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Trends for snow cover and river flows in the Pamirs (Central Asia)

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Abstract

In the often discussed Aral Sea basin (Central Asia), water availability depends essentially on the high mountains located in its eastern part, especially from the Pamir Alay Range where the Vakhsh and Pyandj Rivers, the main tributaries of the Amu Darya River, flow. In this region, the cryosphere, glaciers, and snow cover significantly impact the water cycle and the flow regime, which could be deeply modified by climate change. The present study, part of a project funded by the EU FP6, analyzes the hydrological situation in six benchmark basins covering areas between 1800 and 8400 km^2, essentially located in Tajikistan, with a variety of topographical situations, precipitation amounts, and glacierized areas. Four types of parameter are discussed: temperature, glaciers, snow cover, and river flows. Two time periods are considered: (i) a long time series ending in the 1990s with the collapse of the Soviet Union and based on field observations and data collection; (ii) a May 2000 to May 2002 interval, using scarce monitored data and satellite information to follow snow cover dynamics. The results confirm the global homogeneous trend of temperature increase in the mountain range and its impacts on the surface water regimes. Concerning the snow cover, significant differences are noted regarding the location, the elevation, the orientation and the morphology of the respective basins. Finally the expected changes in the flow river regime are regulated by the combination of the snow cover dynamics and the increasing trend of the air temperature. It confirms the high sensitivity of this region to the warming as identified by the 4rd IPCC Assessment Report.

1 Introduction

The Aral Sea Basin in Central Asia is one of the crisis regions worldwide where the management of water resources is unsustainable, uneconomic and hampered by its cross border extension (Micklin, 1988, 2002; Létolle and Mainguet, 1993; Dukhovny and Avakyan, 2001). The collapse of the Soviet system created new and very serious risks and security challenges for the independent states: Afghanistan, Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, and Turkmenistan (Fig. 1). These challenges involved the disintegration of the water, energy and food sectors and dependence on the now transboundary water resources (Wegerich, 2004, 2008)

Although, already special attention was given to the impacts of global changes and associated adaptation issues, including energy and economic approaches (Froebrich et al., 2007; Wegerich et al., 2007; Savitskiy et al., 2008; Olsson et al., 2009) the impact of climate change on the different aspects of local hydrology of the upper Amu Darya catchment is unidentified. However, the timing of water availability and quantitative estimates of hydrologic effects of climate change are essential for solving the local water conflicts in the Amu Darya Basin. Additionally, a rapid recession of glaciers and their contributions to current runoff could lead to a progressive reduction of the already scarce resources and therefore increase the potential for conflict (Olsson et al., 2010).

Global changes, most particularly climate change, have a very important impact on water availability in the Aral Sea basin because of the basin's particular features. Both of the main rivers, the Syr Darya River in the north and the Amu Darya River in the south (Fig. 1), flow down from the west side of the Pamir and Tien Shan mountains through the large and almost desert plain of Kyzylkum, where precipitation is very low, generally below 200 mm yr^{-1}, and summer evaporation is intense. This means that the main part of the flow depends on precipitation, liquid (rainfall) or solid (snowfall) in the mountain areas.

In such context, the present paper aims to analyze in the upper basin of Amu Darya River the trends of the snow cover extent and of the river flow regimes.

2 Regional settings

The chosen study area is centered on the Vakhsh and Pyandj river basins, which are the main headwater tributaries of the Amu Darya River, the largest in Central Asia (Academiya Nauk Tadjikskoy SSR, 1968). Its basin (Fig. 1) comprises 309 000 km^2

and is shared by Afghanistan and four Central Asia Republics: Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

The Vakhsh River, also known as "Kyzyl-Suu" in Kyrgyzstan and as "Surkhob" in north-central Tajikistan, originates in the alpine regions of the Pamir Alai in the south-east of Kyrgyzstan. It flows from north-central Kyrgyzstan to the south-west of Tajikistan. The largest tributaries of the Vakhsh River are the Miksu and the Obi-hingou Rivers. The Pyandj River originates in the Vakjdjir Pass and forms the border between Afghanistan and Tajikistan. The tributaries of the Pyandj River are located in Afghanistan and Tajikistan. Giese et al. (2004) report an annual mean discharge of 20.0 $km^3 yr^{-1}$ for the Vakhsh River and a mean discharge of 34.3 $km^3 yr^{-1}$ for the Pyandj River. Hence, both rivers contribute over 65 % to the total mean discharge of the Amu Darya River (79.3 $km^3 yr^{-1}$).

In their upper part, both rivers drain the Pamirs, which are the northern prolongations of the Hindu Kush and Karakoram mountain ranges. The elevation is quite high, with large areas higher than 4000 m above sea level. Some peaks reach 7000 m a.s.l. such as the Ismoil Somoni Peak (former Peak of Communism, 7495 m a.s.l.) and the Ibn Sina Peak (former Lenin Peak, 7134 m a.s.l.). This region is rich in glaciers (Dyurgerov and Meier, 2005), containing the Fedchenko Glacier, the longest in Eurasia (77 km).

The climate is continental under the influence of the Westerlies, with very high local contrasts due to the orographic conditions. Figures 2 and 3 present the annual distribution of precipitation and temperature (Williams and Konovalov, 2008) over the studied region delimited by the 70th to 74th meridians and 37th to 40th parallels. For precipitation (Fig. 2), a significant contrast appears between the area located in the north-west from the 72nd meridian and 38th parallel, with values above 600/700 $mm yr^{-1}$ and those located in the south and east with arid conditions and values in some places below 100 $mm yr^{-1}$. The highest amount of precipitation in the region is recorded at the Fedchenko Glacier station. For the whole area, the distribution of precipitation presents a maximum during the winter and early spring and a minimum during the summer and early autumn. The temperature (Fig. 3) in the region globally presents large seasonal amplitude, the extreme values depending essentially on elevation, which gradually increases from west to east.

