Annals of Glaciology 24 1997

The reaction of mountain glaciers to climatic change under continental conditions

M. G. KUNAKHOVITCH, A. M. SOKALSKAYA
Laboratory of Mountain Glaciology, Institute of Geography, Russian Academy of Sciences, Staromonetny 29, Moscow 109017, Russia

ABSTRACT. Data on the distribution of accumulation with elevation were used to calculate ablation, internal accumulation, annual mass balance and glacier runoff for the Tien Shan glaciers with a total area of about 15 500 km^2. The altitudinal profile of normalized ablation is approximated by an exponential curve. Mass-balance components and glacier runoff are calculated for the whole possible range of glacier equilibrium-line positions in the major river and lake basins of the Tien Shan.

For steady state it was found that the equilibrium line rises from 3600 m in western areas to 4400 m in the east, whilst the accumulation area ratio and glacier runoff increase eastward from 63% to 71%, and from 600 to 1200 mm, respectively. Losses of meltwater runoff for internal accumulation average 7% (5–11%).

In abnormally warm years, mass balance may reach −2300 mm w.e. in the west and −855 mm in the east and in the internal Tien Shan (Khan Tengry massif). Glacier runoff volume in those years has been estimated at 40 km^3 year^{-1}, which is 2.5 times as large as for the steady state.

INTRODUCTION

The Tien Shan is a very complicated mountain system in Central Asia with more than 16 000 km^2 glacierization and about 16 000 different glaciers. The high mountain areas of the Tien Shan feed the major rivers of Central Asia and closed drainage basins of the Aral Sea, Lake Balkhash and Issyk-Kul. Glacier runoff contributes 20–80% (Tarim river basin) to the total runoff of these arid regions in summer months (July–August). As mass balance is regularly measured on only a few small glaciers of the study area, it is a challenge to estimate it for the whole glacierization of the Tien Shan or separate large river and lake basins. To solve the problem, we used the calculation method that was applied to the part of the Tien Shan on the territory of the former Soviet Union (Dyurgerov and others, 1992). The completion of glacier inventories for the whole Tien Shan (Central Asian republics and China) made this possible.

METHODS

The whole Tien Shan mountain system is a large area without external runoff. There are seven interior basins: the Aral Sea, Lake Balkhash, and Issyk-Kul, the rivers Tarim, Chu and Djungarskaya (part of the Ily river system) and Tourfan-Khami depressions. All these basins are located in different orographic and climatic environments. Within these major areas there are 310 glaciated river basins with similar snow accumulation and ablation conditions. Consider glacierization in each basin as a large hypothetic glacier covering the area in the whole altitudinal range where real glaciers are located with all the possible aspects (Dyurgerov, 1986). Such a glacier can be characterized by the vertical profiles of the glaciated area and snow accumulation, because altitude is the main parameter of mass-balance variation.

Data from the USSR glacier inventory (Akademii Nauk SSSR, 1969–78; Kuzmichenok, 1993) and China glacier inventory (Academia Sinica, 1986–87) were used to build glacier hypsographic curves. To estimate snow accumulation we used winter mass-balance measurements on glaciers and snow accumulation over meteorological stations all over the Tien Shan (Getker, 1985). Statistical analysis of all available data enabled us to divide the Tien Shan area into 22 basins with similar accumulation distribution with elevation within each basin.

As the ablation depends on many different climatic and orographic factors it is not possible at present to calculate it for the whole mountain system. Khodakov (1965), and later Krenke and Menshutin (1987), showed that different mor-

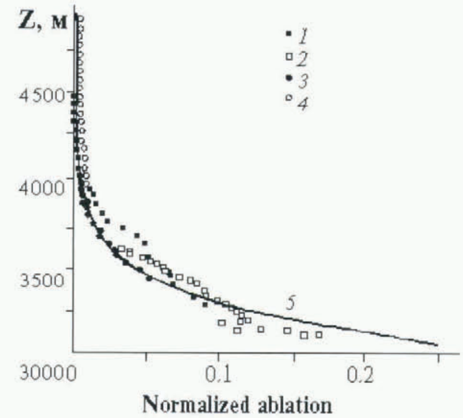

Fig. 1. The distribution of normalized ablation with altitude. Observed data for glaciers 1, Sary Tor; 2, Shumskogo; 3, Davydova; 4, Golubina.

https://doi.org/10.3189/S0260305500012532 Published online by Cambridge University Press

