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Can the mass balance of the entire glacier area of the Tien Shan be estimated?

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ABSTRACT. The total area of glacierization of the Tien Shan in the boundary area of the USSR is about 8000 km^2. The computation of mass balance was determined for this area in 12 river basins.

In computation procedure, the vertical profile of snow accumulation in these regions and exponential dependence of variation of ablation with altitude are used. Thus the mass balance in each basin, b_n, was calculated on the basis of these curves and represented in its relation with the equilibrium line altitude (ELA). It is shown that the relation ELA = $f(b_n)$ is linear when the range of b_n values is close to zero, and in all altitude intervals this relation can be described by hypsographic curves. in all basins b_n is positive up to an ELA elevation of 3450 to 3500 m a.s.l. For average annual altitude of ELA, b_n is negative for all regions. So the glaciers of these mountains add about 4 km^3 of water to the total annual runoff.

INTRODUCTION

Connected with global processes of climate warming and weathering, it is important to estimate the changes of ice reserves and their impact on variations of river runoff and water balance of lakes in Central Asia. For this reason we should find out not only the mass balances of single glaciers, but also of their groups, glacierization of ranges, mountain-glacier basins and the glaciers' systems as a whole. This task needs to be resolved in different ways:

1. For example, with the help of standard meteorological data
– for glacierization of Lemon Creek basin (Tangborn, 1980);
– for glacierization of Central Asia river basins (Konovalov, 1985; Glazyrin, 1985; Ratsek, 1991);

2. According to the data of repeated aerophototopographical surveys, for example:
– for glacierization of the Akshiyrak Range (Kuz'michenok, 1989);

3. By solving the water balance equation, for example:
– for the basin of the grand Aletch glacier (Kasser, 1959);
– for glacierization of Jostedalsbreen (Rogstad, 1951);

4. According to the glaciological data of measurements of mass balance, b_n, ELA, accumulation area ratio (AAR), for example:
– for the glacierized part of Alaska (Meier and Post, 1962);
– for the whole "minor" glacierization of the Earth (Meier, 1984);
– for the group of the Northern Cascade glaciers (Pelto, 1987);
– for the basins of the Caucasus and Tien Shan (Dyurgerov, 1984, 1988; Dyurgerov and Mikhalenko, in press);
– for the glacier basins of the Alps (Chen and Ohmura, 1990).

Mass-balance estimations are presented for the Tien Shan glacier area of the USSR, that is about 8000 km^2. