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Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia

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ABSTRACT

Glaciers are significant fresh water storages in Central Asian high mountains and are considered to substantially contribute to the summer runoff of Central Asian Rivers. We present a comprehensive study of the glacier area changes in the Naryn catchment located in the Tien Shan Mountains. The catchment with a size of 55,944 km^2 is a major tributary of the Syrdarya River which is heavily used for water supply and irrigation. We analysed the glacier retreat based on Landsat MSS, TM and ETM + imagery for the mid-1970s, late 1990s and mid-2000s and based on a SPOT scene for 2007. Our results show a decreasing glacierisation within the catchment, shrinking from 1210 ± 30 km^2 (2.2% glacierisation) in the 1970s to 1019 ± 25 km^2 (1.8% glacierisation) in the late 1990s and further down to 926 ± 23 km^2 (1.7% glacierisation) in the mid-2000s, corresponding to an area loss of 23% in total. The analysis reveals spatially heterogeneous area loss within the catchment. This can be associated with different hypsometries, size distributions, aspects and presences of debris cover. Small glaciers (with an area < 1 km^2) suffered from a strong area loss within the 30-years investigation period.

Trends in air temperature, precipitation and positive degree days (PDD) at climate stations suggest that the glacier retreat is likely to be driven by the increasing summer (April–September) temperature, rather than changes in precipitation: In the period from 1960 to 2007, both summer air temperature and PDDs increased significantly at a rate of 0.19 °C/decade and 3.9 °C/decade respectively, whilst for precipitation no consistent trends were detected. However, rigorous attribution of changes is complicated by the variable glacier response times. In the two headwater sub-catchments of the Naryn basin, Small and Big Naryn, positive trends in spring and autumn discharge were detected and are likely to be associated with the enhanced snow and glacier melt driven by increasing temperatures in those seasons. However, no discharge trends in August – the month with the largest expected glacier contribution – were detected. The strong, significantly positive trends in winter and early spring runoff are associated with strongly increasing winter temperatures and number of days with maximum daily temperature above the freezing point causing snow melt. Hence, increasing glacier area reduction can be explained by the prolongation of the melting season reducing accumulation rather than by increasing annual mean temperatures. Despite the high relative changes, the absolute increase in winter discharge is very small.

1. Introduction

Glaciers are significant fresh water storages in the Central Asian mountains with estimated total volume of 1048 km^3 for the whole Tien Shan Mountains in 1960–1970 (Katalog Lednikov SSSR, 1966–1983; Glacier Inventory of China, 1973 as cited by V.B. Aizen et al., 2007) and 555.7 km^3 for the former soviet part of the Gissaro-Alai and Pamir in 1980 (Konovalov and Shchetinnicov, 1994). They appear to be good indicators of climatic changes (Oerlemans, 1994, 2005) and are believed to significantly contribute to the mean annual and particularly to summer runoff of the two major Central Asian rivers — Amudarya and Syrdarya. The glacier contribution to river runoff in relation to the population in the basin of the Aral Sea is among the highest in the world (Kaser et al., 2010), although the glacier contribution at sub-regional scale remains poorly quantified.

Aizen et al. (1995, 1996) provided estimates based on the annual water balance for a few typical rivers in the Tien Shan Mountains, whereas Kemmerikh (1972) used a hydrograph separation method to estimate the glacier contribution of several rivers. This second

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method, however, relies on the crude assumption of zero snow and precipitation contribution to runoff during late summer and early autumn, and thus strongly overestimates the role of glacier melt.

The variability of the glacier contribution is strongly affected by snowmelt and precipitation. The uncertainty in spatial and temporal (intra- and inter-annual) variability of glacier melt runoff fuels many speculations about the role of glaciers for water supply in Central Asia.

Glacier melt particularly supplies the Naryn River, which has a basin area of about 55,944 km^2 and is the major tributary of the Syrdarya River (Fig. 1). The Naryn River drains to the Toktogul reservoir in Kyrgyzstan, and supplies water to the agriculturally important and heavily irrigated Ferghana Valley in Uzbekistan, downstream the catchment outlet. The Naryn basin itself can be regarded as natural, since there is only little irrigation activity and changes of water usage are negligible. The catchment is located in the north and central Tien Shan region and stretches over the elevation range between 900 and nearly 5000 m a.s.l.

The climate in the basin is strongly dominated by the westerly flows that supply the largest share of precipitation. Annual precipitation ranges between ~280 mm and 450 mm depending on altitude (Aizen et al., 1995). The highest share of precipitation falls in spring and early summer (Aizen et al., 1995; Schiemann et al., 2008). According to measurements, the basin has a nival flow regime with long-term (1963–2008) mean discharge at the basin outlet of about 350 m^3/s (standard deviation of ~300 m^3/s).

About 2% of the basin area is glacierised. The majority of glaciers is concentrated in the eastern part of the basin, with some smaller glacier areas in the western part (Fig. 1), and glacier melt is roughly estimated to supply about 10% of total annual discharge (Aizen et al., 1995). The Naryn basin is constrained by the southern slopes of the Kyrgyz Alatoo and Terskey Alatoo in the north, Akshiirak massif in the east, and Ferghana, At-Bashi and Borkoldoy ranges in the south.

Glacier area changes in Central Asia, and particularly in the Tien Shan mountains, were partly investigated by different research groups already. Based on topographic maps, SRTM and ASTER data sources, V. Aizen et al. (2007) thoroughly studied the changes in glacier area and volume between 1943 and 2003 in the Akshiirak massif, which partly drains to the Naryn basin. The authors found 12.8% decrease in glacier area and a reduction of 9.7 km^3 in glacier volume for the period 1943–2003. Bolch (2007) compared the glacierisation of a few small basins in the northern Tien Shan (Zailiyskiy and Kungey Alatoo) determined from Landsat ETM+ and ASTER images with the Katalog Lednikov SSSR (1966–1983) and found a 32% to 38% decrease of glacier in the period from the 1950s to 1999.

Narama et al. (2006), who documented a rather small glacier area loss of about 8% for the Western Terskey Alatoo and the period 1971–2002, found that small glaciers with a size of less than 1 km^2 are mostly affected by the retreat. Glacier shrinkage was related to positive trends in temperature at two climate stations between 1960 and 2000.

Niederer et al. (2008) reported a glacier retreat of about 28% between 1963 and 2000 for the rather small Sokoluk catchment located in the Northern Tien Shan.

Wang et al. (2009) investigated glacier area changes in the Karlik Shan region, located in the very eastern part of Tien Shan and found a glacier area loss of about 5.3% for the time between 1971 and 2002.

Kutuzov and Shahgedanova (2009) evaluated the glacier area changes in the Terskey-Alatoo since the end of Little Ice Age (~1850), until 1990 and 2003 based on moraine positions and glacier areas delineated from the Landsat and ASTER imagery, documenting a glacier area loss of about 12.6% within the period from 1965 to 2003.

Recently, Narama et al. (2010) have analysed glacier area changes at four selected mountain ranges in the eastern and central Tien Shan from 1970 to 2007 based on Corona, Landsat and ALOS satellite data. They detected varying retreat rates, with higher relative losses occurring in the western and northern Tien Shan, and associated this retreat with the increasing summer temperatures.