The majority of the published studies in Central Asia regarding the impact of climate changes concern the glacierized basins of the Tien Shan Mountains (Aizen et al., 1996, 1997, 2007a,b; Ososkova et al., 2000; Chub et al., 2002; Khromova et al., 2003; Bolch, 2007). Located north of our study area, they are significant because they present similar climatic trends and impacts as in Pamir Alay Range, where the monitoring conditions were more difficult during the last 10 yr. Studying the Tien Shan Mountains is also useful because of the higher density of existing observation stations and data availability than in other area of Central Asia. The above quoted papers point out the shrinking of the glaciers over the past and future decades and the expected impacts of climate change on precipitation (rainfall and snowfall) and flow regimes under different scenarios of warming, influenced by snow cover and glacier melting processes. They are based on modeling approaches and extensively use remote sensing techniques.

The glaciers of Central Asia were exhaustively described by Soviet glaciologists and cartographers, who published their characteristics in a complete inventory (Hydrometeoizdat, 1971–1978). This inventory's glacier extent data correspond to the year 1961. Remote sensing techniques were used quite early by Soviet scientists in order to improve this cartography (Konovalov, 1987). In our study area, new assessments of the glacier extent were made for 1980 (Konovalov and Shchetinnikov, 1994; Shchetinnikov, 1997; Konovalov and Williams, 2005) and a last one quite recently for the years 2000–2001, using Landsat TM and ASTER satellite imagery (Konovalov, personal communication, 2007). This last cartography of the glacierized area in the six benchmark basins is presented in Fig. 4. The Table 1 presents the glaciers extensions for 5 of the 6 studied basins. It demonstrates the rapid shrinking of the glaciers of the Pamir-Alay range, which are in phase with the regional observations (Khromova et al., 2003, 2006) and the overall world trend (Francou and Vincent, 2007).

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Nevertheless, the variation information given for each basin should be considered carefully and comparisons between the basins are not reliable. The glacier extent and the glacier lengths (Oerlemans, 2005) are relevant indicators, but they do not represent the absolute variability of the water stock, which depends on the volume and the shape of the glacial reservoir. This can be assessed with mass balance studies and the only available measurements (World Glacier Monitoring Service, 2005) in the Pamir Alay Range concern the Abramov Glacier in the extreme western part of the Kyzylsu basin, monitored between 1968 and 1998, the local facilities being destroyed by the civil war in 1999.

3 Available data

3.1 Topography

To compute the values listed in Table 1, we used the very recent world digital elevation model, called GDEM, at 30 m of resolution published in June 2009 by NASA and METI and based on the ASTER satellite sensor imaging. This new set of data considerably improved the quality of the topographic description, not only in horizontal, but also in vertical resolution. This explains the differences with the data given in another paper (Chevallier et al., 2009) concerning the same benchmark basins, but using the SRTM digital elevation model with a resolution of 90 m and a quantity of extrapolated local data. On this basis, the hypsometric curves of each basin are shown on the left side of Fig. 5, and the key elevation values are given in Table 2. The right side of Fig. 5 presents the spatial distribution of the basin areas shared in 200-m altitude intervals. It can be noted that, except for the Kyzylsu basin, the five others have the largest part of their area at an elevation above 3500 m a.s.l.

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3.2 Hydroclimatology

The main drawback of this study is the lack of recent hydrological and climate data. The stream gauge stations and the meteorological stations deteriorated because of the civil war in Tajikistan and the troubles in Kyrgyzstan after the collapse of the Soviet Union: consequently, the time series were interrupted or contained large gaps beginning in 1990. Some stations were reinstalled after 2000, but very partially. For example, the hydro-glacio-meteorological monitoring devices of the Abramov Glacier, Kyrgyzstan, in the northwest of the Kyzylsu basin, a reference for the Soviet glaciological studies (Oerlemans and Reichert, 2000), were completely destroyed in 1999.

However, for the meteorological data (precipitation and temperature), we used the monthly data base established for Central Asia by the US National Snow and Ice Center (NSIC) (Williams and Konovalov, 2008) and the NCEP-NCAR reanalysis (Kistler et al., 2001). A few recent data, provided by the Tajik Academy of Sciences, were added. Figures 2 and 3 show the average monthly values of precipitation and temperature extracted from the NSIC database. All stations presented time series over more than 30 yr of observation.

The daily discharge data were collected from three complementary sources: the Tajik Meteorological and Hydrological Agency, the Tajik Academy of Sciences, and the Russian Academy of Sciences. These data sometimes present small differences, probably due to the use of different calibrating curves. In those few cases, we retained an average value.

In order to analyze the current hydrological situation and to reply to the objective of the research, six benchmark basins were chosen in the Pamir Alay range. The selection criteria were for the most part based on the availability of stream gauges on the rivers and of the corresponding data. All six basins are partially covered with glaciers. Three of them contribute to the Vakhsh River and the other three to the Pyandj River (Figs. 2 and 3). Their main characteristics are detailed in Table 2.

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3.3 Snow cover

To study the dynamics of the snow cover in the region, we adopted a similar method to the one already used by our group in Patagonia (Lopez et al., 2008). The Normalized Difference Snow Index of 48 images of the MODIS sensor was downloaded from the NSIC database between May 2000 and May 2002. The resolution is 500 m. The dates were selected visually in order to keep only scenes with a reduced cloud cover, with at least one image per month. The MODIS snow product version 4 used here has some imperfections (Sirguey et al., 2008), which have been partially improved with the recently available version 5. Nevertheless, in our large-scale analysis, the precision of version 4 is sufficient.

4 Results

4.1 Temperature

Figure 6 presents in standardized values the monthly temperatures observed at eight meteorological stations located in the six benchmark basins after smoothing through a 12-month sliding average during the 60-yr period from 1940 and 2000, because of the lack of data after this year. The eight curves show a noteworthy homogeneity, confirmed by their correlation matrix (Table 3).

This confirms that, even in very different locations, elevations, and local weather regimes, the temperature trends are quite homogenous in the whole region over time.

