remote sensing

Supplemental Material for

Recent Changes in Water Discharge in Snow and Glacier Melt-Dominated Rivers in the Tienshan Mountains, Central Asia

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Supplementary methodological information

Glacier mass balance calculations

Changes in glacier mass balance (GMB) directly reflects the impacts of glacier meltwater on alpine water resource. Previous works have found that runoff and precipitation in the mountains have closely negative-exponential relations with their areas, with maximum precipitation and runoff occurs in the glacierized-areas [1]. According to the observed runoff and precipitation datasets, GMB in this study was reconstructed by using the statistical mechanics and maximum entropy principle (SMMEP) model, which has been applied in the Tienshan Mountains [2], e.g., this model's reliability and accuracy were validated in the Urumqi River [1]. GMB was calculated as follows:

$$r_g = r - (r - r_0)\ln(f_g/f) \tag{1}$$

$$p_g = p - (p - p_0)\ln(f_g/f) \tag{2}$$

$$\alpha_g = \alpha - (\alpha - \alpha_0)\ln(f_g/f) \tag{3}$$

where r_g, p_g and α_g are the average depth of the runoff (mm), precipitation (mm) and runoff-coefficient of the glaciers; r (r_0), p (p_0) and α (α_0) are the average (minimum) values of the runoff (mm), precipitation (mm) and runoff-coefficient of the catchments, respectively during the study period; f_g and f are the glacierized-area (km^2) and catchment-area (km^2) of the catchments, respectively.

$$\alpha_b = (\alpha f - \alpha_g f_g)/(f - f_g) \tag{4}$$

$$k_{gr} = (f_g/f)\{1 + [\alpha_b(f_p - f_g p_g) - (fr - f_g r_g)]/f_g r_g\} \tag{5}$$

$$k_{gp} = p_s/p_g \tag{6}$$

where α_b is the runoff coefficient for the bare area; k_{gr} is the ratio of runoff depth of the catchment to the glacier meltwater depth; k_{gp} is the ratio of precipitation at the hydrological-station to the precipitation on the glaciers; p_s is the average precipitation at the hydrological-station during 1979–2015 (mm), it's based on the precipitation gradients in the Tienshan Mountains, at rate of 11 mm/100 m [3]. Combined with the precipitation gradients, the average precipitation for the Shanliguilanke hydrological station in the Toxkan River was calculated from the Aheqi meteorological station, while the average precipitation for the Xiehela hydrological station in the Kumalak River was calculated from the Aksu meteorological station.

According to the glacier mass balance principle, GMB can be estimated by the expression:

$$b_i = c_i - a_i \tag{7}$$

$$c_i = p_{hi}/k_{gp} \tag{8}$$

$$a_i = r_i/k_{gr} \tag{9}$$

where b_i is the annual GMB (mm) in the catchment; c_i and a_i are the annual glacier accumulation and ablation (mm), respectively; p_{hi} is the annual precipitation at the hydrological-station in year i (mm).

Zero-mean normalization

In this study, for the monthly runoff data (x1, x2, …, xn) during 1979–2015, the standardized annual or monthly runoff is calculated as follows:

$$Z_i = \frac{xi - \bar{x}}{S} \tag{10}$$

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{11}$$

where Zi is the standardized value of runoff in year or month i; $\bar{x}$ is the average value of the runoff data, and S is the standard deviation of these runoff data, n is the total number of these data.

In this study, we defined the seasons used in our study during the period from 1979 to 2015, as Spring (from December to February), Summer (from March to May), Autumn (from June to August) and Winter (from September to November).

Winter/Spring snowmelt runoff timing calculations

Generally, under global warming, these rivers in the mountain regions dominated by the snow meltwater are undergoing significant changes, big changes occurred mainly in these seasons which showed obviously climate warming. In our study, we found positive temperatures increase occur in wintertime and springtime when snowmelt contributes substantially to their runoff, this is also the common trends in the Tienshan Mountain regions [4,5]. Thus, it is needed to analyze the snowmelt runoff changes in snowmelt runoff timing, i.e., in wintertime and springtime. Furthermore, to verify the influences of SCA and SD on runoff in these different sources of Toxkan and Kumalak Rivers, the WSCT in this case could be provided as an indicator for runoff change. WSCT was implemented in this study by using the "center of mass of flow theory (CT)", which is a flow-weighted timing that indicates the center mass of the streamflow curve [6]. Note that CT can serve an evidence of observed earlier melting of snow even may not be directly relevance to the actual snowmelt timing [5]. Despite the warming temperatures in summer may bring more snow-glacier meltwater, while the considerable precipitation occurs which may disturb our results. Moreover, snow accumulation starts in Autumn result in a less snow meltwater. Therefore, to reduce the influence of the summertime rainfall on the flow-weight and have a better observation of snowmelt timing in this study, we calculated CT during these seasons of winter/spring (from December 1st to May 31st the following year) when the runoff is dominated by snow meltwater. Annual WSCT was thus calculated as follows:

$$WSCT = \sum (T_j P_j)/P_j \tag{12}$$

where T_j represents time in month (or day) from the starting day of the year (January 1st) and P_j represents the corresponding runoff in month j (or day j). Hence, *WSCT* in this study represents a date given in month or day and has been smoothed by locally weighted regression.