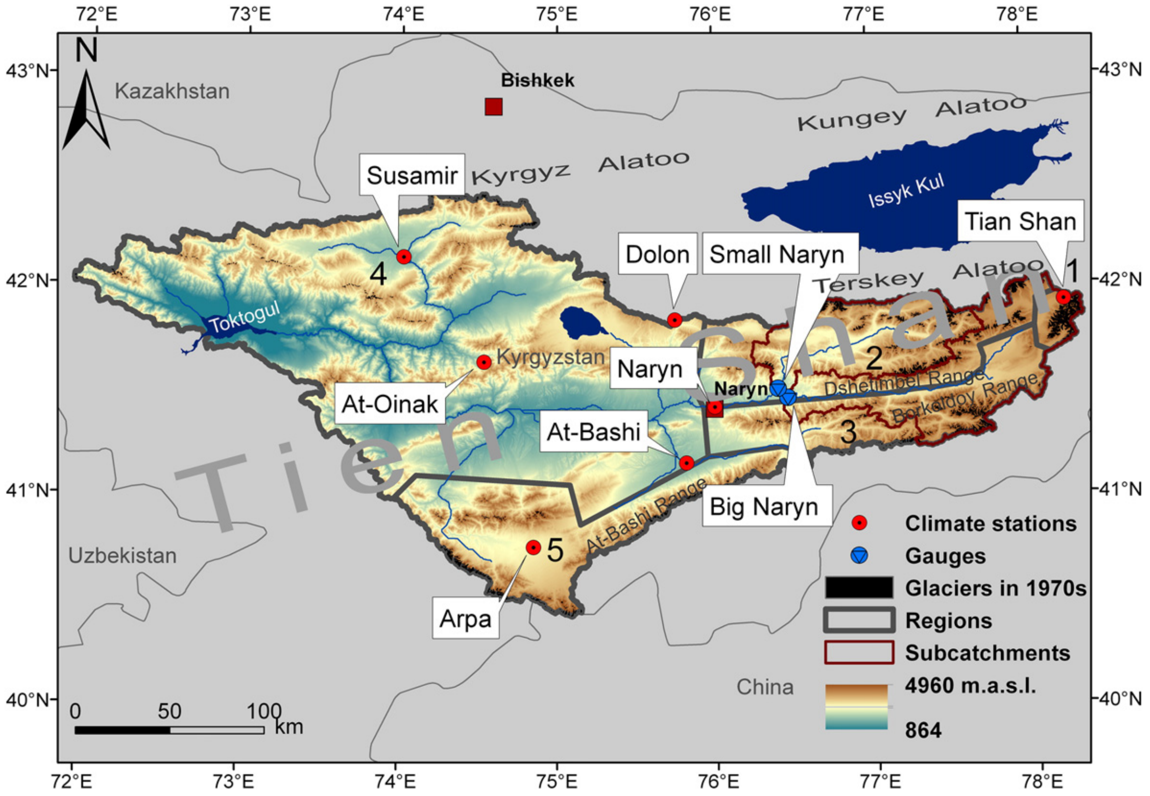

Fig. 1. Location of Naryn catchment in Kyrgyzstan with initial glacierisation of the 1970s and region borders: 1—Akshiirak, 2—Dzhetim, 3—Borkoldoy Too, 4—Lower Naryn, and 5—At-Bashi Kirkasi.

These previous studies primarily focused on selected mountain ranges or small catchments close to or partly in the Naryn basin, rather than consistently analysing glacier area changes for regional-scale river basins. Based on previous works, the general tendency of glacier retreat in Tien Shan is evident, but the implications of glacier area/volume changes to changes in runoff remain unclear. Some authors suggest that the recent glacier retreat in Central Asia resulted in the increasing trends of glacier-fed river discharge (e.g. Giese et al., 2007; V.B. Aizen et al., 2007). In other parts of the world, like in Western Canada, glaciers seem to reach a tipping point, from which further retreat causes negative discharge trends (Stahl and Moore, 2006).

To allow a well-founded discussion about changes in long-term water availability influenced by climate change and glacier retreat, we i) consistently analyse the changes in glacierisation in the whole basin of the Naryn River over the past decades, ii) relate the glacier area changes to the results of trend analyses carried out for precipitation, air temperature and PDD per month at three climate stations (Fig. 1) and iii) relate the trends in monthly discharges from two headwater catchments to changes in driving meteorological variables (temperature and precipitation). This allows understanding whether there are notable changes in runoff in specific months, and whether those changes can be attributed to the observed changes in glacierisation and climate.

Based on Landsat and SPOT satellite imagery, we analyse the glacier area changes between the mid-1970s, late 1990s and mid-2000s. In order to assess the spatial variability in glacier area loss, the entire Naryn catchment was subdivided into regions in a way that contiguous mountain ranges are encompassed. These regions include: Akshiirak, containing the north-western Akshiirak massif; Dzhetim region, containing Dzhetim range, parts of Terskey Alatoo and Suek range; Borkoldoy Too region, covering Borkoldoy Too range; At-Bashi Kirkasi region, containing the northern slopes of At-Bashi range and Lower Naryn region, covering the lower elevated western part of the Naryn catchment (Fig. 1). Trends in meteorological variables and in river discharge are analysed using the Kendall-Theil Robust Line and Mann-Kendall significance tests. So far, only a few studies analysed the significance of the observed trends in Central Asia, which considerably limits statements related to changes in climate.

2. Data and methods

2.1. Remote sensing data

In the current study, we used satellite images from Landsat MSS, TM and ETM+, retrieved from USGS Global Visualization Viewer (http://glovis.usgs.gov), as well as two scenes taken from SPOT (Système Pour l'Observation de la Terre) imagery (acquired via www.gaf.de). Landsat multispectral data are of a resolution ranging from about 80 m for MSS data to about 30 m for TM and ETM+. To determine the changes in glacier area extent especially in the ablation zone, the Landsat images were selected for the snow-free period with lowest possible cloud cover and mosaiced from up to 5 sequential years in the middle of the 1970s, late 1990s and mid-2000s (Table 1).

Additional data available for the eastern Naryn region were taken from SPOT imagery for 22nd of August 2007 with a resolution of 5 × 5 m. The latter data source helped to evaluate the accuracy of the Landsat retrieved glacier area data for the mid-2000s.

2.2. Image processing and glacier delineation

Landsat data were orthorectified using the SRTM DEM (Shuttle Radar Topography Mission digital elevation model) grid (Farr et al., 2007) which is based on radar measurements in February 2000 and has a 90 m resolution. Raw data of Landsat were calibrated according to Chander et al. (2009), and reflectance values were calculated. Glacier area delineation was carried out using multiple approaches: spectral analysis, classification and manual digitizing (e.g. Paul, 2000).

Table 1
Satellite data specifications. Resolution is specified for used channels. The different location specifications for MSS imagery in the second column are due to a different size and shape of scenes and the data grid compared to images of the later sensors TM and ETM+.