Averaging the monthly available data, a linear increasing trend was extracted (Fig. 6). Transformed into a temperature gradient, it gave an average increase of 0.097 °C decade^{-1} between 1940 and 2000 and 0.340 °C decade^{-1} between 1979 and 2000. The IPCC 4th Assessment Report (Trenberth et al., 2007) indicates values for the Northern Hemisphere between 0.072 ± 0.026 and 0.089 ± 0.025 °C decade^{-1} for the 1901–2005 period and between 0.294 ± 0.074 and 0.344 ± 0.096 °C decade^{-1} for

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the 1979–2005 period. Considering those values, the Pamir-Alay region appears in the upper part of the global warming trend.

4.2 Snow cover

Figure 7 displays the variability of the snow cover extent in the six basins during two annual cycles, May 2000 to May 2002, obtained with the MODIS snow product. When the cloud cover exceeded 10 % of the basin area, the value was removed. This explains, for example, the lack of data for the Kudara basin during long intervals in both winters. The snow cover percentage includes snow or firn deposits on the glacierized areas, but not the dirty ice or the debris-covered and snow-free parts of the glaciers' ablation areas in summer. Comparing this percentage with the values in Table 1 and taking into account that glaciers cover 12.8 % of the Kudara basin (2000), the figure shows that during the summer season (August and September, essentially) the snow cover is almost reduced to the glaciers. This is not entirely true: during a field visit in the Obighingou basin in late July 2007, we verified that at middle altitudes snow accumulation due to avalanches remained in the bottom of steep-sided valleys.

However, the main information given by this figure is that for the six basins, the percentage of snow cover remains above 50 % for 6–7 months of the year and reaches approximately 80 % for 4 months or more. The glaciers cover 14.9 % of the six basins, evidence of the preeminent role of the snow cover on the glaciers in the melting processes for the surface flow genesis.

More precisely, at the same scale for each one of the six basins, Fig. 8 shows the snow cover distribution in accordance with the altitude shared in 200-m intervals on four dates of the 2000–2001 annual cycle: 4 June, 16 September, 2 November, 9 March. The dates were chosen regarding the seasonal representativeness and their good quality on the six basins, considering cloudiness. The snow cover distribution can be compared with the hypsometric envelope (same as the left side of Fig. 5) and with the altitudinal distribution of the glacierized areas represented in grey.

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Significant differences can be observed from one basin to another. Comparing the snow cover dynamics on the different basins, we can observe:

i. In the Kyzylsu basin, the snow gradually covers the basin until a March peak and gradually melts following the altitudinal distribution of the available space; in this case, the major part of the basin is a very flat and wide valley floor, with a medium/low amount of precipitation (300–700 mm) and a low ratio of glacier area.

ii. In the Obighingou and Muksu basins, the snow cover occupies nearly the entire basin area from November until June, except at the lowest altitudes, and melts rapidly during the summer; both basins present steep valleys, high amplitude of elevation, with a fairly high amount of precipitation (800–1200 mm) and a high ratio of glacier area.

iii. In the Vanch and Yazgulem basins, the snow cover dynamics is similar to Kyzylsu; however, although the amount of precipitation is comparable, the physical conditions are different; the altitudinal distribution of the area is greater, the valleys are steeper, and the glacier ratio is intermediary.

iv. In the Kudara basin, the snow cover and its dynamics are significantly lower and less active than in the five other basins; the amplitude of the altitudinal distribution of the areas is reduced: the basin occupies the large and dry central Pamir Plateau with annual precipitation below 200 mm; the glacier extent is limited to the western part of the basin influenced by the peaks of the upper Fedchenko area.

On the glaciers, the lowest part (ablation zone) appears free of snow in September at the end of the summer season, confirming the above comments on Fig. 7.

4.3 River flows

Figure 9 simultaneously displays in standardized values the flow discharges, the snow cover, the temperatures, and the precipitations for the Obighingou and Kyzylsu basins

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for the period May 2000 to May 2002. Because of the lack of climate data in this time period, the Lyairun station (LY) was used for Obighingou and the NCEP-NCAR reanalysis temperature data at 600 hPa (approximately 4200 m a.s.l.) and precipitable water were used for Kyzylsu.

Based on Fig. 9 and Table 4, the following comments can be made:

i. For both basins, the snow cover, the flow discharge, and the temperature are quite well correlated positively or negatively. This is less clear with precipitation, taking into account that for Obighingou, the meteorological station is not located in the basin and for Kyzylsu, the information is indirectly given through the reanalyzed precipitable water (Kistler et al., 2001).

ii. The snow cover dynamics combined with temperature appear to be the main regulator of the flow discharge. This is particularly well illustrated by the Obighingou graph in Fig. 9.

iii. In the case of the Kyzylsu basin, the lower percentage of glacierized area, combined with the large flat area at a lower elevation, strongly increases the influence of the rainfall (liquid precipitation). The consequence is that the flow regime will be less influenced by a warming trend if the precipitation trend remains stable or decreases.

5 Discussion

Hagg and colleagues have recently published hydrological modeling approaches to assess the response of global warming in the glacierized basins or Central Asia (Hagg and Braun, 2005; Hagg et al., 2006, 2007), essentially based on the Tien Shan range and the upper valley of the Abramov glacier within the Kyzylsu basin. Within the EC FP6 project Jayhun, Bolgov et al. (2010) applied a model developed by Uzbek hydrologists to simulate and forecast the river flows from the Pamir-Alay Mountains. In both cases, the studies are based on observations and data prior to the year 2000.

In the nearby basin of the Zerafshan River, Olsson et al. (2010) show that the flow regime presents an increase in winter and spring followed by lower runoff levels for July and August, confirming the outcomes of studies for glacierized catchments in the northern Tien Shan Mountains (Aizen et al., 1997).

