THE RETREAT OF TIEN SHAN GLACIERS (KYRGYZSTAN) SINCE THE LITTLE ICE AGE ESTIMATED FROM AERIAL PHOTOGRAPHS, LICHENOMETRIC AND HISTORICAL DATA

BY
OLGA SOLOMINA[1], ROGER BARRY[2] AND MARIA BODNYA[1]

[1]Institute of Geography, Russian Academy of Sciences, Moscow, Russia
[2]National Snow and Ice Data Center, CIRES, University of Colorado, Boulder, Colorado, USA

Solomina, O., Barry, R. and Bodnya, M., 2004: The retreat of Tien Shan glaciers (Kyrgyzstan) since the Little Ice Age estimated from aerial photographs, lichenometric and historical data. *Geogr. Ann.*, 86 A (2): 205–215.

ABSTRACT. The retreat of 293 glaciers in the Tien Shan Mountains (Kyrgyz Republic) from their maximum extent during the Little Ice Age (LIA) is estimated using aerial photographs from 1980 to 1985 and maps at a scale of 1:25000, constructed during period 1956–1990. Two indices of changes are used: the linear distance from the glacier terminus to its Little Ice Age moraine and the difference in absolute elevation of the terminus and the moraine. Historical information about the front positions of glaciers in the 1880s to the 1930s was used as an indirect control of remote sensing data. The age of moraines in key regions was estimated by lichenometry. On average, Tien Shan glaciers have retreated by 989 ± 540 m since the LIA maximum. Their front elevations (*dh*) rose by 151 ± 105 m. These changes are similar to changes observed in the Alps and western Norway, Pamir-Alay and Koryak plateau, but greater than in east Siberia over the same interval. Differences between four regions in Tien Shan (northern, western, inner, central) are generally small, though in the northern Tien Shan the glacier retreat and frontal rise are more prominent (1065 ± 479 m and 215 ± 140 m, respectively).

Key words: Tien Shan, Little Ice Age, glacier retreat, moraines, lichenometry, climatic changes.

Introduction

Mountain glaciers provide important evidence of climatic changes. There are at least two reasons to be interested in glacier variations. The size of glaciers is one of the most simple and readily monitored parameters. In some countries this information goes back for several centuries; in most mountain regions, however, the first data of this kind appeared in the mid-19th century. All over the world (with some local exceptions) glaciers are now smaller than they were at that time. This tendency is consistent with the global warming trend, recorded instrumentally. More detailed interpretation of glacier behaviour and its use as a climatic proxy is not always simple, due to the complexity of factors affecting glacier size: the relative contributions of summer ablation and winter accumulation, their seasonal distribution, and the lag between the change of mass balance and the fluctuations of the terminus. However, in general, the magnitude of glacier variations is a significant parameter for global glacier monitoring (Haeberli 1995).

In this paper we estimate the magnitude of glacier retreat in the Tien Shan Mountains from the **Little Ice Age** (**LIA**) maximum to the 1980s on the basis of aerial photographs using historical data to control the results, and lichenometry to estimate the age of LIA moraines. In the immediate future ASTER (Bishop *et al.* 2000) Landsat images will allow simultaneous glacier images to be obtained, which can be a basis for more accurate and sophisticated analysis of glacier variations on a global scale.

This paper continues the series of publications (Solomina 1999, 2000) on the analysis of the inventory of glacier retreat since the LIA maximum in the mountains of the former Soviet Union.

Study area

The Tien Shan Mountains extend between 40°N and 45°N, and 67°E and 95°E (Fig. 1). The part of Tien Shan located in the former Soviet Union is about 1200 km long. The study area, which coincides with the frontiers of Kyrgyzstan, was limited by the availability of recent aerial photographs

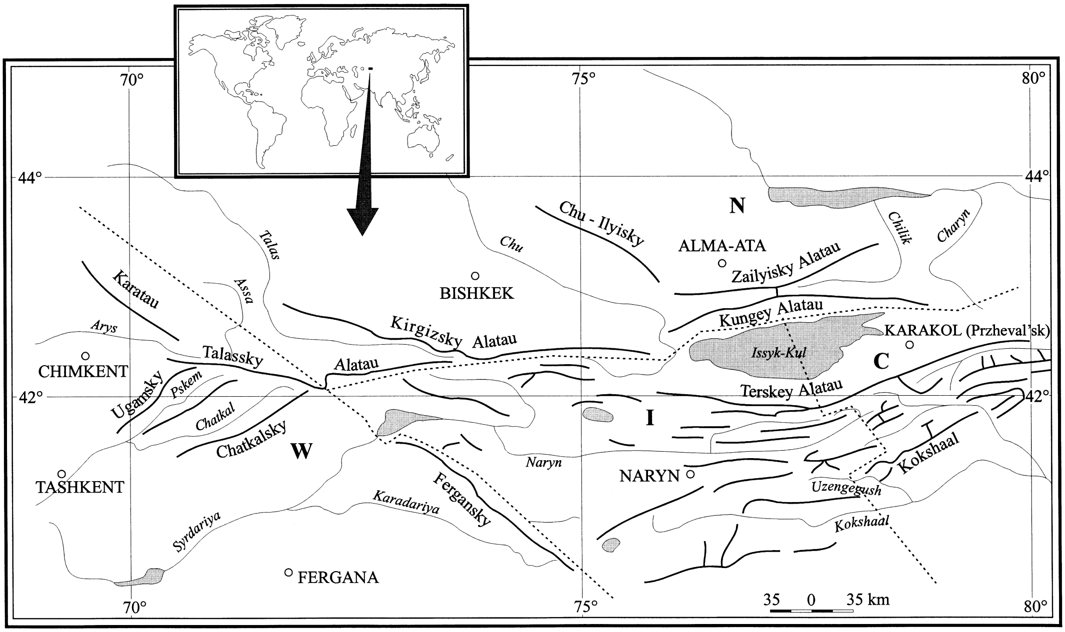

Fig. 1. Area of investigation. Kyrgyzstan. Subdivisions of Tien Shan: W, western; N, northern; C, central, and I, inner.

(provided courtesy of Valery Kuzmichonok). However the territory is over 1000 km long by 400 km wide, and is still large enough to represent a considerable part of the Central Asian mountains.

