Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data

Tobias Bolch *

Institute for Cartography, Technische Universität Dresden, D-01062 Dresden, Germany

Abstract

This paper presents an analysis of precipitation and temperature trends and a GIS-supported investigation of the related glacier change in the mountain ridges Zailiyskiy and Kungey Alatau, which represent an important part of the northern Tien Shan. The recent glacier coverage was delineated in a semi-automated way using a TM4/TM5 ratio image of a Landsat ETM Scene from the year 1999 and a merged ASTER/SRTM3-DEM. The extent of these glaciers is compared to that of the glaciers in the Soviet Glacier Inventory [UdSSR, Academica Nauk (1966 to 1983). Katalog Lednikov SSSR (in Russian), Gidrometeoizdat. Leningrad], which represents the situation in study area in approx. 1955. Regionalization of temperature and precipitation as well as solar radiation calculation was conducted in order to determine the climate situation at the glaciers.

Trend and correlation analysis for the period from 1879 to 2000 at 16 climate stations showed a temperature increase, which have become pronounced since the 1950s. Another strong increase occurred at the beginning of the 1970s and since around 1980, the temperatures have generally stayed at this high level. The trend coefficient was about 0.8 K/100a for the period 1900 to 2000 and about 2.0 K/100a on average for the second half of the last century. The increase was about two times higher than the global average in northern Tien Shan from 1950 until 2000, where the increase was mainly due to temperature rise in autumn and winter. The increase is less pronounced in the mountainous areas, but still obvious. However, the higher temperature increase at the lower stations, located for the most part in cities or larger settlements, may be due in part to increased urbanization. For precipitation, there was a small increase on average, but no clear trend.

On the average, the decrease in glacier extent was more than 32% between 1955 and 1999 in the investigated valleys of Zailiyskiy and Kungey Alatau. The glacier retreat was not homogeneous, but depended strongly on the size, location and climate regime at the glaciers. The area loss of the continental-type glaciers with very predominant summer accumulation, as for those situated in the deeply incised Chon-Kemin valley between Zailiyskiy and Kungey Alatau, was conspicuously less, in parts, than the loss at the more maritime glaciers on the northern slope of Zailiyskiy Alatau. This is consistent with the small increase in summer temperatures. However, under dryer conditions with high solar radiation input, such as with glaciers in the Chon-Aksu valley in Kungey Alatau, the area retreat of the continental-type glaciers can be even more pronounced than that of the more maritime glaciers.
© 2006 Elsevier B.V. All rights reserved.

Keywords: glacier retreat; glacier mapping; climate change; Central Asia; Tien Shan

1. Introduction

The earth's climate has always been characterized by natural variations. However, the mean annual air temperatures rose rather dramatically in the 20th century

---

* Tel.: +49 361 46334809; fax: +49 361 46337028.
E-mail address: tobias.bolch@tu-dresden.de.

(IPCC, 2001). This has caused increasing glacier retreat in many parts of the world (Haeberli and Beniston, 1998; Maisch, 2000). This trend intensified at the end of the last century and the areas of glacial ice coverage strongly diminished in the Alps and Central Asia (Kääb et al., 2002; Khromova et al., 2003; Paul et al., 2004a,b). Analysis of instrumental data is one of the most reliable methods for measuring the climatic conditions. In addition, glaciers are a key indicator of climate change as they react sensitively to climate (Oerlemans, 1994). Nevertheless, climate and glacier changes are not homogeneous worldwide. For example, glaciers in the more continental Pamirs retreated in the 20th century less than glaciers in the more humid parts of Tien Shan (Chaohai and Tianding, 1992; Hagg, 2003).

The northern Tien Shan is an ideal area for the study of the different glacier changes as the climatic conditions vary within short distances. The comparatively dense network of climatic stations in different altitudes allows detailed analyses of temperature and precipitation trends. In addition, this situation offers the possibility to estimate and regionalize climatic parameters using a DEM in order to analyze the causes of the glacier change.

Measuring the area of glacierization and glacier change on earth requires much time and effort. Therefore, satellite data in particular is used more and more often for area-wide detection and analysis of glaciers and glacier changes (Bishop et al., 1998; Paul et al., 2002; Bolch, 2004; Khalsa et al., 2004). The international consortium GLIMS (Global Land Ice Measurements from Space; www.glims.org) was established to monitor glacier extent, their changes, and dynamics worldwide using satellite data, especially from the ASTER-Sensor. A further aim is to assess the causes of glacier change and its implications for the population and the environment (Bishop et al., 2004; Kargel et al., 2005). As a contribution, this paper presents the results of a study of climate and glacier change in northern Tien Shan. In addition, the methods used are described and the possible causes of the different declines of glacial coverage are given.

2. Study area

This study focuses on an area where climate change has a strong impact: the high mountain ranges Zailiyskiy

Fig. 1. Location of the study area; climate station with number, see Fig. 2; map based on SRTM3-DEM, Soviet topographic map 1:500 000.

and Kungey Alatau (42°30′ to 43°30′N, 75° to 79°E) of the northern Tien Shan situated in Central Asia at the border between Kazakhstan and Kyrgyzstan (Fig. 1). These ranges, which stretch from east to west, have an important function as water storage and water supply for the arid surroundings with irrigated farmland. Zailiyskiy Alatau rises from the Kazakh Steppe at an altitude of about 800 m asl. up to nearly 5000 m asl. A central mountain knot with a maximum altitude of a little more than 4500 m asl. connects this first range with the somewhat lower Kungey Alatau (max. altitude 4760 m asl.). The southern edge is an intramontanous basin filled by Lake Issyk-Kul (1608 m asl.). Due to this topography, the overall continental climate is characterized by sharp local differences. Precipitation varies horizontally between <600 mm in the transition zone to the Kazakh Steppe and less then 200 mm at western parts of Lake Issyk-Kul, and >1000 mm at altitudes of >3400 m asl. (Fig. 2). The northern edge is much more humid, because cold northern and northwestern air masses meet the first barrier after the Kazakh steppe here and the cyclones tend to occlude in this area. The minimum precipitation occurs in all areas in winter due to the Siberian anticyclone and the maximum in the northern foothills is in spring due to cyclone activities (Böhner, 1996). This maximum shifts to June in high altitudes of Zailiyskiy Alatau. Separated from the humid air masses, the stations in the Issyk-Kul basin, especially

in the western part, are significantly drier and the summer maximum of precipitation is even more pronounced.

The mean annual air temperature (MAAT) at the northern edge of Zailiyskiy Alatau is at 850 m asl. approx. 9 °C and in the Issyk-Kul basin between 6 and 7 °C. The Tuyuksu glacier station (3434 m asl.) has an MAAT of about −4 °C. The zero degree isothermal line is situated a little higher than 2900 m asl.