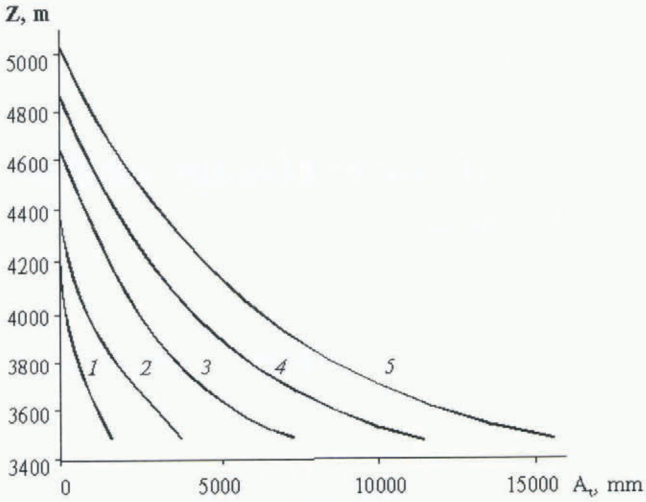

Fig. 2. The distribution of ablation over altitude for different ELA positions: 1, 3850 m; 2, 4050 m; 3, 4250 m; 4, 4450 m; 5, 4650 m.

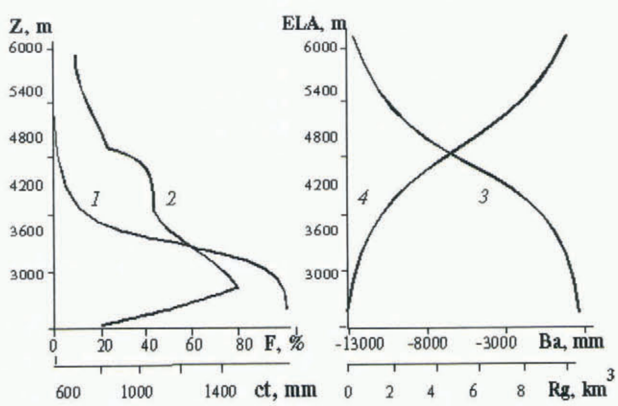

Fig. 3. The distribution of glacier area (1) and accumulation (2) with altitude (Z), and the relations of mass balance (3) and glacier runoff (4) with the ELA for the northern slope of Zailyiskyi Alatau range.

phologic types of glaciers are characterized by similar distribution of ablation with elevation. We found out that normalized (0–1) ablation values for different Tien Shan glaciers can be closely described by the concave curve (Kunakhovitch, 1991) (Fig. 1):

$$a_{ti} = v e^{-kz_i}, \tag{1}$$

where i is the number of the altitude zone, and z_i is normalized (0–1) altitude:

$$z_i = \frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}} \tag{2}$$

where $Z_{\min}$ and $Z_{\max}$ are the lower and upper levels of the Tien Shan glacierization, Z_i is the average altitude of each interval, and v and k are empirical coefficients. The coefficient $k = 10$ was calculated from data from field observations on glaciers.

Thus, we need the value of ablation in only one elevation zone in order to determine the ablation distribution with altitude for the whole basin. The highest equilibrium-line altitude (ELA) at the end of summer seems to be the best choice of the elevation zone i. The ablation here is equal to the accumulation: $a(\text{ELA}) = c(\text{ELA})$.

Using Equation (1), the coefficient v can be expressed as:

$$v = c_t(\text{ELA})/e^{kz(\text{ELA})}. \tag{3}$$

The coefficient v varies during the ablation season and depends on the position of the equilibrium line as shown in Figure 2. Mass-balance values b_{ni} in each interval i were estimated as differences between accumulation and ablation for each ELA:

$$b_{ni} = c_{ti} - v e^{-kz_i}. \tag{4}$$

We use these three curves (ablation, accumulation and hypsographic) for computation of snow ablation, mass balance and glacier runoff for different equilibrium-line positions.