Supplementary Figures

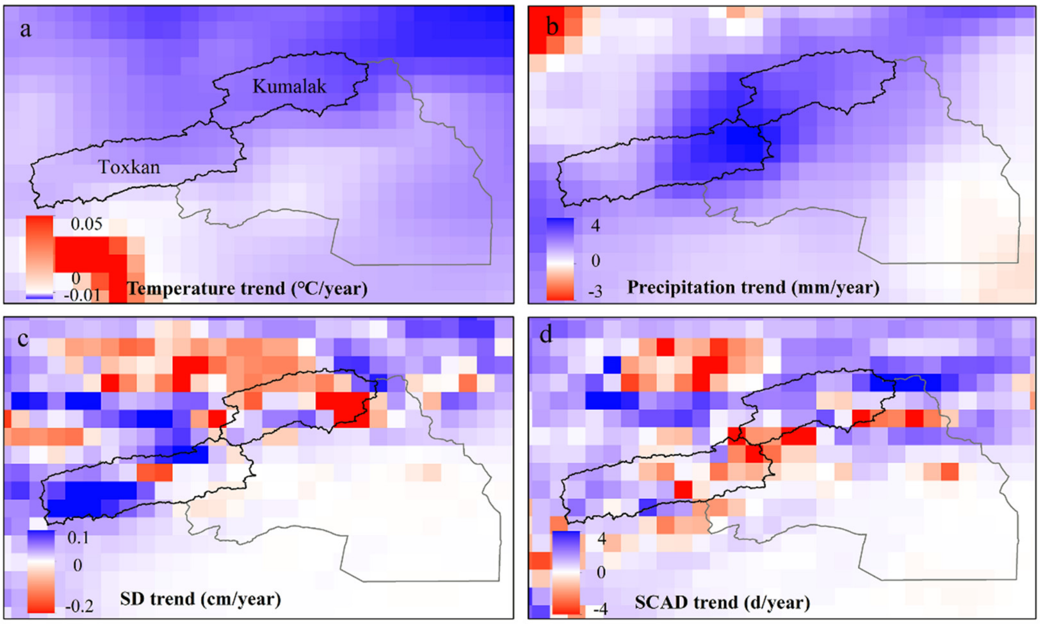

Figure S1. The spatial change rates of temperature, precipitation, SD and SCAD in the Aksu River basin from 1979 to 2015. (**a**) Change rate in temperature; (**b**) change rate in precipitation; (**c**) change rate in SD; (**d**) change rate in SCAD.

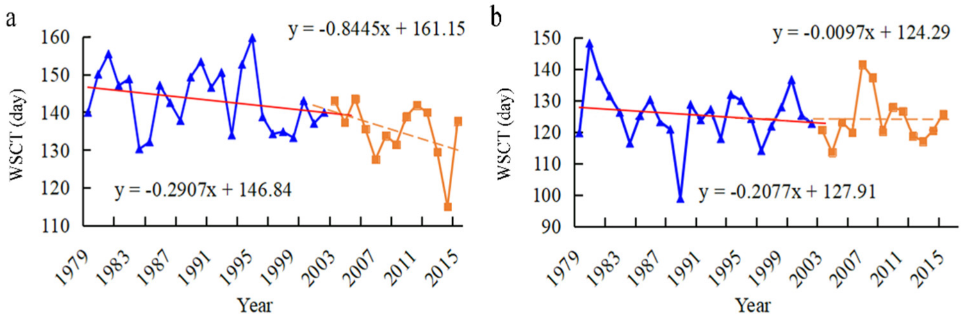

Figure S2. Variations of time series of historical WSCT in the Aksu River catchment. (**a**) Variations of WSCT in the Toxkan catchment; (**b**) variations of WSCT in the Kumalak River catchment.

During 1979–2002, WSCT in the Toxkan and Kumalak Rivers both displayed an advancing trend of about −0.29 and −0.21 d/year, respectively (Figure S2). While since 2002, WSCT in the Toxkan River experienced an 11-day advancement, and the snowmelt runoff during this period increased by about 30.06% compared to the period 1979–2002, while a slower WSCT advancement for the Kumalak River.

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