The equilibrium line altitude is situated around 3800 m asl. at the northern slopes and between 3900 and 4000 m asl. at the southern slopes of the mountain ridges. Most of the glaciers have an ice surface, whereas the tongues of the bigger glaciers are partly covered with debris. Investigations of Dyurgerov et al. (1994) show a higher contribution to the mass balance in the winter months at Tuyuksu glacier on the humid northern slope of Zailiyskiy Alatau than at Sary-Tor glacier in Terskey Alatau and at Urumchi Glacier No.1 (eastern Tien Shan) in the more continental parts of Tien Shan, where the contribution in the summer months is more pronounced ("summer accumulation glacier type" according to Ageta and Higuchi, 1984). Taking the different temperature and precipitation regimes of the study area into account, it can be concluded that the glaciers at the northern slope of Zailiyskiy Alatau are the most maritime of the continental Tien Shan area and the summer snow accumulation is less pronounced there
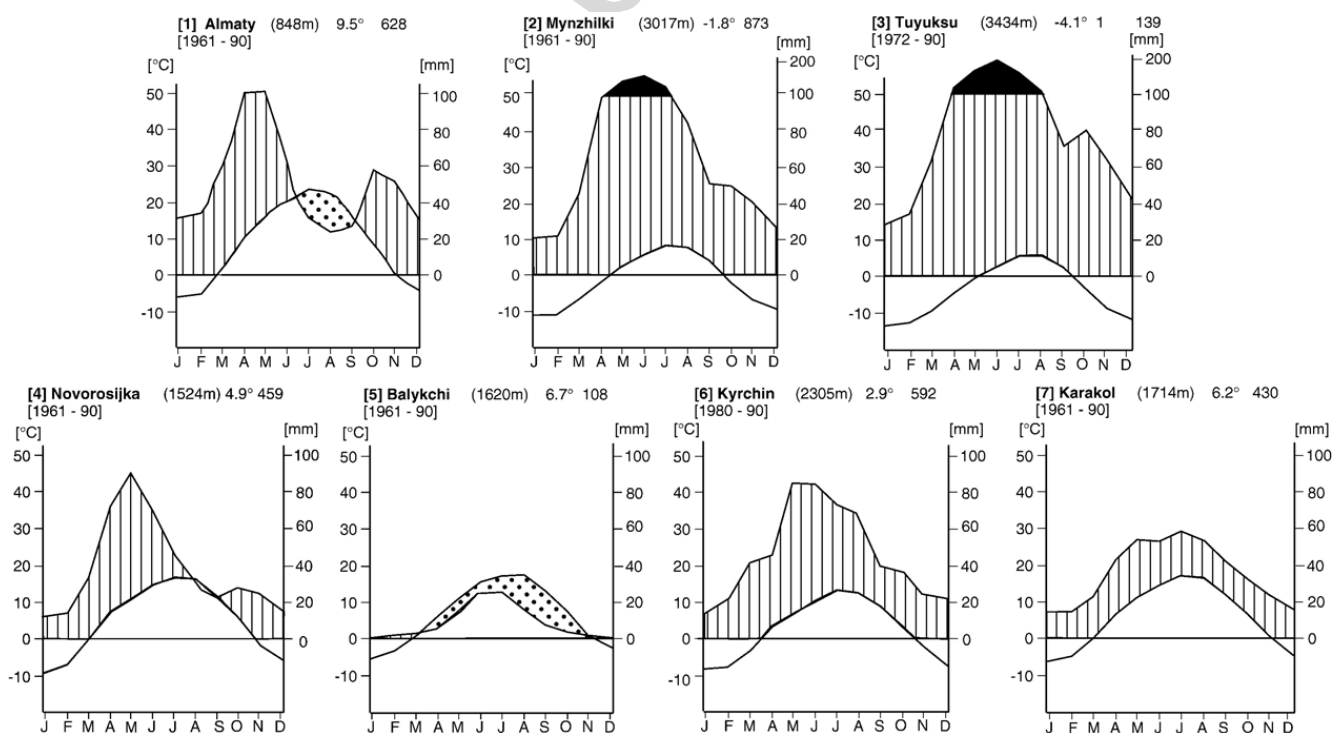

Fig. 2. Selected climate diagrams according to Walter and Lieth (1967); for the location, see Fig. 1.

Fig. 3. Aksu glacier at Kungey Alatau with clearly visible moraines of Little Ice Age; Photo: T. Bolch 2003.

than at the glaciers at Kungey Alatau. Furthermore, radiation is important for glacier change, since 80–90% of ablation is due to radiation heat (Makarevich et al., 1969; Dikich, 2004).

Detailed investigations were done in six selected valleys, which reflect the different climatic characteristics of the mountain ridges.

3. Previous studies

According to Aizen et al. (1997), the trend coefficient of the temperatures from 1940 to 1991 was on average about 0.01 K/a for the whole Tien Shan. The increase was less in northern Tien Shan. The coefficient below 2000 m asl. was 0.006 K/a and above 2000 m asl. it was 0.008 K/a. Marchenko (1999) analyzed climatic stations in the central Zailiyskiy Alatau and concluded a temperature increase of about 0.02 K/a for the period 1879–1996 at the foothills (station Almaty), whereas in higher altitudes, the increase had an annual rate of about 0.01 K/a for the period 1937–1996 (e.g. station Mynzhilki). Giese and Moβig (2004) concluded in a recent analysis that the trend coefficient was in the range between 0.015 K/a and 0.021 K/a in Tien Shan area from 1950 to 2000, where they considered the influence of different start and end times for the trend analysis. The MAAT showed long-term cyclic fluctuations, thus the rise was not continuous. A long-term temperature increase can be seen since the beginning of the 1930s, but at the latest, since the 1950s. A new dramatic increase occurred in the 1970s and the level of the average temperatures is clearly higher than in the cyclic fluctuations before. Interestingly, Giese and Moβig (2004) determined lower trends in the higher altitudes and even negative trends above 2700 m asl. Regarding precipitation, Aizen et al. (1997) concluded a general increasing tendency, whereas Giese and Moβig (2004) did not detect an increase that surpasses the cyclic fluctuations.

A predominant number of glaciers have been retreating in the Tien Shan since the end of Little Ice Age (Solomina et al., 2004, Fig. 3). Only three of 210 glaciers advanced, approx. 30 did not retreat or advance, and all others retreated in the period from 1943 to 1977 (Kotlyakov, 1997). Detailed analyses of the glacier changes at the northern slopes of Zailiyskiy Alatau, based on aerial photos from 1955, 1979 and 1990, were presented by Vilesov and Uvarov (2001). They concluded that the total glacierized area diminished in the whole period by 29.2% and the total volume by 32.2%. Many small glaciers disappeared and several medium-sized ones disintegrated after 1979. A comparison of two maps (scales 1:10,000) of the Malaya Almatinka valley at the northern slope of Zailiyskiy Alatau, showed an area retreat of 20.2% from the years 1958 to 1998 (Hagg et al., 2005). The glaciers of the catchment area of Lake Issyk-Kul have lost approx. one-third of their area in the last 50 years (Dikich, 2004).