$$B_n = \sum_{i=1}^{n} \left(c_{ti} - v e^{-z_i k}\right) \frac{s_i}{S} \tag{5}$$

where S is the total glaciated area, represented by the hyp-

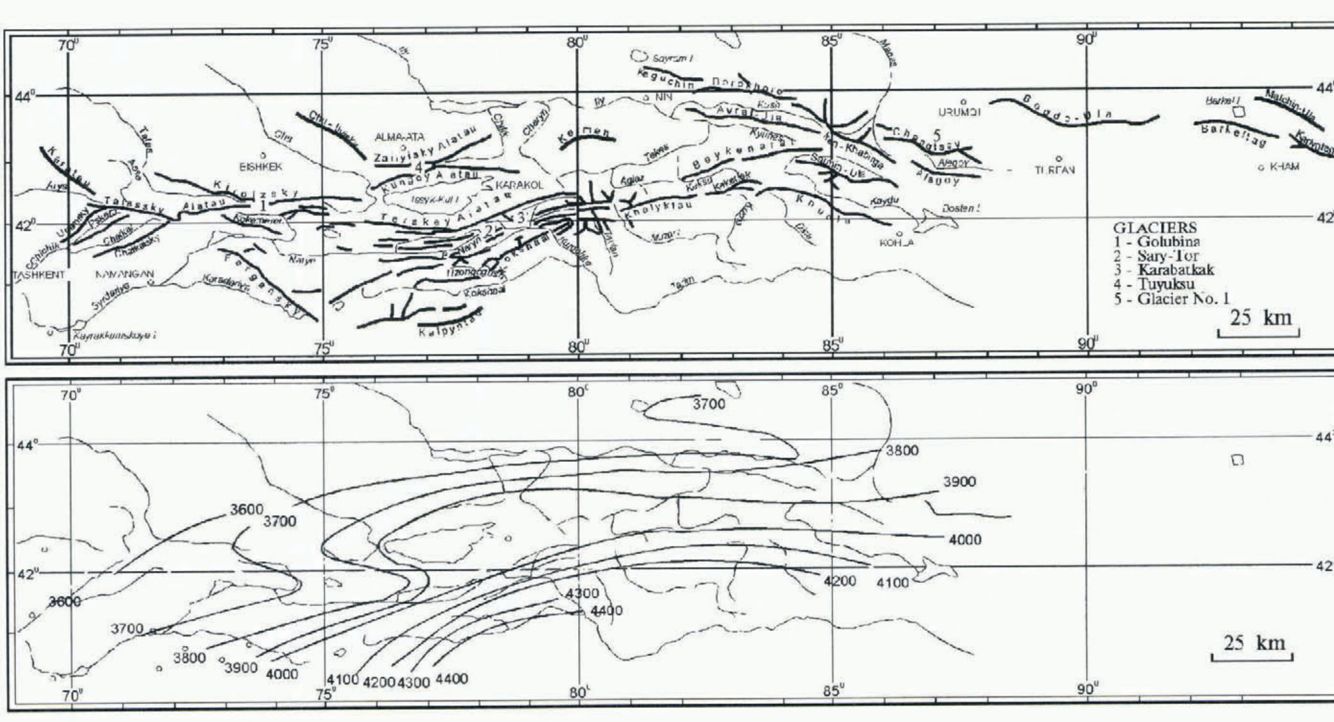

Fig. 4. The distribution of ELA over the Tien Shan in steady-state conditions.

https://doi.org/10.3189/S0260305500012532 Published online by Cambridge University Press

Table 1. The main characteristics of glaciated basins in steady state

Glaciated basin	*Glaciated area*	*AAR*	*ELA*	a_t	R_g	*Internal accumulation*	
	km^2	%	m	mm	km^3	mm	%
Upper Naryn	975	64	4167	771	0.75	43	5
Naryn	137	64	3696	1251	0.17	86	6
Karadarya	113.7	63	4068	846	0.1	51	6
Atbashy	179	65	3614	1590	0.28	97	6
Chirchik	179	65	3614	1590	0.28	97	6
Sum					2.31		
Chu	635	63	3829	946	0.6	53	5
Upper Chu	107	64	3924	721	0.08	21	3
Talas	165	65	3675	389	0.15	55	6
Sum					0.83		
West Issyk-Kul	344.8	63	3961	616	0.21	45	7
East Issyk-Kul	358.4	63	3919	1213	0.43	98	7
Sum					0.65		
Sary Djus	2465	68	4203	894	2.2	98	10
Aksay	2202	65	4298	702	1.55	65	8
Kokshaal	292	62	4469	580	0.17	47	8
Kumalike	2873	71	3709	885	2.54	91	9
Muzart	1784	68	4189	1081	1.93	111	9
Sum					8.39		
Keksu	422	65	3800	978	0.41	81	8
Kash	422	64	3661	1106	0.47	90	8
Kunes	96.7	67	4285	926	0.09	41	4
Tekes	1023.9	66	3893	935	0.96	100	10
Ily	723	61	3883	1273	0.92	106	8
Sum					2.85		
Kaidu	444.5	63	3950	820	0.36	59	7
Sairan	637	63	3741	779	0.5	71	8
Average/*sum*	*17368*	65	3955	947	*15.88*	74	7