Date	Path (p)/Row (r)	Sensor	Resolution	
Landsat				
1975-08-13	p149_r031	MSS	79 m	1970s
1972-09-07	p161_r031	MSS		
1977-07-16	p161_r032	MSS		
1977-08-22	p162_r031	MSS		
1977-09-27	p162_r032	MSS		
1977-09-28	p163_r031	MSS		
1977-09-29	p164_r031	MSS		
1999-08-17	p148_r031	ETM+	30 m	Late 1990s
1999-09-09	p149_r031	ETM+	(Channel 1–5, 7)	
1999-09-16	p150_r031	ETM+		
1998-10-23	p150_r032	ETM+		
2000-08-24	p151_r031	ETM+		
1999-08-21	p152_r031	TM5		
2007-07-30	p148_r031	TM5	30 m	Mid-2000s
2007-09-07	p149_r031	TM5	(Channel 1–5, 7)	
2007-09-06	p150_r031	ETM+		
2002-09-24	p150_r032	ETM+		
2007-09-13	p151_r031	ETM+		
2008-08-05	p152_r031	ETM+		
SPOT				
2007-08-22	200_266	HRG	5 m	
2007-08-22	200_267	HRG	5 m	

In a first step, spectral analysis was modified: instead of using the ratio of TM channels 4 and 5 (as proposed by Paul, 2000 for example), the Normalized Difference Snow Index (NDSI, Crane and Anderson, 1984) was calculated using channels 2 and 5 of TM and ETM+ sensors. So detected snow covered areas were used as a hint for the existence of glaciers, as their accumulation area is most likely to be snow covered even in late summer. As a next step, supervised classification was used in order to obtain areas with the same spectral characteristics as snow, bare glacier, debris on glacier, moraine or other surface types using Landsat MSS and TM/ETM+ data. In a final step, manual digitizing was used to correct false classifications and decide for proper glacier outline delineation under shady or debris covered conditions.

The two SPOT images were orthorectified using the Global Digital Elevation Map retrieved from ASTER-imagery (http://www.ersdac.or.jp/GDEM/E/index.html). To delineate glacier boundaries, a greyscale mapping was performed in order to find a threshold which allows detecting glaciers automatically. However, as for the Landsat imagery, manual corrections were necessary on debris covered glacier tongues and to omit snow patches.

As the additional comparison of the derived glacier masks from both satellite products was done only visually, the orthorectification of each satellite data set with a different DEM had no influence on the accuracy of the glacier delineation.

2.3. Hydro-meteorological data and trend analysis

In order to determine and analyse the potential drivers of glacier changes and investigate the changes in river runoff over the past decades (1960–2007), a trend analysis using the Mann-Kendall test (Kendall, 1975) was carried out for the time series of air temperature and precipitation at selected climate stations (Fig. 1, Table 5). The representativeness of the selected stations for characterising the climatic conditions was investigated by correlation analysis.

In addition to the trends in annual and monthly precipitation and monthly temperatures, we analysed the trends in (i) mean summer (April–September) temperature and (ii) sums of PDDs per month as a proxies for the amount of energy available for melt and the duration of the ablation period, respectively.

It was pointed out by several authors that the central Tien Shan receives the largest share of precipitation during spring and summer months, causing a peak in accumulation (Dyurgerov et al., 1994; Aizen et al., 1995; Narama et al., 2010). Dyurgerov et al. (1994) further highlighted that even small fluctuations in summer accumulation have a significant influence on summer and annual mass balance gradients, and are therefore noticeable in glacier evolution. However, the winter-half year is also relevant for accumulation and thus was taken into account in the annual series.

Finally, the runoff response to changes in meteorological variables and glacierisation was investigated at the gauging stations of Small Naryn (total area: 3879 km^2, glacierised area in the 1970s: 10%) and Big Naryn (total area: 5547 km^2, glacierised area in the 1970s: 12.4%). These are the most elevated gauges in the Naryn catchment recording runoff from heavily glacierised headwater catchments. Trends in mean monthly flow were analysed over the period from 1960 to 2007. The dependence between mean monthly discharge and monthly temperature, precipitation and PDDs was characterised using the Pearson product–moment correlation coefficient (CC).

The trend significance was analysed with the non-parametric Mann-Kendall test applied with the 2-sided option and 10% significance level. Prior to the application of the Mann-Kendall test, serial correlation was removed using a trend free pre-whitening procedure (Yue et al., 2002), as serial correlation may lead to the overestimation of trend significance (von Storch and Cannon, 1995).

The trends in hydrometeorological variables were estimated using the Sen's slope estimator (Sen, 1968) given by:

$$\beta = \text{median}\left[\frac{X_j - X_i}{j - i}\right] \text{ for all } i<j, \tag{1}$$

where X_i, X_j are the values of the considered variable in years i and j, respectively. The linear trend was described by the Kendall-Theil Robust Line given by:

$$X_{tl} = \beta \cdot t + \text{median}(X) - \text{median}(t) \cdot \beta \tag{2}$$

where X_{tl} is the value of the trend line at year t. The trends in discharge were calculated in absolute numbers and as relative changes over the investigated period as follows:

$$dX_r = \frac{X_{ly} - X_{fy}}{\overline{X}} \cdot 100\% \tag{3}$$

where $dX_r$is the relative change of a variable in the investigated time period, X_{ly}, $X_{fy}$are the values of the estimated trend line in the last and the first year respectively, and $\overline{X}$ is the mean value of the time series in the period of investigation. Trends in summer temperature and annual precipitation are presented in form of multiple trend matrices, which indicate the change for different periods of at least 30 years length, with various starts and end years for the time series.

3. Results and discussion

3.1. Glacier area changes

In the 1970s, the glacier area in the Naryn catchment was about 1210 ± 30 km^2, which corresponds to a glacierisation of about 2.2%. In the late 1990s, the glacier cover had decreased to 1019 ± 25 km^2, covering 1.8% of the catchment, and decreased further to 926 ± 23 km^2 (1.7% glacierisation) in the mid-2000s. Between the 1970s and late 1990s, about 16%, and from the late 1990s to mid-2000s about 9% of the glacier area disappeared. During the whole investigation period an area loss of about 23% of the initial glacier area was detected (Table 2).

In total, 1478 glaciers were delineated in the 1970s for the entire Naryn basin. Paul et al. (2013) proposed a round robin approach to assess the accuracy of glacier delineation which is based on repeated delineation of several glaciers by different experts. However, as this method is rather time-consuming, the accuracy of the glacier delineation in this study was assessed by comparing the glacier masks retrieved from the SPOT and Landsat datasets for 2007 and mid-2000s, respectively. The two datasets were processed by two different co-authors. Thus, the accuracy reflects the bulk uncertainty related to the resolution of datasets and to the subjective interpretation by the responsible scientist. Both masks show an agreement of 97.5% in area, which can be regarded as acceptable taking into account the detected area changes.

Fig. 2 shows the initial glacierisation and corresponding area losses for the periods from the 1970s to 1990s and from the 1990s to mid-2000s. The percentage of remaining glacier area during mid-2000s within the five regions is shown as well.

Particularly small glaciers (i.e. with an initial area below 1 km^2) show a strong variation of area changes during the investigation period from the 1970s to mid-2000s. Whilst some of the small glaciers have undergone an area reduction of just a few percent, others suffered a strong relative loss or have even disappeared (Fig. 3).

We explain this phenomenon with the different locations of small glaciers: they are often located at lower elevations compared to the large glaciers (Fig. 4). Hence, a greater number of small glaciers are exposed to higher temperatures.

Moreover, small and large glaciers have different response times. Whilst large glaciers have long response times, small glaciers faster adjust their area to mass losses.

In the next step, area changes were analysed depending on altitude, aspect and slope of the glacier surface. The results are summarised in Table 3 and Figs. 5 and 6.

In all regions, glacier retreat is characterised by the upward shift of the hypsometric curves towards higher elevations (Fig. 5).

The proportion of low-elevated glaciers exhibits a strong reduction, whereas the ratio of high-elevated glacier areas increases. In all five regions of the Naryn basin, the glaciers are mostly located on slopes facing north-west to north-east (Fig. 6a–e). 29% of all glaciers face north for the late 1990s (not in the figure).