The 4th IPCC Assessment Report, Meehl et al. (2007) forecast an increase of 2.5 (scenario B1) to 4.5 °C (scenario A2) of the air temperature during the 21st century in Central Asia, which is compatible with the observations of the last few decades (see above). Considering the gradient of −6.5 °C/1000 m, commonly adopted throughout the world (Singh and Singh, 2001; Hingray et al., 2009), such a temperature increase means a rise of 400–700 m in the 0 °C isotherm. Thus a similar shift to the left can be considered for the snow cover curves in Fig. 8. The consequence would be a substantial decrease in the snow volume, regarding the hypsometric distribution of available space for intercepting snowfall. Even if the amount of precipitation and its distribution are the same in the future as in the present, the hydrological regime will change considerably.

Unfortunately, the time series of discharges, temperature, and precipitation are available only for the years before 2000, mostly before 1990 in Tajikistan, and not later, when the satellite reports of snow cover data appear only after 2000. In this condition, it is quite difficult to reliably model the impact of the snow cover dynamics on the surface flow processes. Our results underlines the major role of the snow cover, emphasizing the profound impact of global warming on this snow cover and consequently on the flow regime.

Regarding the 1940–2000 period, for the six benchmark basins, Fig. 10 compares the correlation coefficient for temperature vs. discharge at a monthly time step for the percentage of the glacierized area and the median basin altitude. For each basin, two meteorological stations were selected, giving two points on the graphs.

Except on the Kyzylsu basin, it can be observed that the quality of the relationship between flow discharges and temperature depends not only on the percentage of the glacierized area, but also on the median altitude of the basin. In the Andes (Pouyaud et al., 2005; Chevallier et al., 2011), the relation is much stronger, but surprisingly there is no snow cover. However, the comparison with the median altitude, which also corresponds to the most extensive area available that actually has a snow cover, would seem to confirm our finding on the major role of snow cover.

Finally, Fig. 11 shows the smoothed (12-month sliding average) standardized values for monthly temperature and discharges during the periods observed from 1940 to 2000 in the six benchmark basins. The linear trends of the discharge curves were overlaid on the curves. A rigorous comparison between the stations should be based on the same periods. However, we prefer here to give a qualitative representation using the whole available information at each station. They show an increasing trend for the Muksu, Obighingou, and Vanch basins, a very slightly increasing trend for Yazgulem basin, and a slightly decreasing trend for Kyzylsu and Kudara.

In stationary conditions in terms of precipitation, when the temperature increases, the glacier melting discharge increases, assuming that the glacierized area variation remains negligible. However, when this variation rises, the average melting flow will reach a peak and decrease rapidly, with the glacier shrinking and eventually disappearing (Jansson et al., 2003; Chevallier et al., 2011). As underlined by Barnett et al. (2005), the conditions are gathered in the Andean as in the Hindukush-Himalayan regions for this process and the Central Asian region can be included with them. This assumption is supported by the Zerafshan River study, mentioned above (Olsson et al., 2010), where the authors assess that *most glaciers already reached probably their transition point at which even higher temperature cannot lead to more glacier melt water*.

During the 1940–1990 period, the precipitation regime in volume remains almost stable, when the temperature increases (Fig. 6 and results above). We also assume that during this period the impact of global warming on the snow cover remains limited and does not influence the flow regime significantly. Taking into account these hypotheses, we deduce the following:

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i. In the Muksu, Obighingou, and Vanch basins, the glacierized area decreased by 10–25 % during the 1960–2000 period (Table 1) but remained high (12–30 %). The glacier mass balance is unbalanced, but still does not significantly affect the glacial reservoir. Consequently, the average flow discharge is gradually increasing.

ii. In the Kyzylsu and Kudara basins, the glacierized area is already quite small (5–12 %) and because of the unbalanced glacier mass, it can be advanced that the peak discharge value is possibly backwards. An additional factor for both basins is the smaller average amount of precipitation than for the previous periods.

iii. The situation in the Yazgulem basin is less clear. The topographic (Fig. 5) and climate conditions (Figs. 2 and 3) are similar to those in the Vanch basin, but the glacier shrinking process is occurring twice as fast (Table 1). Is the observation period not far from the peak of discharge? Only future observations will provide the answer.

6 Conclusions

We chose a "naturalist" approach to studying the state of the cryosphere in the Pamir Alay mountain range. The paucity of data after 1990 and the absence of synchronization with the snow cover time series extracted from the satellite imagery, remains a handicap for a classical modeling procedure, e.g. trough degree-day models. This analysis provides robust and simple results, which are not related to a particular climate scenario and avoid overinterpretation based on a formal hypothesis that is difficult to justify at the regional scale, because of substantial heterogeneity of topographical situations (precipitation, orientation, relief) at the local scale. It confirms that the high vulnerability of this region to the global warming identified by the 4th Assessment Report of IPCC (Trenberth et al., 2007) will have significant consequences on the water cycle.

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Given that in the Andes a bell curve trend has been found for the future of glacial surface flows, it can be assumed that for basins with a medium size area (from 1500 km^2) and when the glacierized area decreases under a threshold (10–20 %), especially in the driest regions, the glaciers' contribution to the surface flow is already irreparable decreased.

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Table 1. Glacier changes from 1961 to 2000.

Basin	River	Glacier area (km^2) 1961[a]	1980[b]	1991[c]	2000[d]	% of glacierized area 2000	Glacierized min elev. (m a.s.l.) 2000	Variation (%) 1961–2000
Vakhsh	Kyzylsu (KYZ)	535.5	486.4	468.2	449.7	5.4	3604	16.0
	Muksu (MUK)	2061.7	1987.5	1946.3	1887.1	28.9	2835	8.5
	Obighingou*	787.4	705.1	659.4	608.5	21.8*	3162	22.7
Pyandj	Vanch (VAN)	333.2	291.6	268.4	255.1	12.2	2606	23.4
	Yazgulem(YAZ)	337.9	262.7	221.0	200.3	10.2	3379	40.7

* The extent of the Obighingou glaciers used by the authors of studies a, b and c does not correspond exactly to the limits used in this paper.
[a] Hydrometeoizdat (1971–1978)
[b] Konovalov (1987)
[c] Konovalov and Shchetinnikov (1994), Shchetinnikov (1997), Konovalov and Williams (2005)
[d] Konovalov (personal communication, 2009) provided to the authors of this paper the glacier extension shown in Fig. 4; the surface areas are computed by the authors.