4. Methods and data

4.1. Climate

The analysis of climate change in northern Tien Shan is based on 16 time series of temperature and precipitation (Table 1), some of them long-term. Several of them are from stations at altitudes higher than 2000 m asl. and four are even located above 3000 m asl.

As the quality of the series was not well known, they had to be tested for inhomogeneities. This was done visually by checking the graphs and by correlation analysis, based mainly on the time series of Almaty, which was homogenized by Böhner (1996). Inhomogeneities due to false values in the time series and location shifts of the stations could be detected and corrected. However, gradually occurring bias, e.g. due to increased

Table 1
Characteristics of the climate stations incorporated into the analyses; data sources: Böhner (2004), Giese (2004), published in Giese and Moβig (2004), Institute for Geography Almaty und Institute for Hydrometeorology Bishkek

Nr.	Name	Location	Altitude (m asl.)	Time period
1	Almaty (Alma-Ata)	Foothills	848	1879–2000
2	Ust-Gorelnik	Zailiyskiy Alatau	1943	1938–1991
3	Verchnij-Gorelnik	Zailiyskiy Alatau	2272	1970–1989
4	Mynzhilki	Zailiyskiy Alatau	3017	1937–1996
5	Tuyuksu	Zailiyskiy Alatau	3434	1972–1996
6	Bol. Alma Ozero	Zailiyskiy Alatau	2450	1932–1996
7	Assy	Zailiyskiy Alatau	2218	1952–1966 1981–1990
8	Novorosijka	Chon-Kemin valley	1524	1931–2000
9	Kyrchin	Kungey-Alatau	2305	1980–1999
10	Balykchi (Rybache)	Issyk-Kul basin	1670	1931–2000
11	Cholpon-Ata	Issyk-Kul basin	1645	1929–2000
12	Krasnij Oktjabr	Issyk-Kul basin	1645	1946–1998
13	Karakol (Prshevalsk)	Issyk-Kul basin	1744	1879–1996
14	Pokrovka	Issyk-Kul basin	1740	1951–2000
15	Karabatkak-Glacier	Terskey Alatau	3415	1956–1999
16	Tien Shan	Terskey Alatau	3614	1930–1996

urbanization, cannot be excluded. The time series of the two mountain stations, Kyrchin and Karabatkak-Glacier, do not correlate with the surrounding stations. As the reason for this was not known, these two stations were not integrated in the trend analysis. Tien Shan station was also not further analysed, as it is located in Terskey Alatau nearby Ak-shirak range and is more representative for the central Tien Shan. The purpose of the correlation analysis was also to determine whether it is possible to transfer the data from one station with longer time series to the ones with shorter time series and to find characteristic stations for areas with homogeneous trends. In doing so, the study area was divided into four parts: the northern foothills with Almaty (848 m asl.) as the representative station, the mountainous areas of Zailiyskiy Alatau (Mynzhilki, 3017 m asl.), the deeply incised Chon-Kemin valley (Novorosijka, 1524 m asl.) and the Issyk-Kul basin (Karakol, 1740 m asl.).

The mean annual temperature and the precipitation of the study area were regionalized and in addition, the potential direct solar radiation was calculated in order to analyze the causes of the variations in glacier change in more detail. To achieve this, as a first step, the study area was divided into two parts for temperature and five parts for precipitation, to obtain homogeneous areas. As a second step, vertical gradients were calculated for each area based on a regression model using the existing climate stations. For the Issyk-Kul basin, a horizontal gradient was also calculated. Then the temperature and

precipitation conditions were regionalized using the SRTM3 DEM data (resolution 90 m) for each area separately and finally merged using ArcGIS 9.0. The results for the temperature were promising, but not entirely so for the precipitation. In order to integrate the important luv and lee effects of the precipitation, this model was combined with the one by Böhner (2006) for all of High Asia, which includes these effects, but has a lower resolution and integrates only three climate stations in northern Tien Shan and Issyk-Kul basin. The radiation was modeled using the "Sunray" program, taking the astronomic and atmospheric standard parameters such as the geographic position or the atmospheric extinction into account (Kastner, 2006). This model has an iterative approach for the extensive calculation of the potential direct solar radiation and is therefore useful for observing its differentiation.

4.2. Glacier identification

The recent glacial ice coverage was mapped using a Landsat ETM+ scene from 8.8.1999. No snow covered the glacier tongues, but a few clouds occurred in the area of the glaciers, mainly at the southern slope of Kungey Alatau. Unfortunately all currently available ASTER scenes were covered by snow or by clouds in the area of interest. Some of these scenes were suitable for DEM generation but not for automated glacier mapping in all selected valleys. A TM4/TM5 ratio image with a threshold of two was used to delineate the glaciers. Misclassified pixels of vegetated areas and lakes were eliminated using the Normalized Difference Vegetation Index (NDVI). A similar approach was successfully utilized for the Swiss Glacier Inventory (SGI, Paul et al., 2002).

Problems arose due to moraine cover on some glacier tongues caused by the similar spectral signal of the surrounding debris. Recent approaches include morphometric parameters such as curvature and slope in order to also delineate the debris covered glacier part in a semi-automated way (Bishop et al., 2001; Paul et al., 2004a,b). Previous analyses show that ASTER DEMs can be suitable for geomorphologic and glacier mapping (Paul et al., 2004a,b; Kamp et al., 2005). For this study, ASTER DEMs with a resolution of 30 m were generated with the PCI Geomatica 8.2 software using two scenes from the years 2000 and 2001. As the scenes do not overlap and some clouds led to errors, these areas and the gaps were filled with SRTM3-Data and resampled to a resolution of 30 m using the SAGA software (Bolch, 2006; Bolch et al., 2005; SAGA-GIS: http://www.saga-gis.uni-goettingen.de/html/index.php). Using only the slope to delineate the glaciers after Paul et al. (2004a,b)

Table 2
Comparison of the glacier areas delineated from the Landsat scene and from the topographic map (scale 1:10,000)

Name	Area 1998 (map) (km^2)	Area 1999 (Landsat, original) (km^2)	Area 1999 (Landsat, improved) (km^2)	Area 1999 WGMS	Difference improved area/area in map absolute (in %)
Molodezhnyj	1.16	1.12	1.12	N.A.	−0.04 (−3.4%)
Zon Kosmodemjanskoj	0.24	0.22	0.22	N.A.	−0.02 (−8.3%)
Tsentralnyj Tuyuksu	2.60	2.19	2.51	2.56	−0.09 (−3.5%)
Igli Tuyuksu	1.21	1.12	1.19	N.A.	−0.02 (−1.7%)
Ordzhonikidze	0.25	0.24	0.24	N.A.	−0.01 (−4.0%)
Mayakovskogo	0.12	0.11	0.11	N.A.	−0.01 (−8.3%)
Manshik Mametovoj	0.32	0.33	0.33	N.A.	+0.01 (+3.0%)
Total	5.90	5.33	5.72	N.A.	−0.18 (−3.1%)

failed with the available DEMs in Tien Shan. The most sensitive geomorphometric parameter describing the surface of the glaciers and their surroundings such as the moraines is the curvature. Hence, the vertical and tangential curvature were calculated using the DEM. By combining the curvatures in a cluster analysis using the SAGA software, the tongues of the bigger valley glaciers, including the covered parts, are clearly visible. With the help of these analyses, the outline of the glaciers with debris parts and the bigger glaciers with cloud cover in the Landsat scene could be manually delineated (Bolch and Kamp, in press).