Tien Shan is traditionally subdivided into western, northern, central, and inner Tien Shan according to its climatic and orographic properties (see Fig. 1). The highest mountains, up to 6000 m or more, are located in central Tien Shan (Kokshaal, Inil'chek, Sary-Dzhaz Ranges); they support the largest dendritic glaciers including the Inylchek, Mushketov and Semenov. In the western part (Talassky, Ugamsky, Pskemsky Ranges) the mountains are lower (2500–3500 m) and the glaciers are smaller in size.

The **equilibrium line altitude** (**ELA**) distribution (Fig. 2, which integrates climatic parameters, varies from 3500–3600 m in western Tien Shan to 4440 m in Khan-Tengry massif in central Tien Shan. Meteorological data show that the western and northern peripheries of Tien Shan have a mild, temperate climate, compared with the more severe, continental climatic conditions of its inner regions (Dyurgerov 1995).

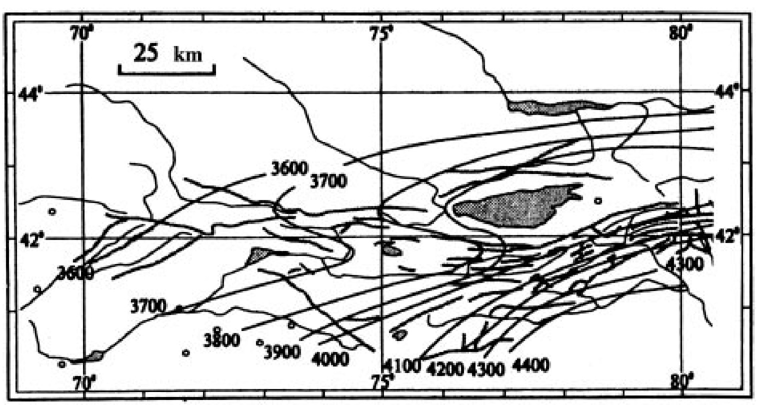

Fig. 2. Modern (1980s) ELA distribution in Tien Shan (Dyurgerov 1995).

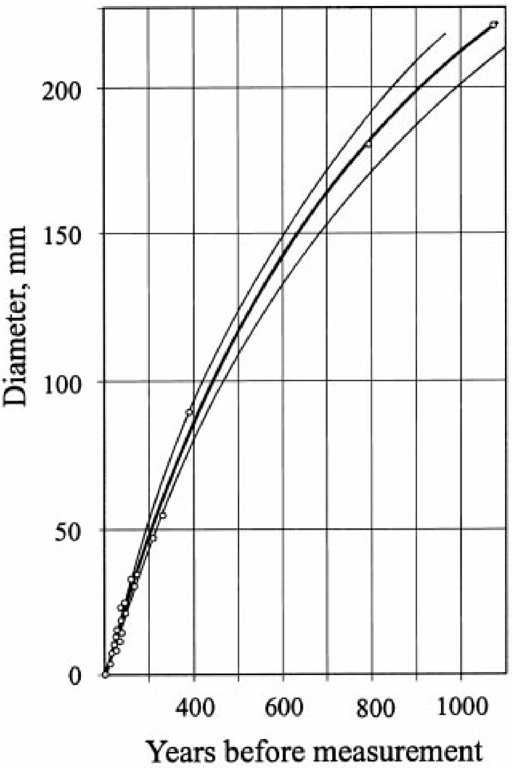

Fig. 3. *Aspicilia tianshanica* growth curve, Tien Shan Mountains (Solomina 1999).

Materials and methods

Aerial photographs

To identify the maximal size of Little Ice Age glaciers we used black-and-white aerial photographs of 1:30000 to 1:70000 scale from the 1980s together with maps of 1:25000 scale, prepared during 1956–1990 (mostly in the 1980s). A total of 293 glaciers from western, northern, central and inner Tien Shan of all types, orientation, and altitudinal ranges, occurring in the area, were included in the data set.

We measured the distance from the largest fresh-looking end moraine covered by sparse vegetation or unvegetated (distinguished from older moraines by a lighter colour on aerial photographs) to the front of the glacier, we also measured the elevation of the foot of this moraine to the elevation of the beginning of lateral moraines, medial moraines and corresponding nunataks. The Glacier Inventory of the Soviet Union (1965–1980) was the source of information for the length (x) of the glacier, its highest point (Zup) and terminus elevation (Zt). Most of the information contained in the Inventory refers to the 1950s and 1960s. For some glaciers the terminus elevation and length were corrected according to more recent (1980s) data. The accuracy for the definitions of the location of the moraines is ±10 m for maps of 1:25000 scale.

Lichenometry

The degree of primary succession combined with lichenometry was used to outline the terrains exposed by glacier retreat after the LIA maximum. Lichenometry shows that in the Tien Shan mountains the moraines which date from the 16th to the 19th centuries are not completely covered by vegetation and therefore could be recognized on aerial photographs.

Figure 3 displays the *Aspicilia tianshanica* growth curve, based on 23 control points, dated by radiocarbon, historic and tree-ring data (Solomina 1999). *Aspicilia tianshanica* is the main age-indicator in Central Asia, though others such as *Xanthoria elegans* and lichens of subgenus *Rhizocarpon* are also used to supplement the *Aspicilia* records. The conventional error estimate of lichenometric dates is ±20% (Bickerton and Matthews 1992).

Figure 4 shows lichenometric dates of moraines of the last millennium for northern, western and central Tien Shan and the Issyk-Kul’ area. The maximum glacier advances of the last millennium in most valleys occurred in the 17th to the mid-19th centuries (Fig. 5) and the magnitudes of glacier advances during the last millennium were nearly identical (Solomina 1999).

Historical information

The earliest glacier descriptions in Tien Shan date from the mid- to late 19th century (Table 1) (e.g. Semenov 1858; Kassin 1915; Korzhenevsky 1930). Table 1 shows that the linear retreat of the glaciers from the end of the 19th century to the mid-20th century was in most cases less than 1000 m. Such information is scarce and often not precise enough to estimate the changes of glacier terminus position. Even the earliest data record just the very end of the Little Ice Age, thus historical information can only be used to constrain the minimum glacier retreat after the LIA maximum.