Areas at those aspects showed a loss of 118 km^2 from the 1970s to late 1990s, which is one third of the whole loss in this period. However, the relative loss is much stronger at the south-facing slopes from south-west to south-east and east (where solar radiation consumption is higher than on northern slopes), with 38% and 41% area loss by the mid-2000s, respectively (Fig. 6f). Compared to that, the relative losses on the northern slopes were smaller (from 11% only on northern slopes up to 28% on north-eastern slopes). In the period from the late 1990s to mid-2000s, the relative changes on the eastern, western and northern facing slopes are comparable to those facing south (not shown).

We interpret these changes as a result of (1) south-facing glaciers losing a vast portion of area in the first period due to higher input of solar radiation input whilst northern glaciers suffer a weaker loss, and (2) an ongoing retreat at both southern and northern aspects caused by increasing temperatures in those elevations during the second period.

Using the SRTM DEM, the slopes of the glacierised areas were estimated at three points in time.

Table 2
Glacierisation and area change in the Naryn catchment during the mid-1970s, late 1990s and mid-2000s.

Year	1970s	Late 1990s	Mid-2000s
Glacier area in km^2	1210 ± 30	1019 ± 25	926 ± 23
Catchment glacierisation in %	2.2	1.8	1.7
Area loss in % relative to the initial area	–	**16**	**23**

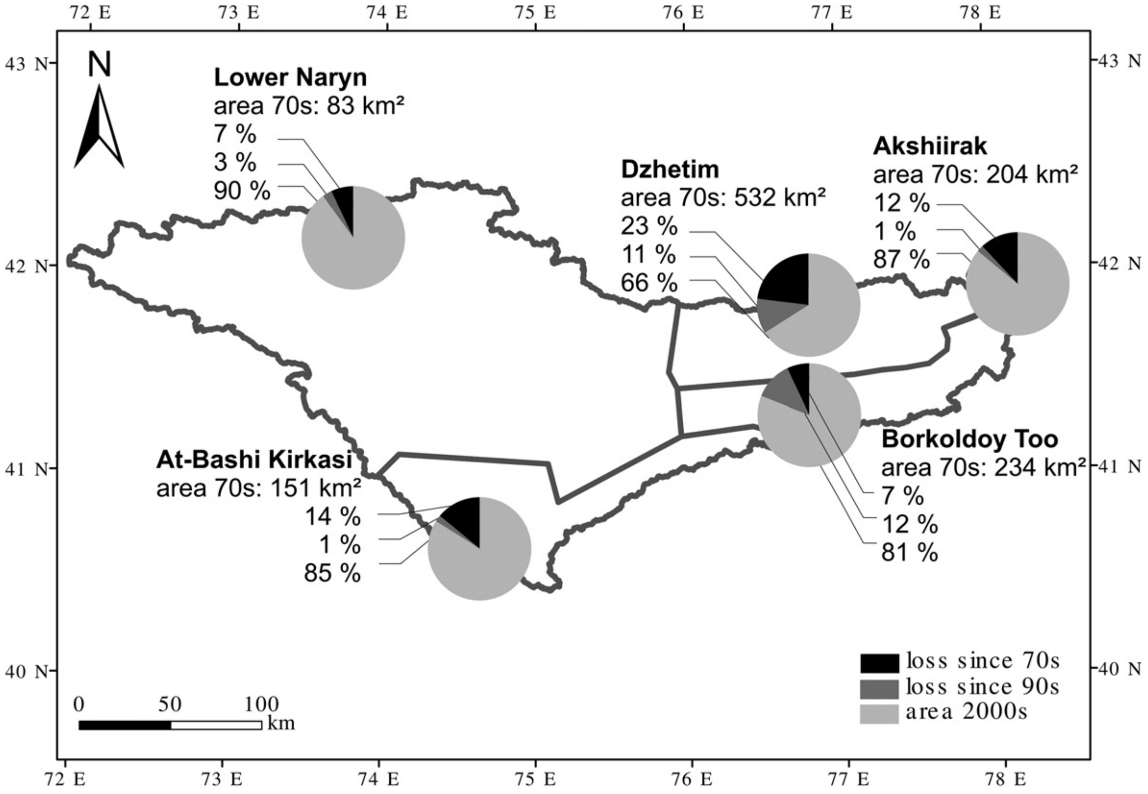

Fig. 2. Glacier area extent of 1970s and glacier area changes from the 1970s to late 1990s and mid 2000s within the five regions.

In all regions, glacier area tends to be larger for glaciers with a flat surface slope (<22.5°) than for glaciers with steeper surface slopes (22.5–45°). Almost 60% of the whole glacier area had a rather flat slope, 38% had slopes up to 45° and only 2% had slopes steeper than 45° during the 1970s. However, the results show no significant dependence of glacier area reduction from slope. For glaciers with steep surface slopes (>45°), no significant area loss can be detected, as glaciers barely exist on those slopes or they occur in high altitudes where temperatures are lower and glacier area loss is small.

For all regions except Borkoldoy Too, the glacier area losses are larger during the first period (1970s to 1990s) compared to the second one (1990s to 2000s). In Borkoldoy Too, the majority of glacier area (>55%) was oriented to north and north-west direction in the 1970s (Fig. 6), in contrast to other regions. Those aspects experienced the lowest glacier area reduction in the first period.

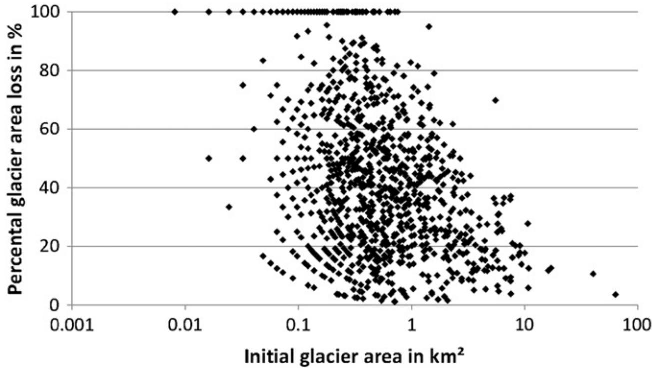

Fig. 3. Percental glacier area loss from the 1970s to mid-2000s depending on glacier area size.

Moreover, the glacier tongues in Borkoldoy Too region are heavily covered by debris that act as insulation and result in the relatively small glacier retreat. We hypothesise that especially debris-covered tongues were not significantly affected by melt in the first period whilst in the second period debris-free glacier areas located in higher elevations experienced the effect of increasing temperature (Section 3.2) which resulted in observed area loss. Compared to other regions, the mean of the hypsometric curve for Borkoldoy is at higher elevations, whereas in Akshiirak, a comparable region with regard to hypsometry, no extensive debris-cover is present on glacier tongues.

The largest area loss was detected in the Dzhetim region: 23% in the first period and 11% in the second period (Fig. 2). Among all regions, Dzhetim has the highest portion of glacier area facing southern and south-eastern aspects which have a higher radiation input. Moreover, Dzhetim contains a high portion of small glaciers, thus showing a quicker response to the increasing temperatures. Although, in Akshiirak region the proportion of glacier area facing southern and south-western directions is comparable to Dzhetim, the area loss in Akshiirak is considerably smaller. This can be explained by tendentially higher elevations and greater glacier size of Akshiirak glaciers compared to Dzhetim.

Although the direct comparison of our results with other regional studies is not straightforward since other authors did not detect the glacier area changes specifically for the Naryn basin but rather for the whole mountain ranges or e.g. for the entire Akshiirak massif, our results are very similar to the glacier area changes in At-Bashi and Akshiirak regions reported by Narama et al. (2010) and V. Aizen et al. (2007), respectively.