sographic curve, s_i is the area of altitudinal zone i, and n is the number of elevation intervals. Glacier runoff R_g is supposed to be equal to integrated ablation, assuming negligibly small evaporation in summer. Thus, using the data of two curves $c_t(Z)$ and $s(Z)$ we found the relationships $b_n = f(\text{ELA})$ and $R_g = f(\text{ELA})$ for each of the 22 basins (Fig. 3). Below, the results for steady-state and extremal conditions are presented.

RESULTS

(1) Steady-state condition; glacier mass balance equals zero and area is constant

We calculated the ELAs in each basin according to the above technique for these conditions.

The ELA spatial distribution is shown in Figure 4. Difference in ELA reaches 900 m within the Tien Shan area. It increases from 3600 m a.s.l. in the lowest western and northern parts to 4500 m in the south, where mountains are much higher (Table 1). Another factor responsible for ELA location is the precipitation amount. Thus, heavy precipitation over the northern and western windward ranges also accounts for low altitudes of glacier equilibrium line in this region.

In the internal Tien Shan the number of glaciers that are located on the windward peripheral slopes and get large amounts of precipitation is one-third of that of glaciers in large valleys which are usually colder and shielded from the main moisture-carrying air streams.

The accumulation area ratio (AAR) is 60% in the west peripheral part of the Tien Shan and reaches 70% in the

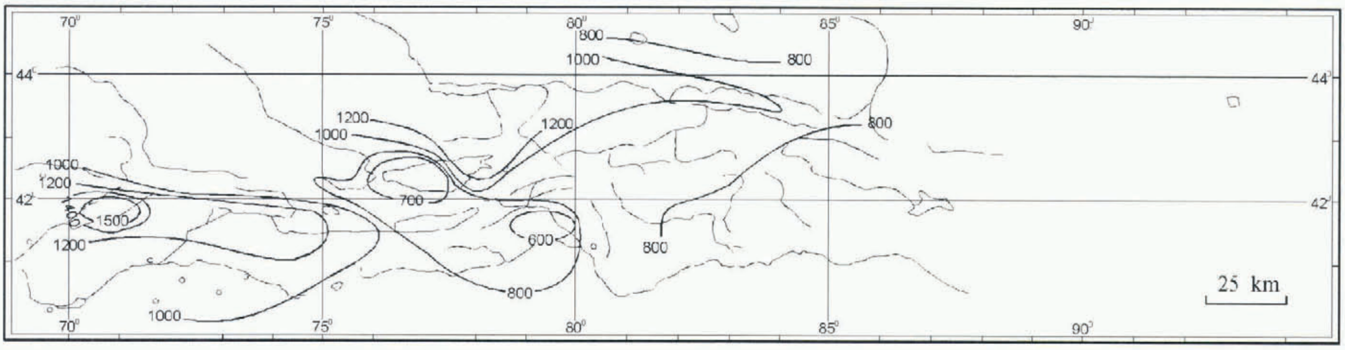

Fig. 5. The distribution of specific glacier runoff (mm) over the Tien Shan in steady-state conditions.