Results

Parameters of glacier retreat

We first present the statistics on glacier retreat, then

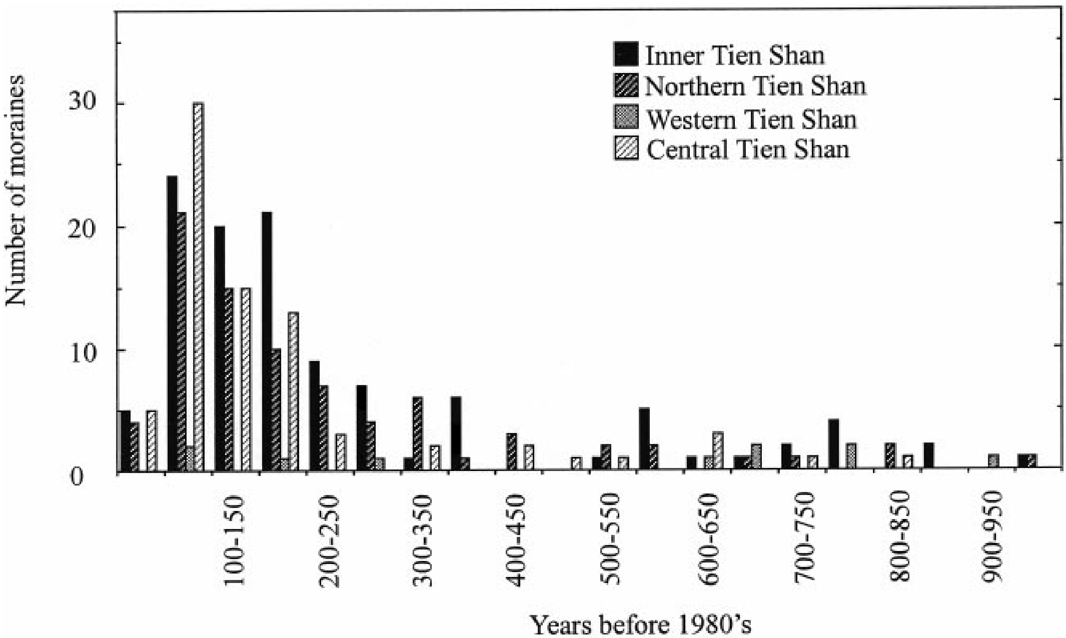

Fig. 4. Lichenometric dates of moraines of the last millennium in northern, western and central inner Tien Shan and Issyk-Kul area.

discuss possible causes. Table 2, which summarizes the glacier statistics for four regions as well as for the whole Tien Shan, shows that on average glaciers in the Tien Shan retreated by 989 ± 540 m in length *(dx)*, and their front elevation *(dh)* increased by 151 ± 105 m. The differences between the four regions in Tien Shan are rather small: the glacier retreat values vary between about 900 and 1100 m. However, it is noticeable that the estimates of glacier retreat by length, and especially by front elevation (1065 ± 479 m and 215 ± 140 m), are higher in the northern Tien Shan than in other regions.

Table 3 shows how the glacier retreat parameters in Tien Shan are related to the length of the glaciers. The eight groups were formed to meet two criteria: comparable group sizes and similar gradations of glacier length. The value of *dx* increases gradually from 496 ± 214 m for the smallest glaciers (500–1400 m long) to 1573 ± 582 m for the largest (6000–60 000 m long). The distribution of the front elevation changes is more complex: the values of *dh* increase from 91 ± 68 m to 182 ± 146 m in the first six groups (up to the glaciers 3600–4200 m in length), but decrease again for the two groups of largest glaciers up to 97 ± 63 m. This might be a result of the predominance of valley glaciers in these groups, which are normally located in wide valleys, eroded, smoothed and flattened by numerous ancient glacier advances. The groups of smaller glaciers usually include many cirque glaciers, where the terminus is often hanging on steep slopes and steps. The moderate linear retreat of these glaciers results in considerable changes of their front elevation.

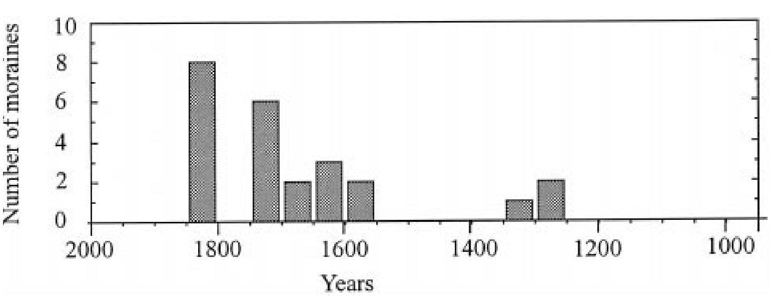

Fig. 5. Lichenometric dates of the outermost moraines of the last millennium in Tien Shan.

Table 1. Historical information on glacier variations in Tien Shan.