An evaluation was carried out in the Malaya Almatinka valley where a detailed map (scale 1:10,000) with the focus on glaciers was produced based on field measurements in the year 1998 (Eder et al., 2002). This map was published in 2001 by the Commission for Glaciology of the Bavarian Academy of Science. Results show that the differences between the cloud and debris cover corrected areas and the glacier areas of the maps are in the order of 3% (Table 2). This is similar to the results from the SGI (Paul et al., 2003).

More than 150 glaciers in six selected valleys were studied in detail using GIS (Fig. 4). The selected

Fig. 4. Central areas of Zailiyskiy and Kungey Alatau with location of the investigated valleys and recent glacial ice coverage; map based on SRTM3-DEM, Soviet topographic map 1:500 000, Landsat ETM scene from August 1999.

valleys represent the different climatic conditions of Zailiyskiy and Kungey Alatau and were accessible by foot to obtain ground-based measurements. Unfortunately the southern slope of Kungey Alatau could not be included in this study due to massive cloud cover on the Landsat ETM and ASTER scenes. The glaciers were compared with the data from about 1955 from the Soviet Glacier Inventory (UdSSR, 1966 to 1983), most of which are also published in the World Glacier Inventory (Bedford and Haggerty, 1996; NSIDC, 1999 updated 2005).

5. Results

5.1. Temperature and precipitation trends

The analysis of the four chosen and characteristic climate stations Almaty, Mynzhilki, Novorosijka, and Karakol (see Chapter 4.1) reveals a clearly visible temperature increase (Fig. 5). However, the increase was not continuous, there were also phases with cooling in between. The first relatively warm period measured in northern Tien Shan occurred around 1915, followed by a cooling to the mid-1930s. This peak is, if at all, not strongly discernible among the average temperatures of the world (IPCC, 2001). However, the worldwide warm period at the beginning of the 1940s was also measured at the Tien Shan stations. At the beginning of the 1950s and especially in the 1970s, a strong temperature increase took place again. Since the end of the 1970s, the temperatures have remained in part clearly above the 1961–1990 average.

Looking at the trend coefficients (Table 3), it is obvious that Almaty and Karakol, two stations not situated in the mountains, have higher trends than the high mountain station, Mynzhilki, and the valley station, Novorosijka. Analyzing all available stations, it could be stated that there is a decreasing trend with altitude, but the trend is still positive in the high altitudes of Zailiyskiy and Kungey Alatau. Compared to the global
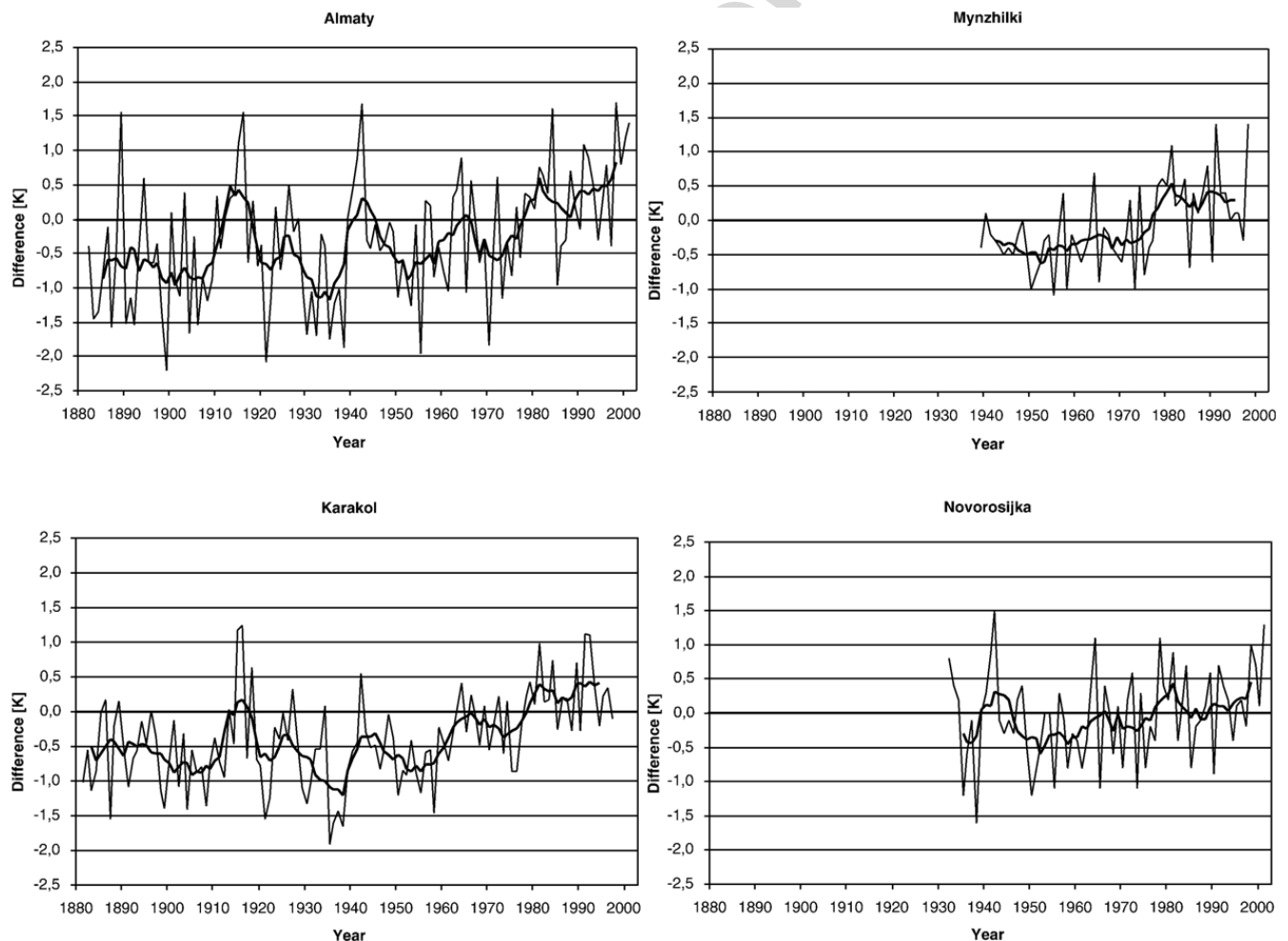

Fig. 5. Time series of temperature deviation from the average of the climate norm period 1961–1990 of selected climate stations; thick line: 7-year moving average.