The presented results highlight a strong heterogeneity in the glacier area loss at different regions of the Naryn basin. The analysis suggests

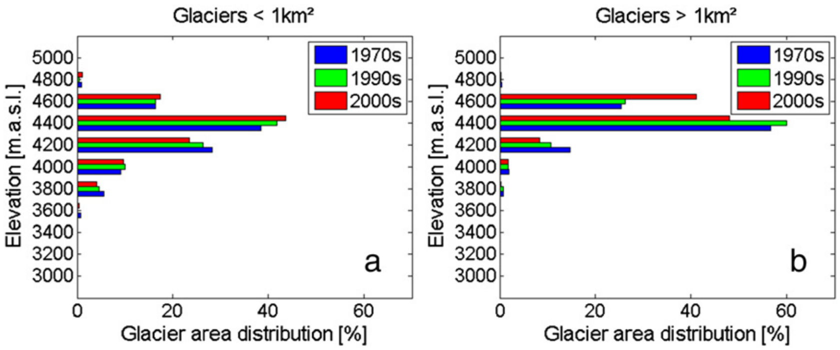

Fig. 4. Hypsometric curves for two glacier size classes with area (a) smaller than 1 km^2 and (b) larger than 1 km^2 for three different time points.

that glacier size, spatial distribution and topographic characteristics significantly modulate glacier area changes due to climatic changes.

3.2. Hydro-meteorological changes

3.2.1. Analysis of temperature time series

The multiple trend analyses for the climate station Naryn indicate a strong statistically significant increase in mean summer (April–September) temperature with about 0.19 °C per decade over the period from 1960 to 2007 (Fig. 7a, yellow to red pixels within the black polygons). For several periods in the long term, the trends are positive and statistically significant, whereas shorter-term trends are predominantly statistically insignificant.

The trends in mean summer temperature at the Naryn station can be regarded as characteristic for the entire Naryn basin, since the correlation coefficients (CC) between the mean monthly temperature at this station and other climate stations are very high (0.979 and higher, Table 4). In the following, we therefore analyse the air temperature at Naryn station.

As shown in Fig. 7a, only little trend fluctuations were discovered whilst significant temperature increases resulted in an overall significant positive trend.

The analysis of monthly temperatures (Table 5) exhibits that the positive trend in temperature during autumn and winter months is extremely steep with changes of about 0.5–1 °C per decade. The changes during the summer months are not significant, except for June. Hence, the trend in mean annual temperature is strongly dominated by the trends in autumn and winter months. We furthermore investigated the trends in PDDs, defined as the cumulative positive temperatures per month (Table 5). These results show an increasing amount of energy available for melt and support the findings in the temperature trend, except for the winter months, where temperatures rise but remain negative. The trend in PDDs results in increasing melt, especially during autumn.

Table 3
Glacier area loss in different regions and for different size classes: (1) <1 km^2, (2) 1–5 km^2, (3) 5–10 km^2, and (4) >10 km^2.

		Glacier area in (km^2)			Glacier area loss in (%)		
Region	Size class 1970s	1970s	1990s	Mid-2000s	70s–90s	90–2000s	70s–2000s
Akshiirak	1	9.3	6.2	5.7	60	11	64
	2	40.2	33.3	32.7	19	1	20
	3	24.3	20.5	19.8	17	4	19
	4	131.0	120.7	118.8	10	5	14
Dzhetim	1	142.4	94.0	70.2	40	28	57
	2	231.6	173.7	149.6	29	16	40
	3	138.3	112.3	103.2	19	9	26
	4	20.9	19.6	17.7	6	9	15
Borkoldoy Too	1	94.6	76.6	62.4	26	19	41
	2	88.9	80.1	70.2	11	14	24
	3	35.9	27.0	25.0	25	7	30
	4	16.1	14.5	14.2	10	2	12
Lower Naryn	1	53.7	41.7	37.5	26	12	35
	2	29.3	24.2	22.3	19	8	26
	3	–	–	–	–	–	–
	4	–	–	–	–	–	–
At-Bashi Kirkasi	1	53.5	40.7	36.7	31	11	38
	2	54.6	44.1	42.0	21	5	25
	3	34.3	30.6	30.3	12	1	13
	4	10.8	10.0	10.0	8	0	8

3.2.2. Analysis of precipitation time series

For changes in precipitation, a more heterogeneous spatial pattern is expected than for changes in mean monthly temperatures. This is also shown by the lower correlation coefficients between the monthly precipitation at the three stations with long available time series (Naryn, Tien Shan and Susamir), forming a profile across the basin (Table 6).

We analysed trends in annual precipitation for the selected climate stations in the period from 1960 to 2007. We used the continuous time series at the Naryn climate station to fill a few existing gaps in other time series based on linear regression (38 and 22 missing months for Tien Shan and Susamir, respectively).

Trends in annual precipitation appeared to be heterogeneous. Whereas for the whole investigation period the trends for Naryn and Tien Shan are small and not significant, for some shorter periods significant positive (Naryn) and significant negative (Tien Shan) trends are revealed (Fig. 7b and c), respectively. As multiple trend analyses indicate, there are relatively weak precipitation trend fluctuations for the Naryn station with trends only becoming either slightly positive over the longer period or, due to significant increase in precipitation since the mid-seventies, significantly positive for later start years of the time series (upper right corner of Fig. 7b). The trends at Tien Shan station exhibit a very strong shift from significantly negative to positive (Fig. 7c), basically due to an abrupt change in 1997. The precipitation time series from Tien Shan station is likely to be biassed by the relocation of the station in 1997 and change in measurement equipment as pointed out by Kutuzov and Shahgedanova (2009).

At Susamir station, however, the analysis over the whole investigation period shows significant negative trends (Fig. 7d).

The analysis suggests that the Naryn basin experienced a reduction of annual precipitation over the past decades, especially pronounced at the high-elevation stations Tien Shan (until 1997) and Susamir. Therefore, the effect of increasing summer temperature on glacier mass balance was further aggravated by decreasing annual precipitation. However, the question on how representatives are a few climate stations for the whole Naryn basin, especially considering the heterogeneity of precipitation patterns in mountain regions, still remains open.

As Table 5 shows, in the period from 1960 to 2007, the high-elevation region in the north-western part of the basin characterised by the