Mountain range	River basin	Number and/or name of glacier	Periods of recession	Periods of advance	*dx* (m)	*dh* (m)	References
Ugamsky	Pskem	Turpakbel Nizhniy	1929–86		–228	–57	Kanaev *et al.* (1967); Solomina and Savoskul (1993)
	Talassky Alatau						
	Talas	192, Chong-Tur	1928–29		–37		Glacier Inventory (1968)
		Left	1930–66		–235		Glacier Inventory (1968)
Fergansky	Chon-Uchseid	56, Chon-Seid	1910–47		– 800 to 900		Kuznetsov (1963)
	Muster	60?	1910–47		–700 to 800		Kuznetsov (1963)
	Kulun	93, Kulun	1910–45		*c.* –2000		Kuznetsov (1963)
Zailiysky Alatau	Kaskelen	107, Tuyuksu	1854–1964		–549	–29	Glacier Inventory (1967)
Kirgizsky	Alamedin	315, Sovetkina	1917–62		–360	–60	Glacier Inventory (1973)
	Issyk-Ata	329, Tushinsky	1906–1960	1962–64	–500		Glacier Inventory (1973)
	Ala-Archa	250, Golubin	1917–70s			–250	Aizin (1984)
	Kungey Alatau						
	Chon-Kemin	49, Dolonata	1927–82	1927–32	–376		Glacier Inventory (1969), Yermolov *et al.* (1986)
	Chon-Kemin	60, Ak–Suu East	1921–82	1963–66, 1975–76, 1979–82	–624		Glacier Inventory (1969), Yermolov *et al.* (1986)
	Chon-Kemin	55, Ak-Suu West	1921–28	1921–28	+15		Glacier Inventory (1969)
			1929–41		–60		Glacier Inventory (1969)
			1958–65		–128		Glacier Inventory (1969)
	Dzhindisu	10, Shnitnikov	1927–62		–1311		Glacier Inventory (1969)
Terskey Alatau	Konurulen	22	early 20C.–1970s	1910	–35 to 40		Glacier Inventory (1976)
	Chichkan	178	early 20C.–1970s	1914–15	–1000		Glacier Inventory (1976)
	Dzhirgalan	370	early 20C.–1970s		–600 to 700		Glacier Inventory (1976)
	Dzhirgalan	371	early 20C.–1970s		–550 to 600		Glacier Inventory (1976)
	Dzhirgalan	380	early 20C.–1970s		–500 to 550		Glacier Inventory (1976)
	Dzhirgalan	385, Aksu-Arasan	early 20C.–1970s		–350 to 400		Glacier Inventory (1976)
	Sary-Chat	321,Kolpakovskiy	1869–1957		–1300		Bondarev (1958)
			1957–77		–200		Dikikh and Kuzmichonok, (1981)
	Kuiliu	66, Karakoltor I	1906–59		–2800		Bondarev (1971a)
			1956–77		–810		Dikikh and Kuzmichonok, (1981)
	Kuiliu	70, Karakoltor II	1906–59		*c.* –1000		Bondarev (1971a)
	Taragay	396, Gregoriev	1911–47		–20 to 150		Avsiuk (1950)
	Sary-Chat	25	1912–54		–300		Orozgozhoev (1968)
Koiliu	Kara-Tor	114	1911–64		800 to 900		Orozgozhoev (1968)
Ak-Shyrak	Kumtor	361, Lisiy	1925–61	1925–32, 1929, 1932, 1933	–175		Bondarev (1963)
	Kumtor	366, Petrov	1869–1942	1911–25? 1943–57?	steady state		Bakov (1975)
			1869–70s		–400		Bakov (1975)
Adir-Tor	Adir-tor	93, Mushketov	1886–1975	1956–57	–800	–20	Bakov (1975)
			1886–1942		–3300		Bakov (1975)
			1942–56		–2000		Bakov (1975)
			1956–57		+4500		Bakov (1975)
	Sary-Dzhaz	44, Semenov	1857–1970s		*c.* –3000		Bakov (1975)
Kok-Shaal-tau	Dzhangart	first western	1906–62		–140		Bondarev (1971b)
	Dzhangart	Ak-Oguz, main	1906–62		–1020		Bondarev (1971b)
	Dzhangart	Ak-Oguz, left	1906–43		0		Bondarev (1971b)
	Dzhangart	to the south of the pass	1906–43		–100		Bondarev (1971b)
Karamoinok	Karakol western	262 and 263	1913–61		–50 to 100		Glacier Inventory (1978)
Dzhungarsky Alatau	Karatal	275, Bezsonov	1909–72		–879	–43	Glacier Inventory (1980)

Table 2. Statistics of Tien Shan glaciers and their retreat.

Statistics	*dx*	*dh*	*x*	*Zup*	*Zt*	*Zem*	*Zrl*	*Zll*	*Zmm*	*Zn*
Western Tien Shan										
Average	951	137	2307	4128	3573	3436	3776	3771		
Median	750	110	2000	4092	3540	3429	3790	3750		
Mode	500	50	1300	4250	3530	3350	3700	3850		
St. Dev.	620	93	1010	305	116	138	101	120		
Min	250	20	700	3740	3350	3050	3550	3550		
Max	3250	400	4893	5400	3820	3750	3950	4010		
Count	48	48	48	48	48	48	37	43		
Northern Tien Shan										
Average	1065	215	3057	4222	3513	3298	3788	3802	3750	3788
Median	1000	210	3050	4196	3505	3300	3750	3830	3750	3775
Mode	1000	80	3600	4150	3500	3300	3700	3900	3750	3750
St. Dev.	479	140	984	206	130	188	147	138	77	96
Min	320	30	1100	3770	3200	2750	3430	3430	3650	3650
Max	2125	850	6100	4788	3790	3700	4130	4070	3850	3930
Count	54	54	54	54	54	54	44	45	8	6
Inner Tien Shan										
Average	866	140	2740	4356	3657	3516	3895	3866	4025	4060
Median	750	115	2500	4467	3695	3520	3910	3910	4010	4000
Mode	500	100	1500	3700	3600	3500	3800	4030	4070	
Min	325	5	500	3590	3250	3150	3350	3390	3780	3950
Max	2375	440	7300	4913	3950	3780	4260	4200	4230	4230
Count	47	47	47	47	47	47	43	45	9	3
Central Tien Shan										
Average	983	129	4525	4792	3775	3654	4081	4076	4098	4132
Median	813	120	3100	4760	3813	3690	4080	4083	4150	4180
Mode	500	40	2400	4840	4050	3700	4000	4000	4200	4110
St. Dev.	544	81	6062	441	244	240	187	194	207	190
Min	270	5	900	3768	2920	2990	3500	3550	3500	3650
Max	2850	446	60500	7439	4205	4110	4600	4520	4454	4454
Count	140	140	144	144	144	140	140	134	61	35
Whole Tien Shan										
Average	989	151	3720	4541	3683	3536	3970	3959	4054	4081
Median	825	120	2900	4519	3665	3520	3950	3930	4110	4130
Mode	500	80	2800	4150	3700	3350	4000	3900	4200	4230
St. Dev.	540	105	4424	469	224	247	219	223	217	212
Min	250	5	500	3590	2920	2750	3350	3390	3500	3650
Max	3250	850	60500	7439	4205	4110	4600	4520	4454	4454
Count	289	289	293	293	293	289	264	267	78	44

dx, distance between the glacier terminus and the end moraine;
dh, difference between the elevation of the terminus and the end moraine;
x, length of glacier;
Zup, maximum elevation at the glacier head;
Zt, minimum elevation at the glacier terminus;
Zem, elevation of the end moraine;
Zrl, elevation of the right lateral moraine;
Zll, elevation of the left lateral moraine;
Zmm, elevation of the medial moraine;
Zn, elevation of corresponding nunatak

Table 4 presents the average values for retreat of various types of glaciers. The largest linear retreat is estimated for the compound-valley glaciers, the smallest is for cirque and cirque-hanging glaciers, which is obviously connected to their size. No significant difference was noticed in the retreat of glaciers of different orientation.