Table 2. The extremal values of the glaciated basins

Glaciated basin	AAR		ELA		a_t		R_g		Internal accumulation	
	min	*max*	*min*	*max*	*min*	*max*	*min*	*max*	*min*	*max*
	%	%	m	m	mm	mm	km^3	km^3	mm	mm
Upper Naryn	81	22	4061	4425	474	1873	0.462	1.826	11	61
Naryn	89	15	3550	3986	722	3083	0.099	0.421	11	156
Karadarya	84	27	3895	4409	579	2657	0.56	2.571	26	183
Atbashy	85	16	3926	4365	491	2067	0.056	0.235	8	99
Chirchik	86	6	3459	3903	875	3890	0.157	0.696	15	234
Chu	84	23	3703	4079	560	2291	0.356	1.455	22	96
Upper Chu	89	9	3798	4213	431	1709	0.046	0.182	8	56
Talas	82	25	3535	4073	507	2194	0.083	0.361	5	117
West Issyk-Kul	85	21	3820	4256	363	1523	0.057	0.241	7	72
East Issyk-Kul	86	15	3759	4220	685	3006	0.373	1.638	25	176
Sary Djus	85	26	4055	4503	530	2245	1.306	5.532	51	122
Aksay	87	14	4143	4610	404	1747	0.889	3.847	28	100
Kokshaal	85	16	4324	4751	341	1435	0.099	0.419	17	71
Kumalike	85	25	4112	4626	543	2188	1.56	6.285	71	98
Muzart	83	20	4013	4542	659	2678	1.175	4.777	82	125
Keksu	85	18	3638	4129	543	2441	0.229	1.029	9	153
Kash	81	49	3506	3970	629	2755	0.265	1.161	13	156
Kunes	96	0	3540	4400	534	1900	0.052	0.16		101
Tekes	80	44	3722	4238	529	2362	0.542	2.424	32	151
Ily	82	38	3639	4376	661	3176	0.478	2.296	14	245
Kaidu	88	15	3800	4246	470	2027	0.209	0.901	7	108
Sairan	113	17	3579	4061	445	1950	0.284	1.243	17	113
Average/*sum*	86.4	21	3799	4290	544.3	2327	*9.337*	*39.7*	22	127

internal and eastern regions. The range of variations in AAR is similar in the Alps. It is worth noting that glaciers with smaller AAR have greater balance gradients for a given topography or hypsometric curve. The average mass-balance gradient for the whole Tien Shan at the ELA level makes up 2.7 mm m^{-1}, varying from 1.6 mm m^{-1} in the western and northern areas to 4.4 mm m^{-1} in the south. Our results differ from those obtained by Kuhn and others (1985) for Kesselwandferner and Hintereisferner, Austrian Alps. The difference may be accounted for by the local topographic peculiarities of these two glaciers. It can be concluded that to maintain steady state a glacier with a relatively low accumulation needs a greater accumulation area.

Assuming glacier runoff, R_g (km^3), equal to integrated ablation, it is evident that in steady state $a_t = c_t$. So the distribution of r_g specific values is the same as that of precipitation (see Fig. 5). Specific r_g increases northwestward from a low of 580 mm in the southern part of Kokshaal river to 1100–1600 mm in the Chirchik river basin and on the northern slope of the Zailyiskyi Alatau range. The amount of internal glacier accumulation makes up 5–8% of the total ablation on the north and west peripheral ranges and may exceed 10% in the interior of the Tien Shan.

In steady state, Tien Shan glaciers contribute about 15 km^3 which is 7–40% of the total annual runoff of the biggest Central Asian rivers. The glaciers contribute more than 2 km^3 of fresh water to the Aral Sea, about 3 km^3 to Lake Balkhash and 0.6 km^3 to Issyk-Kul each year.

(2) Extremal conditions

The range of year-to-year ELA variations is about 400–600 m. In low river basins such as Chirchik and Chu (Ily) where in years with heavy precipitation the ELA can descend as low as 3450–3550 m, it can rise as high as 3900 m in dry years. In the highest part of the mountain system