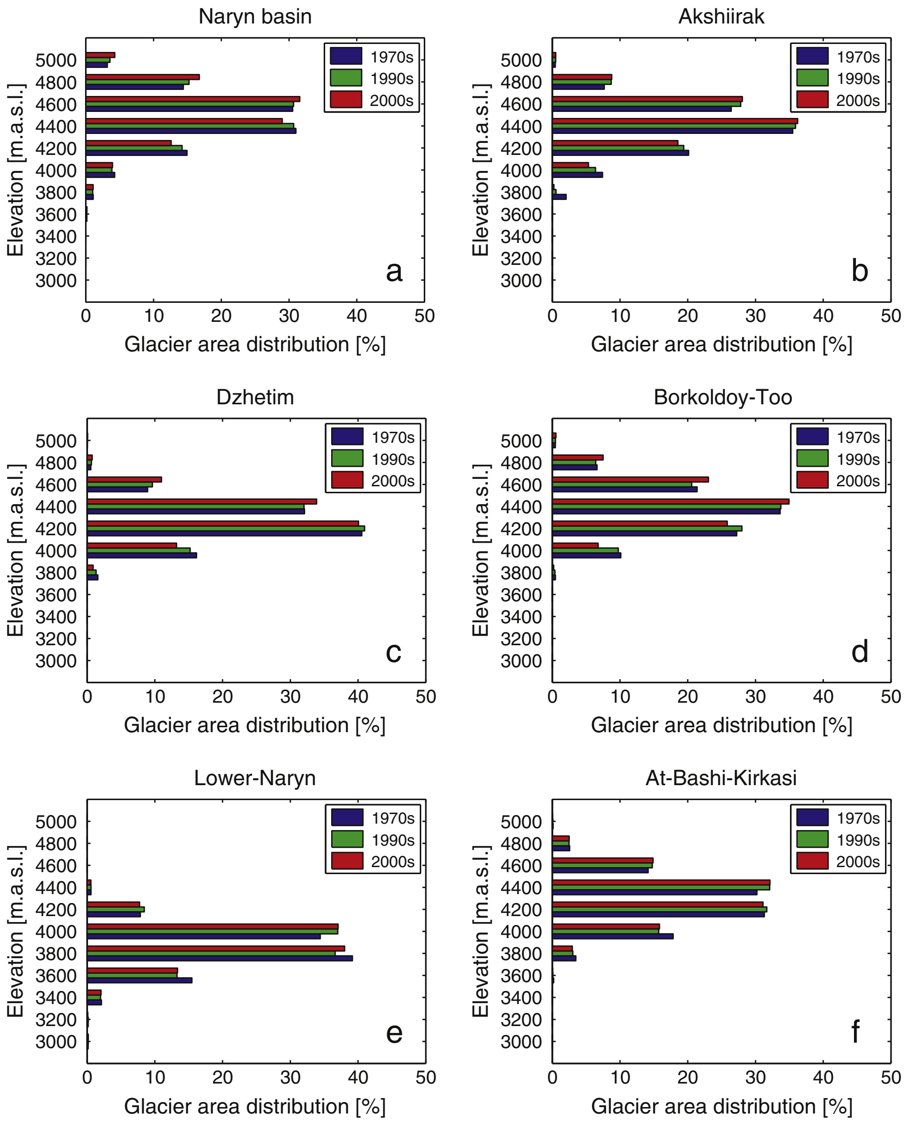

Fig. 5. Hypsometric curves for three points in time for the (a) entire Naryn basin and (b–f) five regions.

Susamir climate station experienced a strong precipitation reduction in the summer half-year with statistically significant negative trends in May and September. V. Aizen et al. (2007) pointed out that the summer precipitation, typically occurring as snow at the elevations of glaciers, increases the surface albedo and reduces ice melt. The decrease in precipitation in the western part of the Naryn basin may have enhanced the glacier retreat in the summer half-year. The monthly trends for the Naryn and Tien Shan stations are heterogeneous and mainly not statistically significant, although the negative non-significant trends at Tien Shan station are rather clustered in the summer months. The analysis suggests that the negative trends in annual precipitation at Tien Shan and Susamir stations are driven by the decreasing summer precipitation over the past decades. This may have enhanced glacier exposition to direct solar radiation and fostered glacier retreat.

3.2.3. Analysis of trends in mean monthly discharge

The Small and Big Naryn stations gauge the most glacierised and snow-dominated headwater sub-catchments, and therefore reflect the effect of past changes in temperature and precipitation regime, as well as glacier and snow storage changes, on discharge from headwaters (Table 5). The link between the changes in temperature and precipitation to changes in discharge was explored by performing a correlation analysis.

The highest portion of glacier runoff in both sub-catchments is expected to occur in August, as also supported by the correlation analysis of temperature and discharge (Fig. 8), which shows a relatively high correlation between August temperature and river flow. The annual distribution of correlations between the mean monthly discharges and mean monthly temperature exhibits an expected pattern for a glacier- and snowmelt-dominated catchment, with relatively high correlations in spring and June, and another peak in August, indicating the snow and glacier melt response to changes in temperature (Fig. 8). The correlations in winter and autumn months are small, and indicate that the mean monthly temperatures are poor indicators for runoff during these months. During the cold period, with daily mean temperatures below zero, the maximum daily temperatures drive the melt processes and trigger runoff formation.

The correlations between runoff and precipitation are very small in most months. This can be expected for the winter half-year (October–March), when snow storage acts as a buffer and introduces a time lag between precipitation input and runoff response. However, even in the summer half-year (April–September) there seems to be no strong correlation between station precipitation and monthly flow. This can

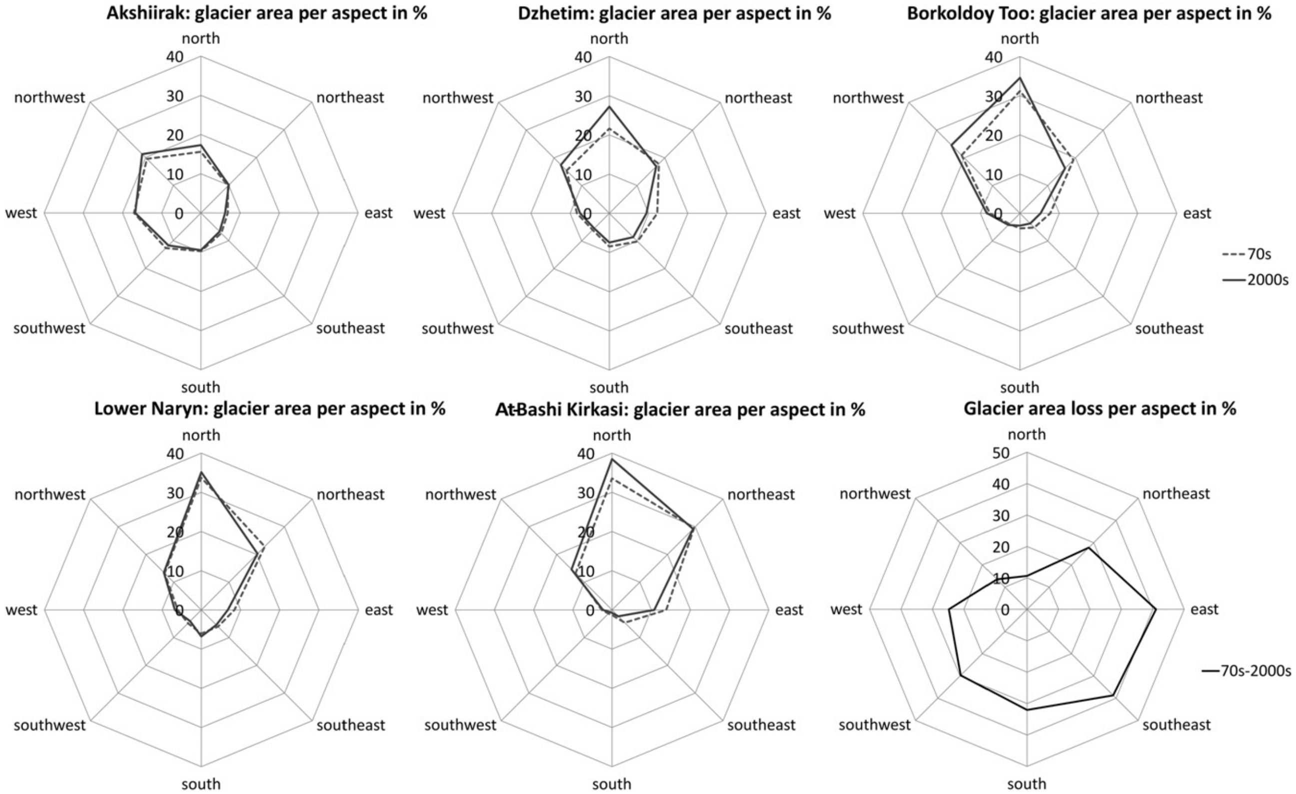

Fig. 6. Distribution of glacier area across different aspects for (a–e) five regions of the Naryn catchment. (f) Relative area loss per aspect in the entire Naryn catchment.