Table 3
Trend coefficients of the temperature of selected climate stations

Climatic station	Altitude (m asl.)	Trend coefficients [K/100 years]				
		1900 – 2000	1952 – 1996	1972 – 1996	1972–1996 Summer	1972–1996 Winter
Almaty	849	0.86	2.37	2.26	−1.25	+8.08
Mynzhilki	3017	N.A.	1.93	1.41	−2.14	+4.79
Novorosijka	1524	N.A.	0.97	0.92	N.C.	N.C.
Karakol	1740	N.A.	2.56	2.69	N.C.	N.C.

average temperature increase between 1950 and 2000, where the trend coefficient is estimated at approx. 1.0 K/100a (IPCC, 2001), the increase in the study area was, on average, about two times higher.

Two facts should be mentioned regarding the trends. First, the stations at the foothills are located mostly in the area of larger settlements and therefore, the higher temperature increase could certainly be partly due, at least in part, to increased urbanization of the surroundings. Second, the choice of the beginning and ending times for the calculation of the trend coefficients has an important influence on the value. For this study, they were chosen on the basis of the availability of the data, and in such a way that the trends are clearly visible but not unrealistically exaggerated.

A more detailed analysis of the temperature development showed that the increase in the MAAT is due in particular to the strong rise of the temperatures in autumn and winter, whereas the temperatures of the summer half-year remained at the same general level. Since the 1970s, this trend has become even more pronounced.

It is well known that the variation in precipitation is spatially and temporally much higher than the variation in temperature. A homogeneous trend in precipitation,

as in temperatures, could not be detected. Since the 1950s at the latest, precipitation has risen little at the stations below 2000 m asl., whereas it has decreased at the high mountain stations since the middle of the 1960s (Fig. 6). At the Almaty station, summer and winter precipitation rose on average about 2.5 mm/a in the time interval from 1950 to 1992. However, if only the period from 1972 to 1992 is considered, there was a decrease of approx. 9 mm/a, which was caused by a stronger decrease in winter precipitation. In Mynzhilki (3017 m asl.), the trends are somewhat contradictory. From 1950 to 1992 there was a decrease of 3 mm/a, whereas in the period of 1972 to 1992, an increase of about 11.5 mm/a was observed. The trend was similar in summer and winter. In recent times these trends have seemed to reverse; thus it could not be stated that there is a general change in precipitation conditions.

5.2. Glacier retreat

The best investigated glacier in northern Tien Shan is the Tuyuksu glacier in the Malaya Almatinka valley. Accumulation and ablation measurements are conducted, the ELA is determined and the area has been measured since 1956 (Makarevich et al., 1969; Hagg et al., 2005). Based on data the nearby climate Mynzhilki station (3017 m asl.), the mass balance was reconstructed back to the year 1937 (Dyurgerov et al., 1996). The cumulative mass balance showed a nearly continuous retreat, which increased conspicuously at the beginning of the 1970s. This sharp bend can also be found in the Karabatkak-Glacier in Terskey Alatau, south of Issyk-Kul and Urumchi Glacier Nr. 1 in eastern Tien Shan (Cao, 1998). Comparing the curve of the cumulative mass balance of the Tuyuksu glacier with the retreat of the area, it is obvious that they have a similar
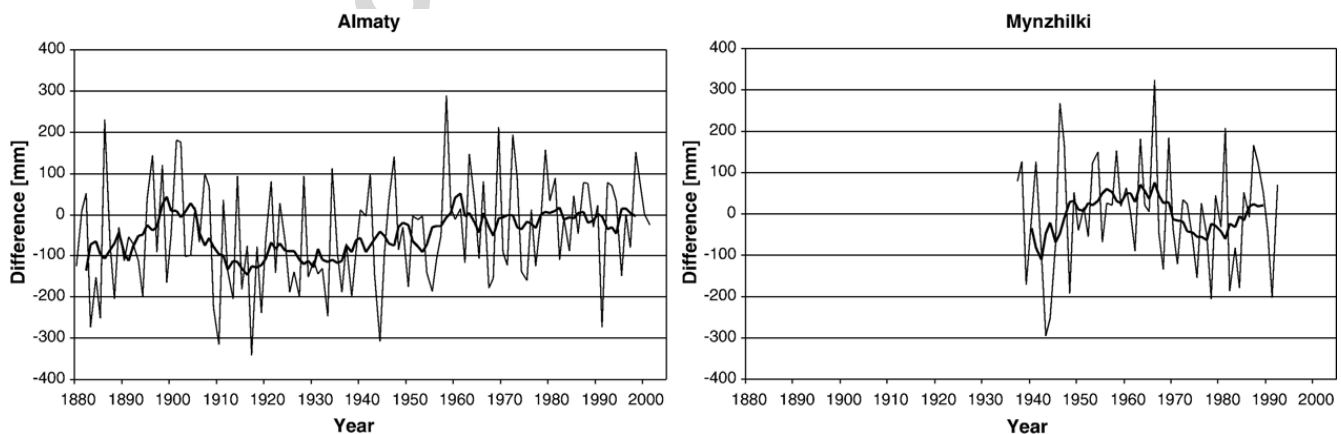