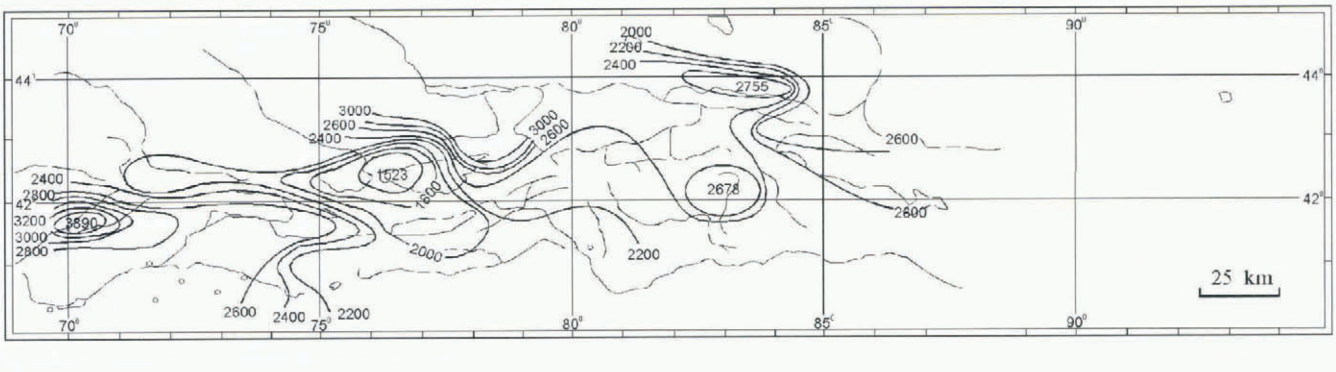

Fig. 6. The distribution of maximum glacier runoff (specific values, mm) over the Tien Shan in extremely warm years, or in lowest ELA position.

https://doi.org/10.3189/S0260305500012532 Published online by Cambridge University Press

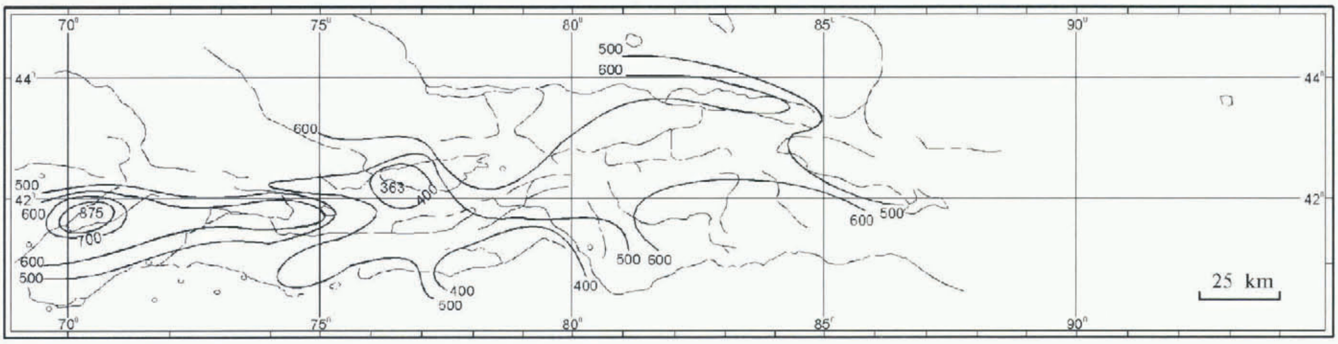

Fig. 7. The distribution of minimum glacier runoff (specific values, mm) over the Tien Shan in extremely cold years, or in highest ELA position.

(Khan Tengry area) the ELA varies from 4050 to 4600 m under different meteorological conditions (Table 2).

In high-accumulation years when the AAR on peripheral ranges of the Tien Shan is nearly 90%, mass balance can reach 700 mm and glacier runoff about 870 mm. The refreezing of meltwater within deep snowpack is also greater in extremal years (positive mass balance), comprising 200 mm, or about 20% of annual ablation. In more continental areas, b_n and R_g never exceed 400 and 340–600 mm, respectively (Fig. 6). But the total area of glaciers in these areas is very significant; only the glaciers of Khan Tengry can produce more than 4 km^3 of water per year.

In extremely warm years mass balance may reach −2300 mm on the western and northern glaciers. This results in R_g of nearly 4000 mm year^{-1} (Fig. 7). Thus glaciers lose three times more water than in extremely cold years. The glacier runoff from high internal regions (Khan Tengry, Ak-Shiyrak, Kokshaal, etc.) does not exceed 860 mm even in extremely warm years (Fig. 6).

The possible reaction of mass balance of the Tien Shan glaciers to climatic changes is shown in Table 3. An increase of 1°C in summer temperature would reduce the AAR by 10% in the Ily river basin (we use this basin as the key area because of the extensive climatic parameters and mass-balance data available). For example, if the mean summer temperature increased by 1°C, the mass balance would change by up to −400 mm in the Issyk Kul, Chu and Talas basins.