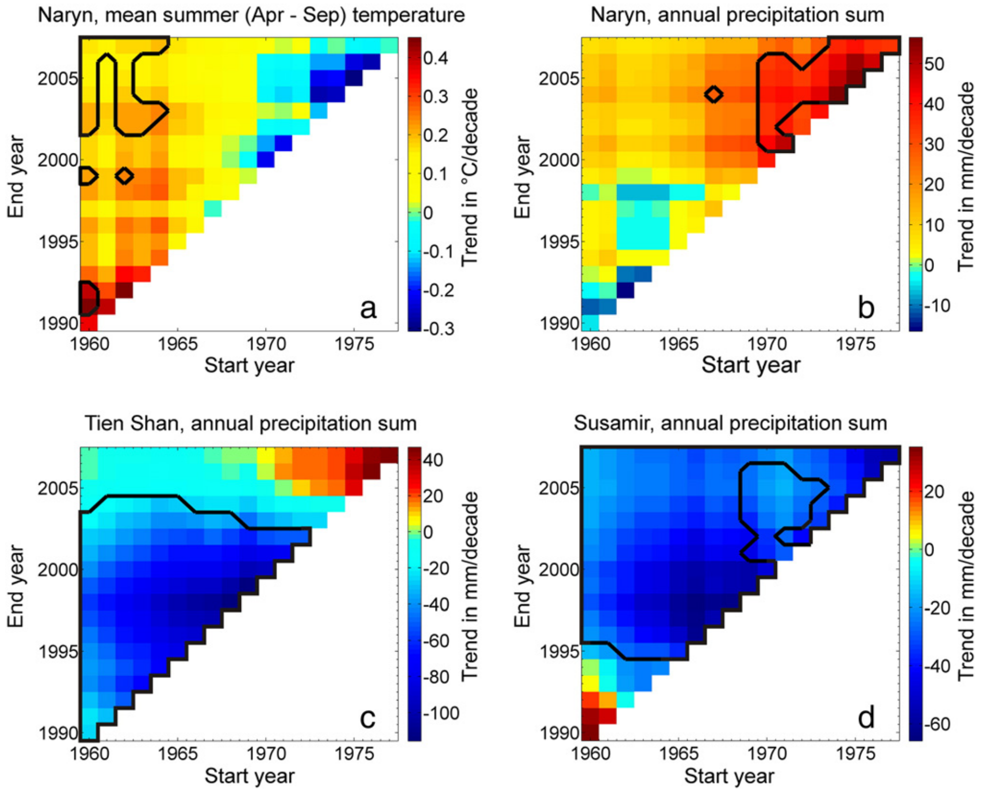

Fig. 7. Trends (blue — negative, red — positive) in (a) mean summer temperature at Naryn station, and (b–d) annual precipitation sum at stations Naryn, Tien Shan and Susamir, depending from start and end years of time series used in the trend analysis. Cells within a black polygon show a significant trend.

Table 4
Correlation coefficients (CC) between mean monthly temperature time series at Naryn climate station and other stations in the Naryn basin with shorter time series. Numbers in brackets indicate the length of the time series in years.

Station	Naryn	Susamir	Tien Shan	At-Bashi	Dolon	At-Oinak	Arpa
Altitude m.a.s.l.	2039	2061	3614	2025	3040	3040	3000
CC	–	0.989 (55)	0.984 (57)	0.998 (26)	0.988 (32)	0.979 (20)	0.988 (22)

Table 6
Correlation coefficients (CC) between the monthly precipitation sums at three stations in the Naryn basin: Naryn, Tien Shan and Susamir. The number in brackets indicates the length (in months) of the time series used to compute the regression coefficients.

Stations	Naryn	Tien Shan	Susamir
Naryn	1	0.58 (538)	0.57 (554)
Tien Shan		1	0.45 (547)
Susamir			1

be explained by the still very high influence of snow/glacier storage in the summer months, but also by the low representativeness of the station precipitation records for the rainfall patterns in the Naryn basin. The snow storage typically reaches its minimum in August, when the glacier contribution is maximal.

The trend in August discharge in Small Naryn is significantly negative, whereas the one in Big Naryn is positive and not significant (Table 5). The results indicate that the increasing glacier melt and retreat do not positively affect the discharge in August. The absence of significant positive trends in August discharge can be explained by the weak and non-significant trend in August temperature (Table 5).

A high relative and absolute increase in discharge was detected for Big Naryn from May to July, which corresponds to the positive temperature trends. The catchment is not anthropogenically influenced, so it can be assumed that all reported changes in the hydrological regime are natural. The rough estimates of changes in potential evaporation based on the empirical approach of Thornthwaite (1948), which solely relies on temperature, suggest that evaporation changes are insignificant during the ablation season, mainly due to small changes in air temperature (Table 5). In winter and spring months, when stronger changes in temperature were detected but temperatures remain relatively low, the resulting small overall evaporation does not influence the water budget. Unfortunately, it was not possible to account for factors such as relative humidity, and wind speed influencing evaporation due to the lack of data. Thus, we conclude that the increase in discharge is partly driven by enhanced snowmelt and partly by glacier melt. Furthermore, a significant increase in temperature and discharge was detected in September, which indicates an enhanced glacier melt for the Big Naryn. The differentiation of those two components is, however, not possible using a data-based methodological approach followed here without detailed information on snow cover. A model-based analysis should be used to separate the flow contribution of snow and glacier storages, and quantify the actual evaporation.

Despite the detected glacier area loss, there was no significant positive trend in mean summer discharge (April–September) observed for the Small Naryn (about 0.1% relative change) that would be expected from the enhanced glacier melt. The trend in August runoff in the Small Naryn is even significantly negative (Table 5). This contrasts with the strongly positive summer flow trends (about 23% relative change) in the Big Naryn catchment.

Although the relative glacierisation of the Small Naryn (10% in 1970s) and Big Naryn (12.4% in 1970s) and the absolute glacier area loss for both catchments (133.2 km^2 vs. 156.4 km^2 for Small Naryn and Big Naryn, respectively) are comparable, the effect on runoff changes is different. A rough estimate shows, that in the Small Naryn catchment a glacier area loss of 100 km^2 occurs together with an increasing mean discharge of about 1.3 m^3/s for the whole investigation period, whilst in the Big Naryn the corresponding increase in mean discharge is 7.1 m^3/s. Possibly, despite the comparable absolute glacier area loss in both catchments, the volume losses are different due to the high share of large glaciers in the Big Naryn basin. Large glaciers are known to exhibit more negative mass balances, as they slowly adjust their area to the changing climate conditions due to long response times. Therefore, their size is in strong disequilibrium with the present climate, and mass balance is more negative than on small glaciers, which are more adapted to the current climate (Huss et al., 2010).

Additionally, the precipitation differences may have partly contributed to the different catchment responses. This, however, cannot be conclusively clarified based on only two climate stations.

Further, we found significant positive discharge trends in winter and partly in spring months at both stations, although the absolute

Table 5
Changes in mean monthly temperature (°C/decade), mean monthly sums of PDD (°C d/decade) and potential evapotranspiration (PET, mm/decade) at the Naryn climate station, in monthly precipitation (mm/decade) at the Naryn, Tien Shan and Susamir stations, and relative (%) and absolute (m^3/s) changes in mean monthly discharge for the gauges of Small Naryn and Big Naryn for the period 1960–2007. Statistically significant trends are indicated in bold.