Table 5 shows the correlation coefficients of *dx* and *dh* versus other glacier parameters: elevation of terminus, highest point, end moraine, lateral and medial moraine elevations. The coefficients significant at the 99.9% level are in bold. A positive correlation is expected for *dh* and *dx*, although for the largest glaciers this correlation is not significant. The most consistent negative correlation is obvious for both *dx* and *dh* parameters and the elevation of the terminal moraine, with the exception of the largest glaciers.

Table 3. Glacier retreat parameters in the Tien Shan grouped according to glacier length.

x (m), number of glaciers		Statistics	*dx*	*dh*	*x*	*x* (m), number of glaciers		Statistics	*dx*	*dh*	*x*
500–1400,	(*n* = 31)	av.	496	91	1165	3100–3500,	(*n* = 34)	av.	1149	167	3276
		med.	500	80	1200			med.	1063	140	3250
		mode	375	50	1300			mode	1000	80	3200
		st dev.	214	68	237			st dev.	633	110	135
1500–2000,	(*n* = 49)	av.	775	155	1741	3600–4200,	(*n* = 37)	av.	1118	182	3843
		med.	750	140	1700			med.	1125	175	3800
		mode	375	50	1600			mode	1000	30	3600
		st dev.	348	98	181			st dev.	432	146	217
2100–2500,	(*n* = 39)	av.	825	166	2341	4300–6000,	(*n* = 39)	av.	1244	136	4993
		med.	750	140	2300			med.	1200	120	5000
		mode	500	200	2400			mode	1250	70	4300
		st dev.	419	106	137			st dev.	577	70	485
2600–3000,	(*n* = 44)	av.	951	154	2820	6000–60000,	(*n* = 17)	av.	1573	97	13555
		med.	750	125	2800			med.	1750	80	7800
		mode	750	120	2800			mode	1750	150	7300
		st dev.	530	110	149			st dev.	582	63	12963

Eleven surging glaciers were included in the data set according to the list provided by Bakov and Chen Dianmin for the Tien Shan (in Dyurgerov 1995, p. 73). Nearly all of them belong to the group of the largest glaciers, and comprise the majority of this group. This might explain the lack of correlation between *dx* and *dh*, and *dx*, *dh* versus *Zem*, which are generally characteristic of the other size groups.

The linear trend of annual temperature for the period of the longest meteorological records (1882–1988) varies regionally in Tien Shan (Table 6. It is much more prominent in the northern Tien Shan (Alma-Ata meteorological station: 0.035°C/yr), compared with the century-long records for the Issyk-Kul' area (Przhevalsk: 0.006°C/yr) and inner Tien Shan over the period 1935–1985 (Naryn: 0.0098°C/yr) (Dikikh 1997; Fig. 6). In general, the air temperature rose more in winter, although in the northern Tien Shan the summer trend is also quite high: 0.012°C/yr, compared to 0.007°C/yr for Przhevalsk and 0.002°C/yr for Naryn, respectively. The information about long-term trends in precipitation is more limited and less reliable. In general the century-long trend (1898–1990, Przhevalsk) is not significant.

Table 4. Glacier retreat parameters sorted by the morphological types of glaciers.

Type of glacier (number of glaciers)	Statistics	*dx*	*dh*	*x*	*Zup*	*Zt*	*Zem*	*Zrl*	*Zll*
Compound valley (28)	average	1438	130	7119	4974	3633	3493	3983	4025
	st dev.	623	84	6034	716	211	217	203	165
Valley (153)	average	1030	153	3428	4557	3693	3541	3979	3967
	st dev.	552	100	1303	334	218	259	194	206
Kettle-hole (11)	average	945	149	2491	4112	3528	3379	3811	3765
	st dev.	452	97	1179	248	175	172	191	253
Corrie valley (41)	average	889	161	2217	4292	3691	3529	3930	3878
	st dev.	370	93	680	378	214	204	232	219
Corrie (20) + corrie-hanging (10)	average	548	111	1580	4236	3715	3604	3962	3881
	st dev.	215	67	668	356	236	208	289	257
Hanging (5) + niche (5)	average	629	125	1620	4437	3661	3536	3858	3960
	st dev.	368	97	371	396	187	166	223	293
Other types									
Flat summits (1)									
Dendritic (3)									
Asymmetrical (6)									
Hanging valley (10)									