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Table 2. Characteristics of the six benchmark basins.

Basin	River	Gauging station	Area (km^2)	Elevation (m a.s.l.) Basin max	Basin Med	Basin Min
Vakhsh	Kyzylsu (KYZ)	Dombrachi	8322	7109	3398	1861
	Muksu (MUK)	Davsear	6521	7445	4643	2012
	Obighingou (OBI)	Sangvor	1879	7443	4081	2223
Pyandj	Vanch (VAN)	Vanch	2084	6599	3865	1550
	Yazgulem (YAZ)	Yazgulem	1963	6317	4023	1657
	Kudara (KUD)	Kudara	4431	6920	4492	2658

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Table 3. Matrix of the correlation coefficients *R* for eight selected temperature stations (the abbreviations correspond to those shown in Fig. 3 and to the full names given in the title of the Fig. 6).

	SA	AL	FE	LR	LK	IR	RU
AB	0.817	0.736	0.728	0.816	0.832	0.536	0.696
SA		0.743	0.743	0.744	0.762	0.726	0.583
AL			0.730	0.870	0.913	0.795	0.787
FE				0.756	0.726	0.637	0.626
LR					0.911	0.709	0.796
LK						0.731	0.776
IR							0.792

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Table 4. Matrix of the correlation coefficients *R* between discharges, snow cover, temperature, and precipitation for the Obighingou and Kyzylsu basins (May 2000 to May 2002) at a monthly time step. Qsang and Qdom are the discharges at Sangvor and Dombrachi; Sobi and Skyz are the snow covers of the Obighingou and Kyzylsu basins; Tlya and Plya are the temperature and precipitation recorded at Lyairun; Trea and Prea are the temperature and the precipitable water extracted from the NCEP-NCAR reanalysis.

	Sobi	Tlya	Plya		Skyz	Trea	Prea
Qsang	−0.821	0.669	−0.551	Qdom	−0.895	0.817	0.558
Sobi		−0.816	0.409	Skyz		−0.945	−0.702
Tlya			−0.179	Trea2			−0.821

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Fig. 1. Location of the study site. Elevation above 4000 m is in light brown color.

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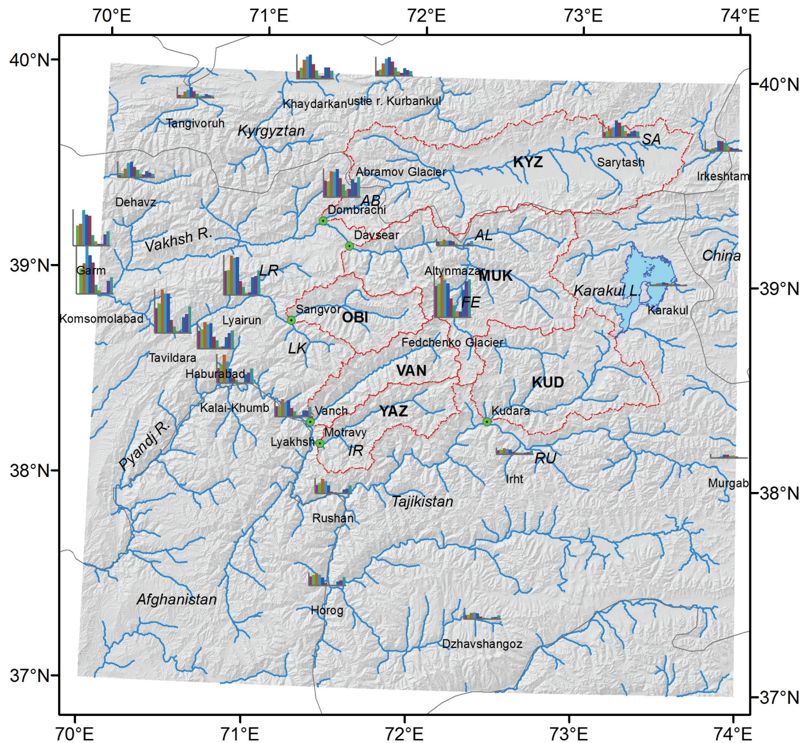

Fig. 2. Topography, hydrography, and precipitation, with the location of the six benchmark basins in the study area. The green points mark he hydrological gauging station. The histograms represent the monthly inter-annual means of precipitation from January to December. In order to not overcharge the figure, the values are not given on the y-axis: the size is proportional to the amount of precipitation. The total annual precipitation varies from 75 mm (Murgab, right on the figure) to 1180 mm (Fedchenko in the center of the figure). Source for topography: ASTER GDEM (2009); source for precipitations: NSIDC-NOAA (2005).

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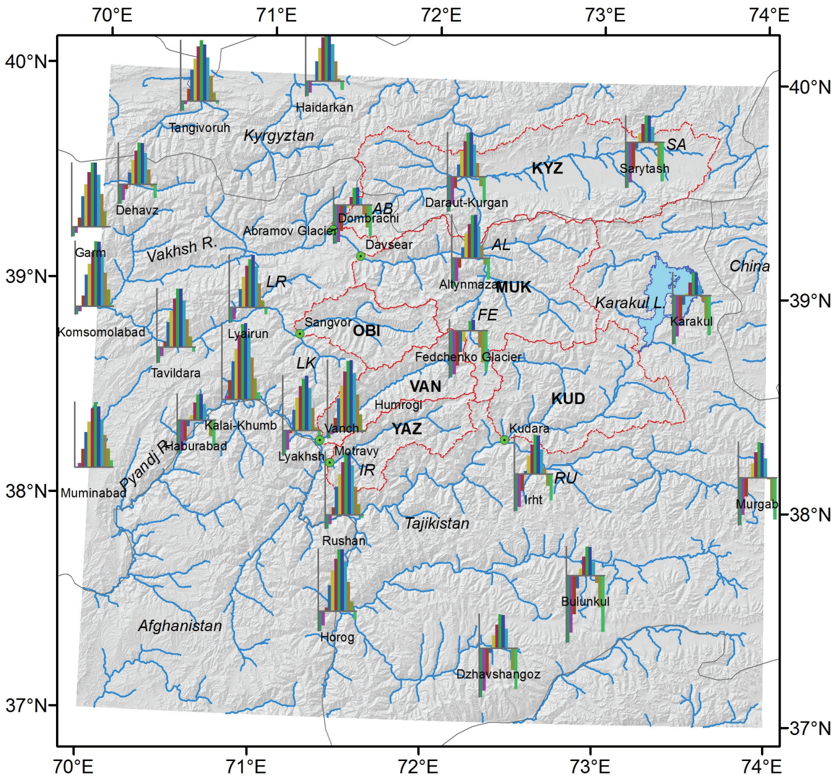