CONCLUSION

Our emphasis has been on calculations of mass balance and glacier runoff for large areas. But it is evident that these estimates should be tested against actual observation data. However, standard hydrological data may be used to test the calculated glacier runoff only for separate basins with a glacial area of more than 50%. Only a few records on

Table 3. The mass balance of basins under different climatic conditions

Glaciated basin	*AAR in Ily basin (%)*								
	10	20	30	40	50	60	70	80	90
Upper Naryn	−1101	−601	−385	−234	−114	6	95	191	297
Naryn	−1832	−1022	−665	−411	−209	−11	173	342	529
Karadarya	−1621	−903	−583	−355	−174	−9	147	296	457
Atbashy	−1222	−679	−436	−263	−128	−7	110	222	355
Chirchik	−2299	−1276	−830	−510	−257	−13	217	443	716
Chu	−1344	−737	−474	−289	−144	−8	123	244	386
Upper Chu	−988	−543	−352	−215	−107	−6	90	179	290
Talas	−1299	−717	−459	−276	−135	−7	115	244	388
West Issyk-Kul	−906	−504	−328	−204	−100	−5	82	162	254
East Issyk-Kul	−1794	−987	−639	−390	−193	−10	163	329	527
Sary Djus	−1350	−742	−476	−290	−143	−7	118	235	365
Aksay	−1045	−575	−368	−224	−111	−6	91	189	298
Kokshaal	−855	−471	−303	−186	−91	−5	76	153	239
Kumalike	−1302	−710	−454	−275	−134	−7	111	221	342
Muzart	−1596	−869	−557	−338	−165	−8	137	273	423
Keksu	−1463	−814	−529	−325	−164	−8	136	277	435
Kash	−1649	−914	−590	−363	−177	−9	152	305	477
Kunes			−483	−285	−1456	−8	126	265	392
Tekes	−1427	−790	−512	−313	−155	−8	129	260	406
Ily	−1903	−1066	−695	−429	−212	−11	186	383	612
Kaidu	−1207	−669	−432	−265	−129	−7	112	222	350
Sairan	−1170	−648	−418	−256	−125	−7	107	213	334

observed glaciers are available to test the calculated values of mass balance. The values for large areas could be tested by data from the repeated topographic surveys, but these were carried out only on separate glaciers or groups of glaciers, not for the whole Tien Shan.

REFERENCES

Academia Sinica. 1986–87. *[Glacier inventory of China III. Tien Shan Mountains.]* Lanzhou, Lanzhou Institute of Glaciology and Cryopedology. [In Chinese.]

Akademii Nauk SSSR. 1969–78. *Katalog lednikov SSSR [Inventory of glaciers of the USSR]*, **13**(2), Parts 1–3; **14**(1), Parts 1–11. Leningrad, Gidrometeoizdat.

Dyurgerov, M. B. 1986. Raschet balansa massy lednikovykh sistem/Computations of mass balance in glacier systems. *Mater. Glyatsiol. Issled.* 57, 8–15 (Russian); 144–148 (English).

Dyurgerov, M. B., M. G. Kunakhovich, V. N. Mikhalenko, A. M. Sokalskaya and V. A. Kuzmichenok. 1992. Can the mass balance of the entire glacier area of the Tien Shan be estimated? *Ann. Glaciol.*, **16**, 173–179.

Getker, M. I. 1985. [Snow resources of mountains in Central Asia.] (D.Sc. thesis, Institute of Geography, Moscow.) [In Russian.]

Khodakov, V. G. 1965. O zavisimosti summarnoy ablyatsii poverkhnosti lednikov ot temperatury v vozdukha [Relationship between the sum of ablation of the glacier surface and air temperature]. *Meteorol. Gidrol.*, **7**, 48–50.

Krenke, A. N. and V. M. Menshutin. 1987. Calculation of mass balance of glaciers by remote-sensing imagery using similarity of accumulation and ablation isoline patterns. *J. Glaciol.*, **33**(115), 363–368.

Kuhn, M., G. Markl, G. Kaser, U. Nickus, F. Obleitner and H. Schneider. 1985. Fluctuations of climate and mass balance: different responses of two adjacent glaciers. *Z. Gletscherkd. Glazialgeol.*, **21**, 409–416.

Kunakhovitch, M. G. 1991. [Mountain glacier mass balance: similarity and numerical computation.] (Ph.D. thesis, Institute of Geography, Moscow.) [In Russian.]

Kuzmichenok, V. A. 1993. Ledniki Tyan'-Shanya. Komp'yuternyy analiz kataloga [The glaciers of Tyan'-Shan'. Computerized analysis of the inventory]. *Mater. Glysatsiol. Issled.* 77, 29–41.

https://doi.org/10.3189/S0260305500012532 Published online by Cambridge University Press