See Table 2 for abbreviations

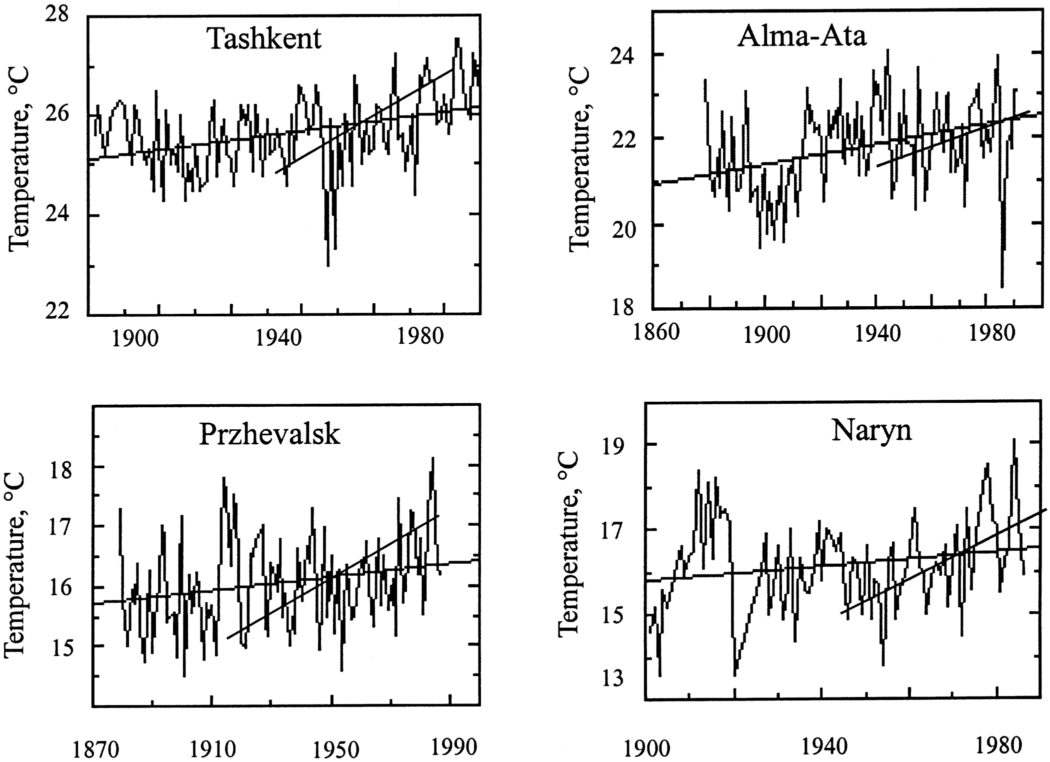

Fig. 6. Summer temperature trends measured over the last 150 years at Tashkent (western Tien Shan), Alma-Ata (northern Tien Shan), Przhevalsk (central Tien Shan) and Naryn (inner Tien Shan).

Table 5. Correlation coefficients of glacier retreat (*dx, dh*) versus other glacier parameters.

x (m), number of glaciers	Correl. parameters	*dh*	*x*	*Zup*	*Zt*	*Zem*	*Zrl*	*Zll*
500–60000, *n* = 293	*dx*	**0.54**	**0.47**	0.18	–0.08	**–0.31**	–0.01	0.05
500–60000, *n* = 293	*dh*		–0.05	0.03	–0.04	**–0.46**	–0.04	–0.03
500–1400, *n* = 31	*dx*	**0.67**	0.00	**0.48**	0.43	0.28	**0.48**	**0.53**
500–1400, *n* = 31	*dh*		0.14	**0.68**	**0.68**	**0.44**	**0.68**	**0.72**
1500–2000, *n* = 49	*dx*	**0.73**	0.35	0.00	0.04	–0.30	0.10	–0.09
1500–2000, *n* = 49	*dh*		0.29	0.25	0.17	–0.29	0.16	0.04
2100–2500, *n* = 39	*dx*	**0.80**	0.13	–0.34	–0.33	**–0.58**	–0.38	–0.40
2100–2500, *n* = 39	*dh*		0.19	–0.34	–0.33	**–0.58**	–0.38	–0.40
2600–3000, *n* = 44	*dx*	**0.58**	–0.01	–0.12	–0.20	**–0.41**	–0.18	–0.26
2600–3000, *n* = 44	*dh*		–0.15	–0.13	**0.57**	**–0.66**	–0.27	–0.19
3100–3500, *n* = 34	*dx*	**0.75**	–0.01	–0.36	–0.24	**–0.51**	–0.25	–0.37
3100–3500, *n* = 34	*dh*		0.01	–0.24	–0.27	**–0.64**	–0.41	–0.40
3600–4200, *n* = 37	*dx*	**0.65**	0.07	–0.22	–0.12	**–0.42**	–0.18	–0.10
3600–4200, *n* = 37	*dh*		0.07	–0.22	–0.12	**–0.42**	–0.18	–0.10
4300–6000, *n* = 39	*dx*	**0.60**	0.17	0.02	0.04	–0.15		0.16
4300–6000, *n* = 39	*dh*		–0.07	0.15	–0.05	–0.35	–0.06	0.15
6000–60000, *n* = 17	*dx*	0.08	0.44	0.05	0.05	0.42	0.41	0.26
6000–60000, *n* = 17	*dh*		–0.36	0.01	0.01	0.25	–0.05	0.37

See Table 2 for abbreviations

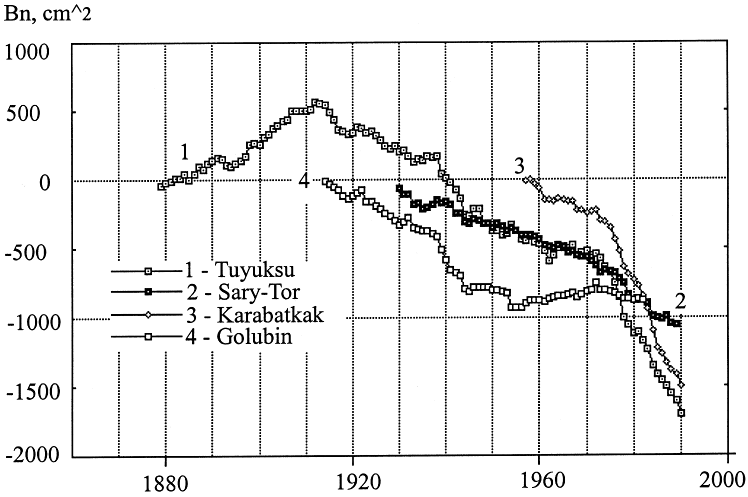

Fig. 7. Mass balance reconstruction (cumulative curves) of Tien Shan glaciers (by V. Mikhalenko).

Mass-balance reconstructions for Tien Shan glaciers (Fig. 7) show that the mass decrease of glaciers in the 20th century began in the 1910s. The most dramatic loss of mass in the northern and western Tien Shan during the period 1956–1992 is reported by Dyurgerov (1995).

The long-term trends on temperature and mass-balance measurements during the 1950s to 1990s are consistent with the highest values of glacier retreat in northern Tien Shan after the LIA maximum.

ELA shift

The estimates of front elevation enable us to estimate the shift of the equilibrium line altitude (*dELA*, as a half of the front depression) and to compare it with other regions. This method is considered to be inaccurate (Torsnes *et al*. 1993), but being very simple it is of great utility, especially in the case of large samples. Maisch (1992) compared the directly measured *dELA* between the 1850s and present (77 m) with the front depression calculated for 684 Alpine glaciers (165 m) and concluded that half of this value is close to the measured *dELA*.

Figure 8 presents the ELA elevation on Tuyuksu glacier in the Zailyisky Alatau Range observed and reconstructed based on meteorological data (Palgov 1968; Dyurgerov 1995). On average, for 1879–1990, the ELA rose by 100–120 m. The *dELA* estimate based on front elevation change for the northern Tien Shan is about 100 m (see Table 2).