Fig. 6. Time series of precipitation deviation from the average of the climate norm period 1961–1990 of selected climate stations; thick line: 7-year moving average.
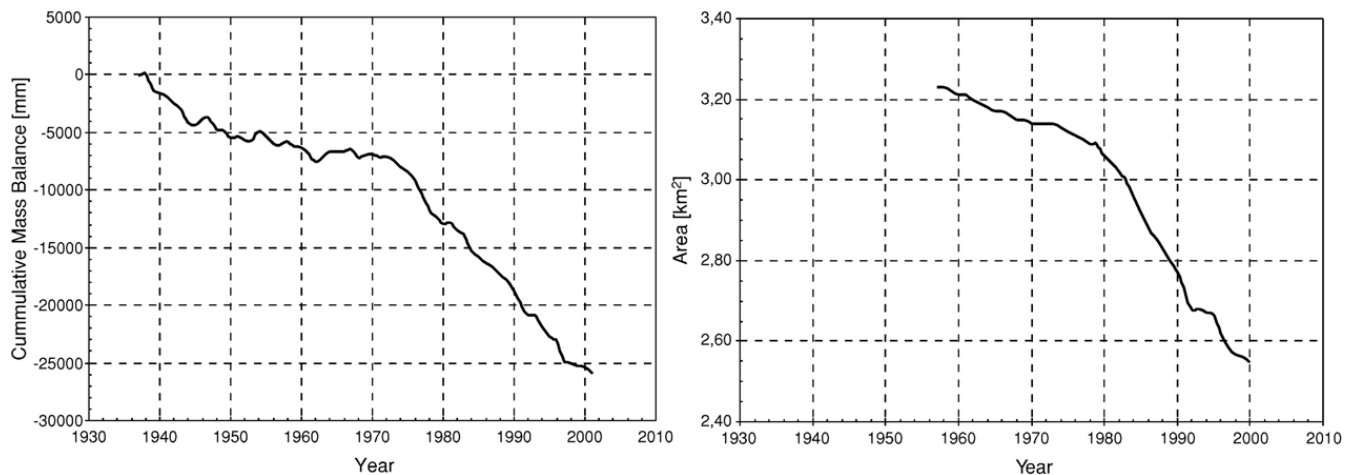
Fig. 7. Left: cumulative mass balance of the Tuyuksu glacier, 1937–56 calculated from climate data, from 1957 measured data; right: area change since 1957 (sources: Dyurgerov et al., 1996, WGMS, http://www.geo.unizh.ch/wgms/).

tendency (Fig. 7). However, the stronger retreat did not begin until the end of the 1970s. This is in good correlation with investigations by Aizen and Aizen (1994) who showed that first the ice surfaces sank and that since the beginning of the 1980s the glacier tongues have melted back strongly. The area of the Tuyuksu glacier diminished from 1957 to 1999 by approx. 21%.

The investigations presented here concentrated on the change of the surface area of the glaciers for the time period 1955 to 1999 in correlation with the location and climatic conditions. First it has to be mentioned that the glacierized areas calculated from an existing map (scale 1:10,000) of Malaya Almatinka valley from the year

1958 (Simon et al., 1961) differ more than 5% from the glacier areas (open parts) cited in the Soviet Glacier Inventory of this region (Vilesov and Khonin, 1967). Therefore, the numbers presented later relating to the retreat of the glacierized areas, which are based on the Soviet Glacier Inventory or the WGI could also have these uncertainties. An impression of glacier retreat in Malaya Almatinka valley is given in Fig. 8.

In the six investigated valleys, three glaciers advanced, seven had more or less the same size and at all the others, a particularly strong area loss could be measured from about 1955 until 1999. The glacier coverage diminished on average about 32.6%. However, the glacier retreat varies strongly and is dependent on size, location and climate conditions. In general, larger glaciers react more slowly to a modification of the climate which is clearly evident in the study area (Fig. 9).

Looking at the investigated valleys, the greatest decline in glacial coverage occurred in the west–east oriented Chon-Aksu valley in Kungey Alatau (−38.2%,

Fig. 8. Glacier retreat in Malaya Almatinka valley; glacier outlines from 1958 (digitized from map, dashed line), from 1990 (digitized from map, dotted line) and from 1999 (extracted from Landsat ratio image, thin black line: without debris correction, thick black line: with debris correction) on Landsat panchromatic image of 1999.
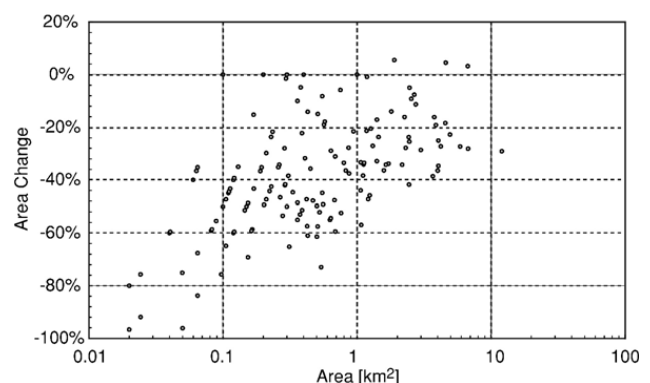

Fig. 9. Scatter plot showing relative change in glacier size from 1955 to 1999 versus glacier size.

Table 4
Glacier characteristics of the investigated valleys

	Orientation	Average altitude (m asl.)	Average radiation (W/m^2)	Average MAAT (°C)	Average annual precipitation (mm)	Average glacier area (km^2)	Glacierized area		Glacier retreat	
							1955	1999	Abs.	(in %)
Malaja Almatinka	S–N	3767	154.6	−5.2	1354	0.63	9.1	5.7	−3.4	−37.6
Bolshaja Almatinka	S–N	3872	171.8	−5.7	1300	0.84	25.2	16.5	−8.7	−34.5
Levyj Talgar	S–N	3929	178.3	−6.0	1318	1.12	72.3	48.4	−23.9	−33.1
Turgen	SW–NE	3852	180.9	−5.6	1210	0.98	35.6	22.6	−13.0	−36.5
Upper Chon-Kemin	W–E	3978	198.0	−6.3	1032	1.24	38.5	32.2	−6.3	−16.4
Chon-Aksu	W–E	4023	216.3	−7.3	872	0.97	62.8	38.8	−24.0	−38.2
Total	–	3938	189.9	−6.2	1142	1.04	243.5	165.4	−78.1	−32.6

Table 4), where the glaciers receive the highest radiation input and the lowest precipitation. The area loss of the glaciers in the north-facing Malaya Almatinka valley in Zailiyskiy Alatau is a bit less (−37.6%), despite the fact that the average glacier size is about one-third smaller than in Chon-Aksu valley. The smallest retreat in the northern slopes of Zailiyskiy Alatau could be measured in the Levyj Talgar valley (−33.1%), where the average glacier size is the largest. The glacier retreat of 16.4% in the upper Chon-Kemin valley is less than half of that recorded in the other investigated valleys. The comparatively low rate of area decline in this valley was also assessed for the time period 1955 to 1975 (Tokmagat-betov, 2004). One reason for the on average small retreat is certainly the pronounced glacial ice coverage and the high average altitude of these glaciers. Yet, as these characteristics are similar to those found in the Levyj Talgar valley, there has to also be a climatic reason for the overall small retreat. The glaciers in this valley are of continental-type with a very high contribution of summer snow to accumulation, because of less precipitation overall, which is also concentrated mainly in the summer months.