Fig. 3. Spatial temperature distribution. The histograms represent the monthly interannual temperature means from January to December. In order to not overcharge the figure, the values are not given on the y-axis: the size is proportional to the temperature, varying from −25 °C in January (Bulunkul, southeast on the figure) to +28 °C in August (Kalai-Khum at the north summit of the Piandj river loop of the figure). Source for topography: ASTER GDEM (2009); source for temperature: NSIDC-NOAA (2005).

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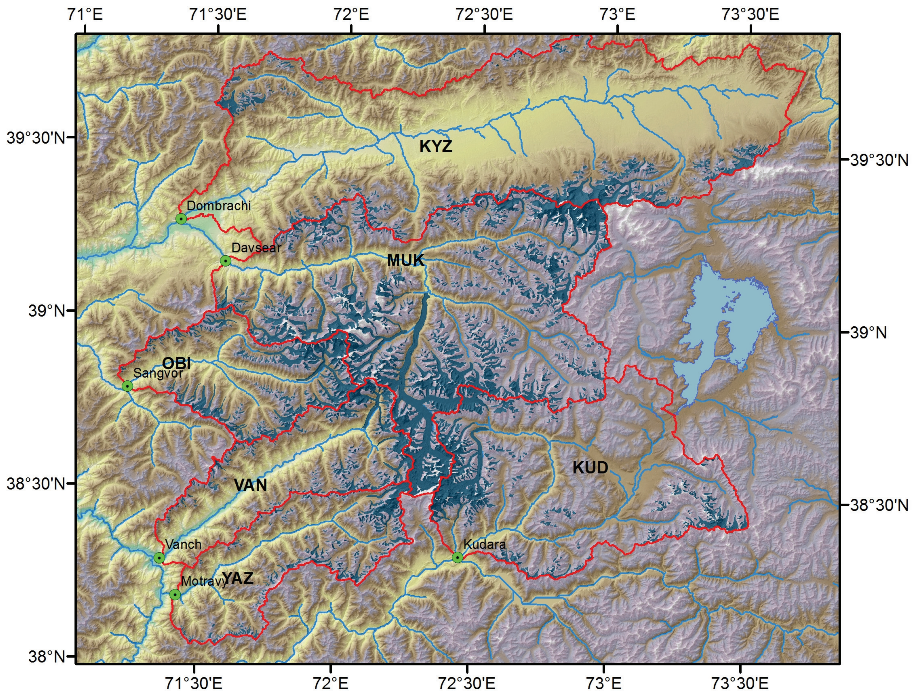

Fig. 4. Topography of the studied zone and location of the glaciers (in dark blue color) within the six benchmark basins (Landsat TM imagery, 2000, courtesy of V. Konovalov).

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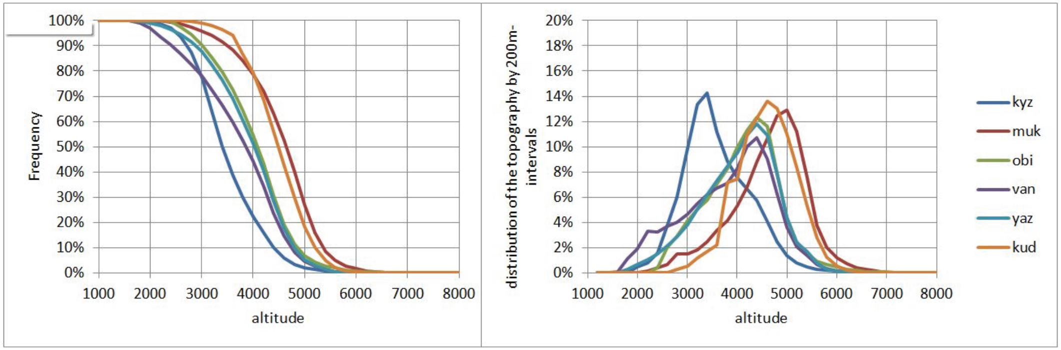

Fig. 5. Hypsometry of the six benchmark basins and their spatial distribution by 200-m intervals using ASTER GDEM (2009).