The *dELA* estimate in Tien Shan (75–100 m) is similar to the value estimated for the Alps (77 m; Maisch 1992), for western Norway (70 m; Torsnes *et al.* 1993), Pamir-Alay and Koryak Plateau (Solomina 2000). It is greater in the Caucasus; Panov (1993) estimates it as about 90 m for the end of the 19th century, when the glaciers had already retreat-

Table 6. Temperature trends (°C/year) in Tien Shan.

Region	Met. station	Elevation (m)	1882–1988 summer	1882–1988 year	After 1930 Period	After 1930 summer	After 1930 year
Western	Tashkent		0.008	0.01	1930–1989	0.021	0.027
	Pskem	1400			1933–1989	0.005	0.01
Northern	Alma-Ata[a]	825	0.012	0.035	1930–1989	0.005	0.006
	Minzhilky	3017			1938–1987	0.022	0.012
Central	Przhevalsk[a]	1714	0.007	0.006	1930–1989	0.019	0.023
	B.Kizil-su	2555			1948–1987	0.009	0.055
	Tien-Shan[a]	3614			1930–1989	0.012	0.009
Inner	Narin[a]	2039	0.002	0.0098	1930–1989	0.002	0.032

[a] After Dikikh (1997)

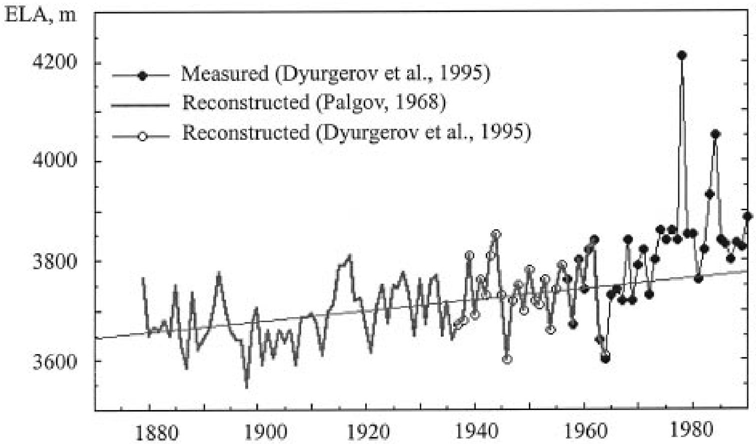

Fig. 8. ELA elevation observed (Pal'gov 1968) and reconstructed (Dyurgerov 1995).

ed from their LIA maximum positions. The lowest LIA *dELA* values (20–40 m) are recorded in eastern Siberia (Solomina 2000).

Conclusions

1. Given the limitations imposed by the available materials, the glacier changes in the Tien Shan since the LIA maximum up to the 1980s can be estimated only in general terms.
2. According to lichenometry, the maximum glacier advances in the last millennium occurred in most valleys of Tien Shan between the end of the 17th and the first half of the 19th centuries.
3. On average, Tien Shan glaciers have retreated by 989 ± 540 m since the LIA maximum. Their front elevations (*dh*) rose by 151 ± 105 m. Differences between four regions in Tien Shan are generally small, though in northern Tien Shan the glacier retreat and frontal rise are more prominent (1065 ± 479 m and 215 ± 140 m, respectively).
4. The greatest linear retreat is estimated for the compound-valley glaciers, the smallest is for cirque and hanging glaciers.
5. No significant difference was noticed in the retreat of glaciers of different orientation.
6. Consistent negative correlations exist for both *dx* and *dh* parameters versus the elevation of the LIA terminal moraine.
7. The 20th century temperature trends and mass-balance measurements for the 1950s to 1990s are in agreement with the retreat of Tien Shan glaciers and support the highest values of glacier retreat in the northern Tien Shan after the LIA maximum.
8. The LIA *dELA* values estimated in Tien Shan are close to those of the Alps, Western Norway, Pamir-Alay and Koryak plateau; they are smaller than in the Caucasus, but greater than in east Siberia.

Acknowledgements

Detailed cartographic data for Tien Shan were kindly provided by Dr V.S. Kuzmichonok (Kyrgizkartografiya). We are grateful to Dr M. Dyurgerov, Dr V. Konovalov and Dr V. Mikhalenko for providing meteorological data, maps and pictures. O. Solomina was supported by Fulbright Foundation grant N 99-05-64946. This paper is also a contribution to the GLIMS project (NASA NAG-5-9722).

Dr Olga Solomina and Mrs Maria Bodnya, Institute of Geography, Russian Academy of Sciences, Staromonetny-29, Moscow 109017, Russia.
E-mail: solomina@gol.ru

Professor Roger Barry, National Snow and Ice Data Center, CIRES, University of Colorado, Boulder, CO 80309-0449, USA.
E-mail: r.barry@kryos.colorado.edu

References

Aizin, V.B., 1984: Modern glaciation of Ala-Archa basin (Sovremennoye oledeneniye basseina Ala-Archa). *In*: Glazirin, G.E. and Getker, M.I. (eds): Hydrology of mountain areas (Gidrologiya gornikh oblastey). 105(186): Trudi SARNIGMI. Moscow. 111–120.

Avsiuk, G.A., 1950: Flat summit glaciers (Ledniki ploskikh vershin). *Proceedings of the Institute of Geography (Trudy Instituta Georgafii)*, 5: 15–44.

Bakov, E.K., 1975: About the spatial variations of large dendritic glaciers in Tien Shan (O prostranstvennom izmeneii krupnikh dendritovikh lednikov Tian-Shania): Glaciological studies in the Tien Shan (Gliatsologicheskoye issledovaniya na Tian Shane). Ilim. Frunze. 73–81.

Bickerton, R.W. and Matthews, J.A., 1992: On the accuracy of lichenometric dates: an assessment based on the "Little Ice Age" moraine sequence of Nigardsbreen, southern Norway. *The Holocene,* 2(3): 227–237.

Bishop, M.P., Kargel, J.S., Kieffer, H.H., MacKinnon, D.J., Raup, B.H. and Shroder, J.F., 2000: Remote-sensing science and technology for studying glacier processes in high Asia. *Annals of Glaciology,* 31:164–170.