6. Discussion and conclusions

In discussing the climate trend, it has to be noted that the investigations of Aizen et al. (1997) and Giese and Moβig (2004) resulted in a similar trend of the average temperature increase, when taking into account that the higher trend coefficient of Giese and Moβig (2004) is due to the more pronounced temperature increase of the 1990s. However, their statement is in contradiction to the trend at high altitudes. Whereas the more distinctive increase above 2000 m asl. (Aizen et al., 1997) would explain the glacier's retreat, the statement of even decreasing temperatures at altitudes above 2700 m asl. (Giese and Moβig, 2004) would not. The own analyses confirm that the MAAT temperatures have increased on

average at the latest since the 1950s at all climatic stations in Zailiyskiy and Kungey Alatau and in the Issyk-Kul basin. Another strong increase occurred in the 1970s and since then the temperatures have remained at this high level, whereas this is mainly dependent on the increase in the temperatures in the autumn and winter months. The reason for the latter is probably the weakening of the Siberian anticyclone, which also causes somewhat higher winter precipitation. Temperature increases from 1950 to the end of the century were higher in northern Tien Shan than the global average. In investigating the temperature trend in the mountains, based on six stations ≥ 1943 m asl., the present analysis shows that the temperature increase was less pronounced in the Zailiyskiy Alatau mountains than at the foothills or in the Issyk-Kul basin, but still clearly positive. Larger inhomogeneities can be excluded due to similar trends in all stations and high correlation coefficients among the time series of all stations. Regarding the precipitation it can be concluded that there is on average a small increase, which is less pronounced at higher altitudes, but no significant trend. This is basically in accordance with the investigations of Aizen et al. (1997) and Giese and Moβig (2004); however, while the former stated that this is a clear trend for precipitation, the latter did not.

In general, the glacier retreat in northern Tien Shan correlates well with increased air temperatures. The higher loss of mass at the Tuyuksu glacier since the 1970s can be well explained by the strong temperature increase since that time and the prolonged ablation period due to the rise of the temperatures in late autumn. This investigation about the change in the glacierized area in the selected areas is in agreement with that of Vilesov and Uvarov (2001), who noted a more pronounced disintegration of glaciers since 1979 and a retreat at northern slopes of Zailiyskiy Alatau of nearly 30% from 1955 to 1990, and with Dikich (2004), who determined an area loss of about one-third at the glaciers of Issyk-Kul basin

since the middle of the last century. However, the glacier retreat is not homogeneous throughout the whole mountain ranges, but depends not only on the size, but also strongly on the climatic regime. The glacier retreat of the more maritime glaciers at the northern slopes of Zailiyskiy Alatau with higher contribution of the winter precipitation to the mass balance is mostly higher than that of the more continental glaciers like in Chon-Kemin valley. The mass balance of these continental glaciers is not as negative as that of the more maritime types, as the increase in temperatures is less in summer. Yet under dryer conditions with high solar radiation input, the retreat of the continental-type glaciers can be even higher than that of the more maritime glaciers of northern Tien Shan. This situation is found in the Chon-Aksu valley.

The average loss of glacier ice coverage in the investigated valleys in northern Tien Shan between 1955 and 1999 is more than 32%. Taking into account that the area loss of the Tuyuksu glacier between the mid-1950s and the 1970s was comparatively small, the retreat of the glacierization in northern Tien Shan and especially at the northern slopes of Zailiyskiy Alatau is a little higher than the retreat of about 23% between 1973 and 2001 at Ak-Shirak Range in the central Tien Shan (Khromova et al., 2003) and also higher than in the Alps, with an average retreat of around 20% between 1973 and 1998 (Paul et al., 2004a,b).

Acknowledgements

References

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

Aizen, V.B., Aizen, E.M., 1994. Features of regime and mass exchange of some glaciers on central Asia periphery. Bulletin of Glacier Research 12, 9–14.

Aizen, V.B., Aizen, E.M., Melack, J.M., Dozier, J., 1997. Climate and hydrologic changes in the Tien Shan, central Asia. Journal of Climate 10, 1393–1404.

Bedford, D., Haggerty, C., 1996. New digitized glacier inventory for the former Soviet Union and China. Earth System Monitor 6 (3), 8–10.

Bishop, M.P., Shroder, J.F., Hickman, B.L., Copland, L., 1998. Scale-dependent analysis of satellite imagery for characterization of glacier surfaces in the Karakoram Himalaya. Geomorphology 21, 217–232.

Bishop, M.P., Bonk, R., Kamp, U., Shroder, J.F., 2001. Terrain analysis and data modeling for Alpine glacier mapping. Polar Geography 25, 182–201.

Bishop, M.P., Barry, R.G., Bush, A.B.G., Copeland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Hall, D.K., Kääb, A., Kargel, J.S., Molnia, B.F., Olsenholler, J.A., Paul, F., Raup, B.H., Shroder, J.F., Trabant, D.C., Wessels, R., 2004. Global Land Ice Measurements from Space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. Geocarto International 19 (2), 57–85.

Böhner, J., 1996. Säkulare Klimaschwankungen und rezente Klimatrends Zentral-und Hochasiens. Göttinger Geographische Abhandlungen 101 (Göttingen).

Böhner, J., 2004. Climate Data from Almaty Station Kindly Provided.

Böhner, J., 2006. General climatic controls and topoclimatic variations of Central and High Asia. Boreas 35(2), 279–295.

Bolch, T., 2004. Using ASTER and SRTM DEMs for studying glaciers and rock glaciers in northern Tien Shan. Proceedings of the Conference Teoretièeskije i Prikladnyje Problemy Geografii na Rubešje Stoletij, vol. 1. Kazakh State University, Almaty/Kasakhstan, pp. 254–258.

Bolch, T., 2006. GIS-und fernerkundungsgestüze Analyse und Visualisierung von Klimaänderung und Gletscherschwund im nördlichen Tien Shan mit einem Vergleich zur Bernina-Gruppe/ Alpen. PhD Thesis, Institute for Geography, Universiät Erlangen-Nürnberg, Germany.

Bolch, T., Kamp, U., in press. Glacier mapping in high mountain areas using DEMs, Landsat and ASTER Data. Proceedings of the 8th International Symposium on High Mountain Remote Sensing Cartography, 20–27 March 2005, La Paz, Bolivia.

Bolch, T., Kamp, U., Olsenholler, J., 2005. Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas. In: Oluic, M. (Ed.), New Strategies for European Remote Sensing. Millpress, Rotterdam, pp. 119–127.

Cao, M.S., 1998. Detection of abrupt changes in glacier mass balance in the Tien Shan Mountains. Journal of Glaciology 44 (147), 352–358.

Chaohai, L., Tianding, H., 1992. Relation between recent glacier variations and climate in the Tien Shan mountains, Central Asia. Annals of Glaciology 16, 11–20.

Dikich, A.N., 2004. Gletscherwasserressourcen der Issyk-Kul-Region (Kirgistan), ihr gegenwärtiger und zukünftiger Zustand. Schriftenreihe des Zentrums Internationale Entwicklungs- und Umweltforschung, vol. 19. Giessen.