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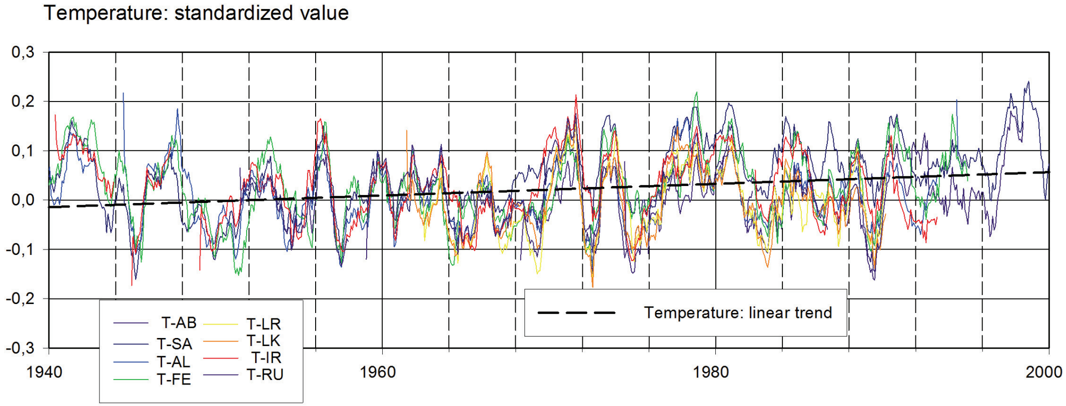

Fig. 6. Monthly temperature trends (1940–2000), represented in standardized values and 12-month sliding averages at eight meteorological stations of the six benchmark basins: Abramov Gl. (AB), Altynmazar (AL), Fedchenko Gl. (FE), Irht (IR), Lyairun (LR), Lyakhsh (LK), Rushan (RU), and Sarytash (SA).

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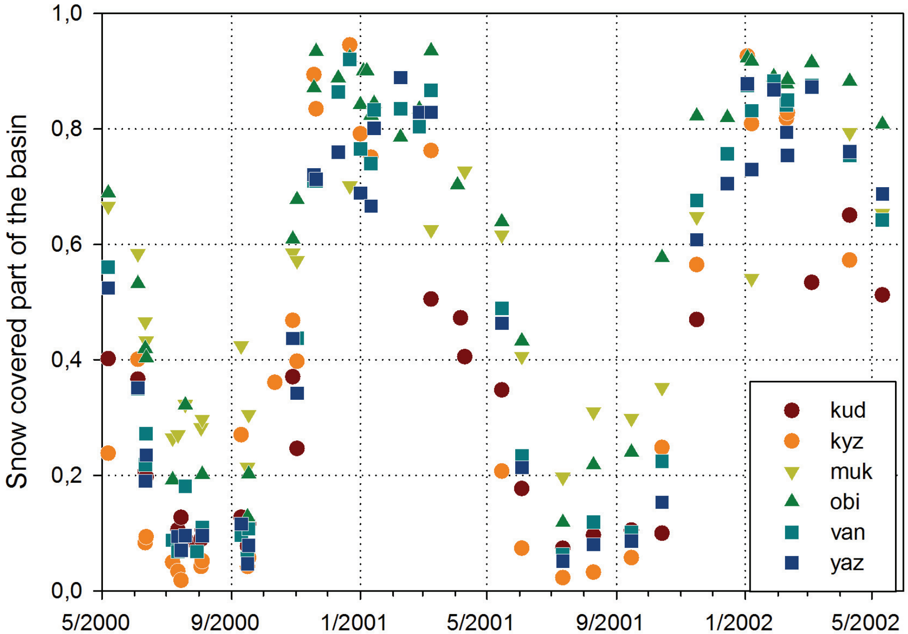

Fig. 7. Percentage of snow cover for the six basins (May 2000 to May 2002). MODIS snow product. Only the points with a less than 10 % cloud cover over the complete basin area were retained.

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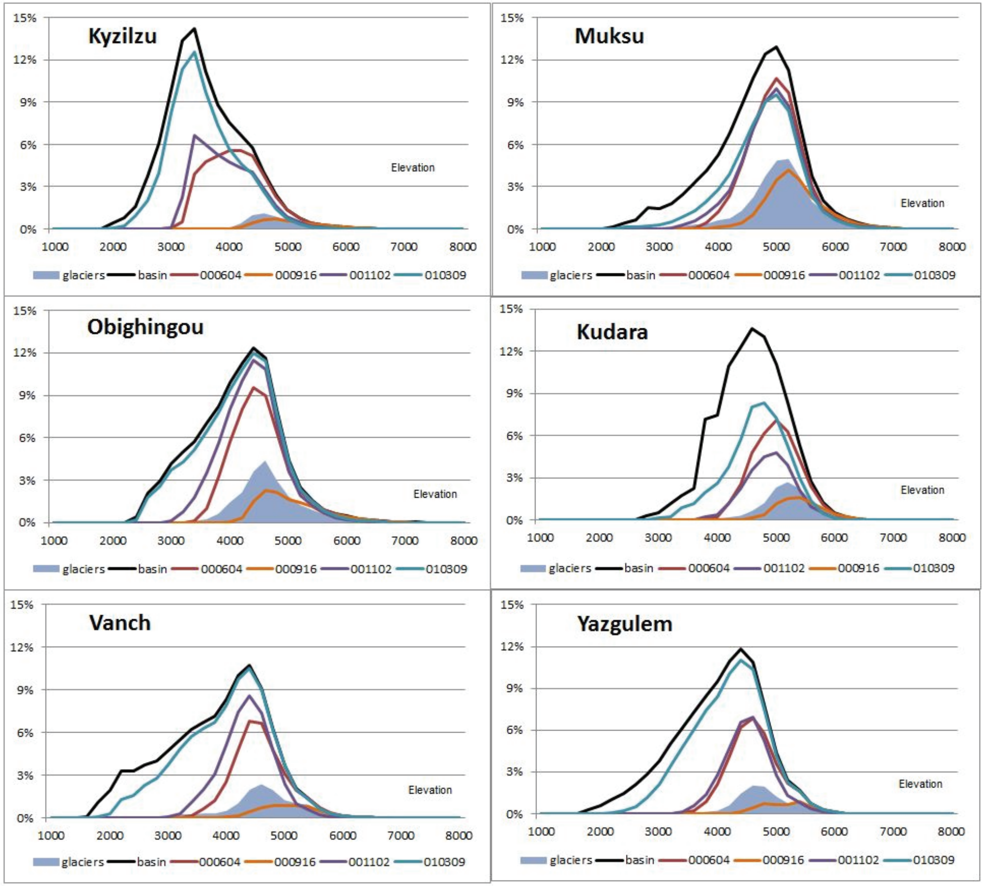

Fig. 8. Snow dynamics for the six basins on four dates between June 2000 and March 2001 (4 June, 16 September, 2 November, 9 March). The areas are calculated for 200-m intervals in elevation.