Bondarev, L.G., 1958: Kolpakovskogo glacier (Lednik Kolpakovskogo). *Proceedings of the Tien Shan Geographical Research Station* (*Raboty Tian-shanskoi fiziko-geograficheskoi stantsii*), 1: 55–64.

Bondarev, L.G., 1963: Essays on Ak-Shiirak glaciation (Ocherki po oledeneniyu Ak-Shiirak). Academy of Science Press. Frunze..

Bondarev, L.G., 1971a: About the half-century development of several Tien Shan glaciers (O poluvekovom razvitii nekotorikh lednikov Tian Shania). *In*: Zabirov, R.D. (ed.): Some regularities of Tien Shan glaciation (Nekotoriye zakonomernosti oledeneniya Tian Shania). Ilim. Frunze. 120–129.

Bondarev, L.G., 1971b: Special features of century-scale phases of variations of Tien Shan glaciers (Osobennosti vnutrivekovikh faz izmenchivosti lednikov Tian'-Shania). *In*: Zabirov, R.D. (ed.): Some regularities of Tien Shan glaciation (Nekotoriye zakonomernosti oledeneniya Tian Shania). Ilim. Frunze. 137–144.

Dikikh, A.N., 1997: Global warming, its manifestation in Tien Shan and reaction of glaciers (Glogal'noye potepleniye klimata, ego proyavleniye na Tian'-Shane i reaktsiya lednikov). *Data of Glaciological Studies,* 83: 135–140.

Dikikh, A.N. and Kuzmichonok, V.A., 1981: Analyses of glacier fluctuations of the inner Tien-Shan by the photogrammetric survey in the International Geodetic Year and in 1977 (Analis kolebanii lednikov vnutrennego Tian'-Shania po materialam s'emok v period MGG i v 1977 g.). *In*: Glaciological studies in Kirgizia (Gliatsiologicheskiye issledovaniya v Kirgizii). Ilim. Frunze. 35–56.

Dyurgerov, M.B. (ed.), 1995: Tien Shan glaciation. Oledeneniye Tian-Shania. Moscow.

Glacier Inventory of the Soviet Union, 1965–1980: Gidrometeoizdat. Leningrad. 13(2), 14(1–2).

Haeberli, W., 1995: Glacier fluctuations and climate change detection operational elements of a worldwide monitoring strategy. *World Meteorological Organizatio Bulletin,* 44(1): 23–31.

Kanaev, L.A., Podkopaeva, L.D., Schetinnikov, A.S. and Yazikov, L.E., 1967: Results of monitoring of some glaciers of Uzbekistan (Resul'tati nabliudenii za sostoianiem nekotorikh lednikov Uzbekistana). *Trudi SARNIGMI,* 30(45): 3–18.

Kassin, N.G. 1915. Hydrologic studies carried out in the Issik-Kul' basin in 1914 (Gidrologicheskiye issledovaniya, proizvedenniye v basseine ozera Issik-Kul' v 1914 g). Sankt-Petersburg. 268 p.

Korzhenevsky, N.L. 1930. Glacier inventory of Central Asia (Katalog lednikov Srednei Asii). Tashkent. 200 p.

Kuznetsov, Yu.Ya., 1963: About the recession of glaciers of Fergansky Range (O sokrashenii lednikov Ferganskogo khrebta). *Geologya i Razvedka,* 4: 145–147.

Maisch, M., 1992: Die Gletscher Graubundens. Reconstruction und Auswertung der Gletscher und deren Veraenderungen seit dem Hochstand von 1850 im Gebiet der oestlichen Schweizer Alpen. *Physische Geographie. University of Zuerich,* 33A: 324; B:128.

Orozgozhoev, B.O., 1968: Main features of glaciation of Koiliu river basin (Osnovnoye cherti oledeneniya basseina r.Koiliu). Achivements of soviet glaciology (Uspekhi sovetskoi gliatsiologii). Ilim. Frunze. 216–224.

Palgov, N.N., 1968: General meteorological parameters, firn line and ablation in the former life of Tsentral'ny Tuyuksu glacier in Zailiisky Alatau (Osnovniye meteorologicheskiye usloviya, firnovaya liniya i abliatsiya v proshloy zhizni Tsental'nogo Tuiuksuiskogo lednika). *Data of Glaciological Studies,* 14: 82–90.

Panov, V.D., 1993: Evolution of modern glaciation of Caucasus. Gidrometeoizdat. Leningrad. 432 p.

Semenov, P.P., 1858: The first trip to Tien Shan or Sky Range (Pervaya poezdka na Tian' Shan' ili Nebesny khrebet). *Proceedings of Russian Geographical Society (Vestnik RGO)*: 1–24.

Solomina, O.N., 1999: Mounatin glaciation of Northern Eurasia in the Holocene (Gornoye oledeneniye Severnoy Evrazii v Golotsene). Nauchniy Mir. Moscow. 264 p.

Solomina, O.N., 2000: Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum. *Annals of Glaciology,* 31: 26–30.

Solomina, O.N. and Savoskul, O.S., 1993: Dynamics of Turpakbel' Nzhniy Glacier in Holocene and history of Tien Shan glaciation (Dynamika lednika Turpakbel' Nizhniy v golotsene i istoriya oledeneniya Tian-Shania). *Data of Glaciological Studies,* 76: 47–53.

Solomina, O.N. and Kamniansky, G.M., 1998: Fluctuations of four Pamir-Alay glaciers revealed by lichenometry. *Data of Glaciological Studies,* 84: 158–164.

Torsnes, I., Rye, N. and Nesje A, 1993: Modern and Little Ice Age equilibrium-line altitudes on outlet valley glaciers from Jostedalsbreen, Western Norway: an evaluation of different approaches to their calculation. *Arctic and Alpine Research,* 25(2): 106–116.

Yermolov, A.A., Solodkov, P.A. and Firsov, M.I., 1986: Fluctuations of glaciers Ak-Suu East, Ak-Suu West and Dolonata in 1921–1982 (Kolebaniya lednikov Ak-Suu Vostochnii, Ak-Suu Zapadnii i Dolonata za period 1921–1982 gg.). *Trudy SARNIGMI,* 117: 103–110.

Manuscript received November 2002, revised and accepted August 2003.