Dyurgerov, M.B., Mikhalenko, V.N., Kunakhovich, M.G., Chaohai, L., Zichu, U., 1994. On the cause of glacier mass balance variations in the Tien Shan Mountains. Geological Journal 33 (2/3), 311–317.

Dyurgerov, M.B., Uvarov, V.N., Kostjashkina, T.E., 1996. Mass balance and runoff of the Tuyuksu Glacier and the north slope of the Zailiyskiy Alatau Range, Tien Shan. Zeitschrift für Gletscherkunde und Glazialgeologie 32, 41–54.

Eder, K., Geiss, T., Hornik, H., 2002. Neukartierung und DGM-Aufbau für das Tujuksu-Gletschergebiet im Tian Shan. Zeitschrift für Gletscherkunde und Glazialgeologie 38 (2), 129–138.

Giese, E., 2004. Climate Data from Stations in Kyrgyzstan Kindly Provided.

Giese, E., Moβig, I., 2004. Klimawandel in Zentralasien. Schriftenreihe des Zentrums Internationale Entwicklungs- und Umweltforschung, vol. 17. Giessen.

Haeberli, W., Beniston, M., 1998. Climate change and its impacts on glaciers and permafrost in the Alps. Ambio 27 (4), 258–265.

Hagg, W., 2003. Auswirkungen von Gletscherschwund auf die Wasserspende hochalpiner Gebiete. Vergleich Alpen-Zentralasien. Münchener Geographische Abhandlungen, A, vol. 53. München.

Hagg, W., Braun, L., Uvarov, V.N., Makarevich, K.G., 2005. A comparison of three methods of mass balance determination in the Tuyuksu Glacier Region, Tien Shan. Journal of Glaciology 50 (171), 505–510.

IPCC (Ed.), 2001. Climate Change 2001 — The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Kääb, A., Paul, F., Maisch, M., Hoelzle, M., Haeberli, W., 2002. The new remote-sensing-derived Swiss glacier inventory: II. first results. Annals of Glaciology 34, 362–366.

Kamp, U., Bolch, T., Olsenholler, J., 2005. Geomorphometry of Cerro Sillajhuay, Chile/Bolivia: comparison of DEMs derived from ASTER remote sensing data and contour maps. Geocarto International 20 (1), 23–34.

Kargel, J., Abrams, M., Bishop, M., Bush, A., Hamilton, G., Jiskoot, H., Kääb, A., Kieffer, H., Lee, E., Paul, F., Rau, F., Raup, B., Shroder, J., Soltesz, D., Stainforth, D., Strearns, L., Wessels, R., 2005. Multispectral imaging contributions to global land ice measurements from space. Remote Sensing of Environment 99, 187–219.

Kastner, R., 2006. Verbreitungsregel der Lächenwälder in der Gebirgswaldsteppe im Nordwesten der Mongolei. Ph. D Thesis, Institute for Geography, University Erlangen-Nürnberg, Germany.

Khalsa, S.J.S., Dyurgerov, M., Khromova, T.E., Raup, B., Barry, R.G., 2004. Space-based mapping of glacier changes using ASTER and GIS tools. IEEE Transactions on Geoscience and Remote Sensing 42 (10), 2177–2182.

Khromova, T.E., Dyurgerov, M., Barry, R.G., 2003. Late-twentieth century changes in glacier extent in the Ak-shirak Range, Central Asia, determined from historical data and ASTER imagery. Geophysical Research Letters 30 (16), 1863, doi:10.1029/2003GL017233.

Kotlyakov, V.M. (Ed.), 1997. World Atlas of Snow and Ice Resources, vol. 2. Institute for Geography, Russian Academy of Sciences, Moscow.

Maisch, M., 2000. The long-term signal of climate change in the Swiss Alps: glacier retreat since the end of the Little Ice Age and future ice decay scenarios. Geografia Fisica e Dinamica Quaternaria 23 (2), 139–152.

Makarevich, K.G., Palgov, N.N., Tokmagambetov, T.G., 1969. Oledeniye Zailiyskogo Alatau. Akademia Nauk, Moscow. (in Russian).

Marchenko, S.S., 1999. Sovremennoje i ozhidaemje v 21. v. izmenenije merzlotno-klimaticheskikh uslovnij b severnom Tjan-Shanje. Criosfera Semli 3 (2), 13–21 (in Russian).

NSIDC, 1999, updated 2005. World Glacier Inventory, World Glacier Monitoring Service and National Snow and Ice Data Center/World Data Center for Glaciology. Boulder, CO. Digital media.

Oerlemans, J., 1994. Quantifying global warming from the retreat of glaciers. Science 264, 243–245.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., Haeberli, W., 2002. The new remote sensing derived Swiss Glacier Inventory: I. methods. Annals of Glaciology 34, 355–361.

Paul, F., Huggel, C., Kääb, A., Kellenberger, T., 2003. Comparison of TM-derived glacier areas with higher resolution data sets. Proceedings of the Conference Observing Our Cryosphere from Space. EARSel eProceedings, vol. 2, pp. 15–21.

Paul, F., Huggel, C., Kääb, A., 2004a. Combining satellite multispectral image data and a digital elevation model for mapping of debris-covered glaciers. Remote Sensing of Environment 89 (4), 510–518.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T., Haeberli, W., 2004b. Rapid disintegration of Alpine glaciers observed with satellite data. Geophysical Research Letters 31 (21), L21402, doi:10.1029/2004GL020816.

Simon, N., Töppler, J., Pillewitzer, W., 1961. Zur kartographischen Aufnahme des Gletschergebietes Tujuksu. Petermanns Geographische Mitteilungen 4, 310–317.

Solomina, O.N., Barry, R.G., Bodnya, M., 2004. The retreat Of Tien Shan glaciers (Kyrgyzstan) since the Little Ice Age estimated from aerial photographs, lichenometric and historical data. Geografiska Annaler. Series A 86 (2), 205–216.

Tokmagatbetov, T.G., 2004. Lednikovo-Morennyj Kompleks Gor Jugo-Voctochnogo Kazakhstana (in Russian). PhD-Thesis, Institute for Geography, Academy of Science of the Republic of Kazakhstan in Almaty.

UdSSR, Academica Nauk, 1966 to 1983. Katalog Lednikov SSSR. Gidrometeoizdat, Leningrad. (in Russian).

Vilesov, E.N., Khonin, R.V., 1967. Katalog Lednikov SSSR, Tsentralnyj i Yuzhnyj Kazakhstan, vol. 13. Leningrad (in Russian).

Vilesov, E.N., Uvarov, V.N., 2001. Evoljutsija sovremennogo oledeninja Zailijskogo Alatau v XX Veke. Kazakh State University, Almaty. (in Russian).

Walter, H., Lieth, H., 1967. Klimadiagramm-Weltatlas, vol. 3. G. Fischer, Jena.