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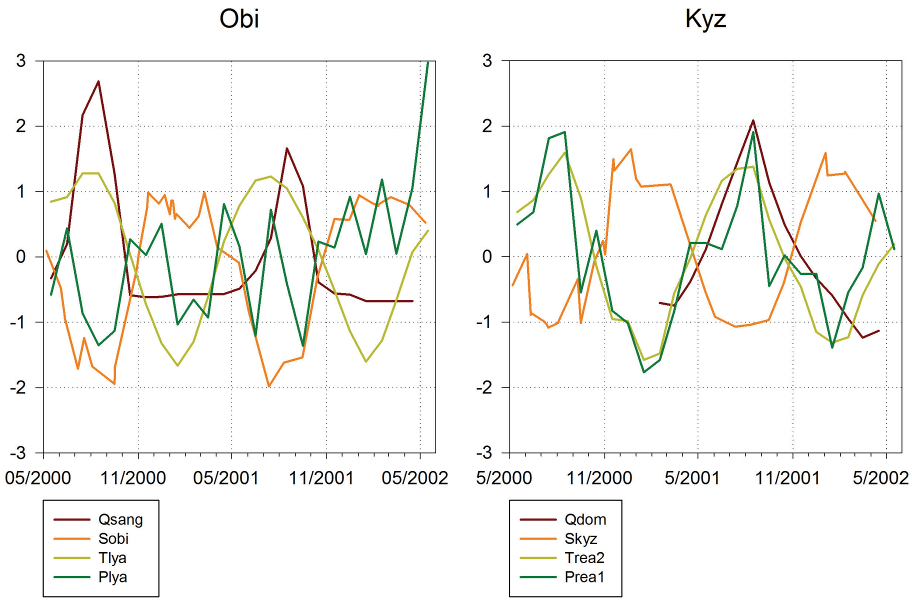

Fig. 9. Flow dynamics (standardized values of discharges, Q, snow cover, S, and temperature, T) of the Obighingou and Kyzylsu River basins (May 2000 to May 2002). For Obighingou, the temperature was taken at the Lyairun station, for Kyzylsu, the NCEP-NCAR reanalysis data at 600 hPa for the nearest point of the grid was used.

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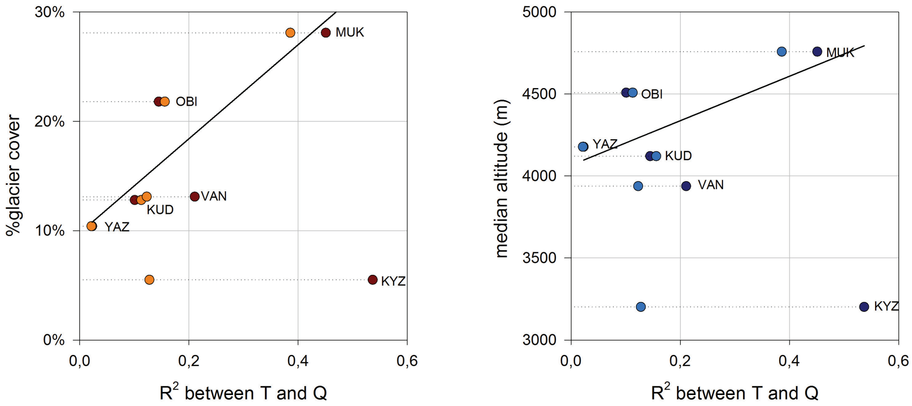

Fig. 10. For the six benchmark basins, comparison of the discharge vs. temperature correlation coefficient R^2 with the percentage of glacierized area and the median altitude of the basins. For each basin, two meteorological stations were used, giving two points (grey and black) on the graphs.

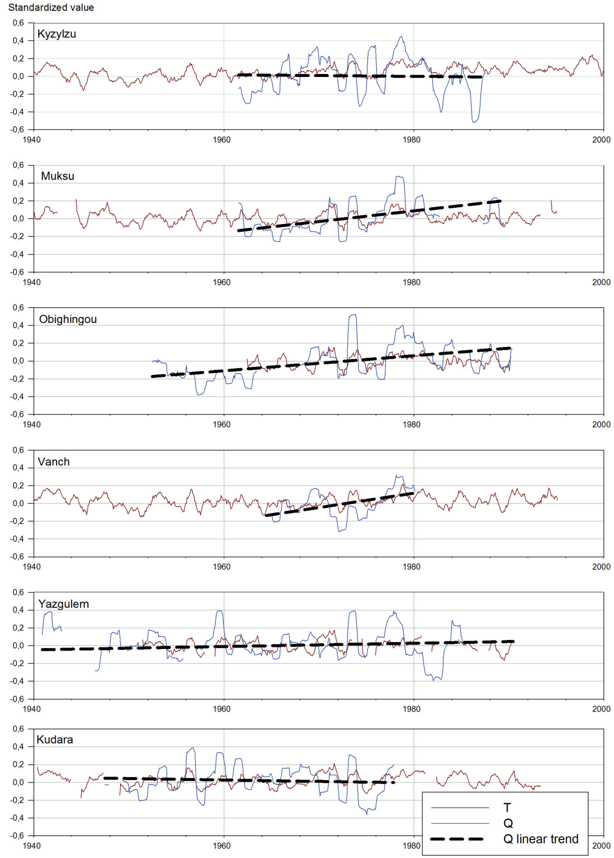

Fig. 11. Discharges vs. temperature (1940–2000): standardized values and 12-month sliding averages. The medium dashed bold lines represent the linear trend of the flow discharges based on the available data. The following meteorological stations were used: Sarytash for Kyzylsu basin, Altymazar for Muksu B., Lyairun for Obighingou B., Fedchenko Gl. for Vanch B., Rushan for Yazgulem B., Ihrt for Kudara B.

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