2012 Evaluating the Sensitivity of glacier rivers to climate change based on hydrograph separation of discharge. *J. Hydrol.* **434–435**, 121–129.

Kong, Y. & Pang, Z. 2014 Statistical analysis of stream discharge in response to climate change for Urumqi river catchment, Tianshan Mountains, Central Asia. *Quat. Int.* **336**, 44–51.

Kong, Y., Pang, Z. & Froehlich, K. 2013 Quantifying recycled moisture fraction in precipitation of an arid region using deuterium excess. *Tellus* **65B**, 19251.

Labat, D., Godderis, Y., Probst, J. & Guyot, J. 2004 Evidence for global runoff increase related to climate warming. *Adv. Water Resour.* **27**, 631–642.

Lafreniere, M. & Sharp, M. 2003 Wavelet analysis of inter annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta. *Hydrol. Process.* **17**, 1093–1118.

Li, Z., Shen, Y., Wang, F., Li, H., Dong, Z., Wang, W. & Wang, L. 2007 Response of glacier melting to climate change. *J. Glaciol. Geocryol.* **29** (3), 333–342.

Li, Z., Wang, W., Zhang, M., Wang, F. & Li, H. 2010 Observed changes in streamflow at the headwaters of the Urumqi River, eastern Tianshan, Central Asia. *Hydrol. Process.* **24**, 217–224.

Mikhalenko, V. 1997 Changes in Eurasian glaciation during the past century: glacier mass balance and ice core evidence. *Ann. Glaciol.* **24**, 283–287.

Oerlemans, J. 2001 *Glaciers and Climate Change*. A. A. Balkema Publishers, Rotterdam, The Netherlands.

Pang, Z., Kong, Y., Froehlich, K., Huang, T., Yuan, L., Li, Z. & Wang, F. 2011 Processes affecting isotopes in precipitation of an arid region. *Tellus* **63B**, 352–359.

Sen, P. 1968 Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **63**, 1379–1389.

Torrence, C. & Compo, G. 1998 A practical guide to wavelet analysis. *Bull. Am. Meteorol. Soc.* **79**, 61–78.

Valdés-Galicia, J. & Velasco, M. 2008 Variations of mid-term periodicities in solar activity physical phenomena. *Adv. Space Res.* **41**, 297–305.

Xu, Z., Takeuchi, K. & Ishidaira, H. 2003 Monotonic trend and step changes in Japanese precipitation. *J. Hydrol.* **279**, 144–150.

Xu, X., Pan, B., Hu, E., Li, Y. & Liang, Y. 2010 Responses of two branches of Glacier No. 1 to climate change from 1993–2005, Tianshan, China. *Quat. Int.* **1–2**, 143–150.

Xu, J., Chen, Y., Lu, F., Li, W., Zhang, L. & Hong, Y. 2011 The nonlinear trend of runoff and its response to climate change in the Aksu River, western China. *Int. J. Climatol.* **31**, 687–695.

Ye, B., Yang, D., Jiao, K., Han, T., Jin, Z., Yang, H. & Li, Z. 2005 The Urumqi River source Glacier No. 1, Tianshan, China: changes over the past 45 years. *Geophys. Res. Lett.* **32**, L21504.

Zhang, Q., Liu, C., Xu, C. Y., Xu, Y. P. & Jiang, T. 2006 Observed trends of annual maximum water level and streamflow during past 130 years in the Yangtze River basin, China. *J. Hydrol.* **324** (1–4), 255–265.