Station/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T (Naryn) °C/decade	**0.81**	**0.57**	0.43	0.04	0.12	**0.17**	0.17	0.11	**0.44**	**0.28**	**0.97**	**0.48**
PDD (Naryn) °C d/decade	0	0	1.22	0.88	3.7	**4.98**	5.13	3.29	**13**	**7.59**	**7.44**	0
P (Naryn) mm/decade	0.3	−1.28	**1.97**	0.78	−0.01	1.24	0.05	1.99	**−2.83**	0.46	0.14	1.37
P (T. Shan) mm/decade	−0.3	0	−0.57	0.77	1.49	−3	−3.01	−3.06	−1.65	**3.76**	0.83	0.44
P (Susamir) mm/decade	**1.79**	−1.2	0.3	−1.4	**−0.5**	−2.97	−3.03	−0.58	**−2.1**	−1.69	−2.24	1.67
PET (Naryn) mm/decade	0	0	0	−0.4	0	0.36	0.7	0.16	**1.81**	**0.79**	0	0
Q (Small N.)												
%	**28.5**	**27.5**	**35**	19.3	25.4	0.7	−0.7	**−20.3**	8.8	**21.3**	8.8	19.2
m^3/s	**3.3**	**2.9**	**4.1**	4.2	12.2	0.6	−0.7	**−18.2**	3.8	**4.9**	1.4	2.4
Q (Big N.)												
%	**44.8**	**50.8**	**40.1**	18	**35.7**	25.2	**21.2**	8.3	**26.5**	17.1	12.9	**40**
m^3/s	**7.6**	**8.5**	**7.3**	5.2	**22.1**	26	**24.2**	8.1	**11.4**	4.1	2.5	**7.1**

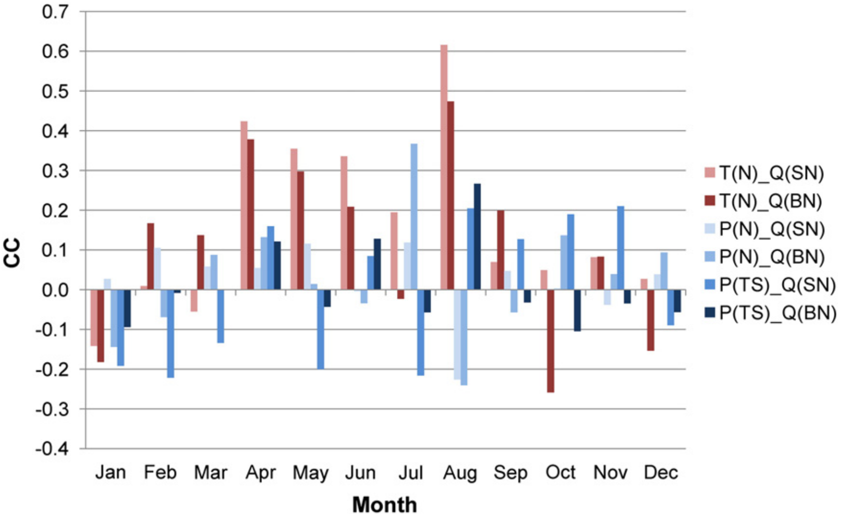

Fig. 8. Correlation between the mean monthly discharge at gauges Small Naryn (SN)/Big Naryn (BN) and mean monthly temperature (T) and monthly precipitation sums (P) at climate stations Naryn (N) and Tien Shan (TS). The legend T(N)_Q(SN) means that the correlation of mean monthly temperature from Naryn station with discharge of Small Naryn gauging station.

changes in monthly discharge of a few cubic metres per second are very small (Table 5). As glaciers are likely to be snow covered during winter and early spring, and no glacier melt occurs, this suggests that the increase in winter discharge is driven by snowmelt or an increasing share of liquid precipitation enhanced by the increased temperature. However, this should be backed up by a model driven analysis. The correlation analysis between discharge and mean monthly temperatures indicates very low correlations in winter, late autumn and early spring (Fig. 8). However, diurnal temperature variations, especially at low elevations, may have exceeded the freezing point more often and for longer time, and resulted in higher snowmelt or a higher share of liquid precipitation. We analysed the trend in number of positive degree days based on the daily maximum temperature at the Naryn station from December to March. Indeed, positive trends for all four months (not shown) were detected, of which, however, only the trend for February was statistically significant. This suggests that the increasing runoff in winter is driven by the increasing number of days in which the maximum daily temperatures exceeds the melting threshold.

However, the steep temperature trends in winter months lead to relatively small absolute changes in runoff from headwater catchments. The strong increase in winter temperatures, which however stay below the freezing point for the majority of the time, is thus not melt-effective and cannot be regarded as a driver of glacier retreat. Therefore, analyses of mean annual temperature trends sometimes used to explain glacier retreat are misleading for Central Asia, where positive trends in winter strongly dominate the trend in mean annual temperature.

4. Conclusion

The presented study analysed the changes in glacierisation in the Naryn river basin from the 1970s to mid-2000s based on various remote sensing sources. Contrary to previous studies, which typically focussed on the analysis of glacier area or volume changes for mountain ranges stretching across catchment boundaries, we investigated the glacier area changes and trends in climatological variables and discharge on the scale of a river basin in order to assess the implications of glacier changes for water availability.

The initial glacierised area in Naryn basin of about 1210 ± 30 km^2 shrunk by 23% for the period from the 1970s to mid-2000s. Our investigation has shown that glacier retreat accelerated during the investigated period and strongly depends on the glacier size distribution. Small glaciers with an initial area of less than 1 km^2 experienced a stronger area loss than larger glaciers. Small glaciers exhibit also a strong variation in the percental area loss.

The area loss-rates in different parts of the Naryn basin appeared to be heterogeneous and were explained by the different shares of glacier area having south-facing aspects, by differences in hypsometry, and glacier size distribution. Especially at lower altitudes and south-facing slopes, the area losses were large, whilst north-facing glaciers in high altitudes suffered less relative area shrinkage.

Glacier area reduction is likely to be driven by the statistically significant summer temperature increase in the recent decades. A significant positive trend in summer (April–September) temperature was detected for the period from 1960 to 2007.

Based on runoff trend analysis from two headwater catchments with a comparable glacierisation of about 10 and 12.4%, the Small Naryn and Big Naryn, we could not identify a significant increase in August discharge, which has the highest share of glacier melt water. Changes in August discharge are small and not significant for the Big Naryn basin, and even significantly negative for the Small Naryn, and were explained by the small changes in August temperature. The glacier area retreat is thus not manifested in increasing river flow in the most critical month for water supply.

The Small and Big Naryn basins showed contrasting flow trends in summer half-year (April-September) despite a comparable absolute glacier area loss since the 1970s. Nevertheless, the Big Naryn may have lost a larger glacier volume due to the presence of large glaciers, and this has potentially led to the increasing summer flow trends in this catchment.

For both summer- and winter-half years, the analysis of monthly temperature trends indicated different rates whereas winter reveals a stronger increase. This however does not influence the glacier melt as glaciers are typically snow covered in the winter period. Since the trend in mean annual temperature is dominated by the non-relevant strong winter temperature increase, its role as driver for glacier area retreat in the Tien Shan region is questionable. Glacier retreat seems not to be dominated by summer melt, but by the longer melting season, reducing accumulation.

Acknowledgement

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloplacha.2013.05.014. These data include Google map of the most important areas described in this article.

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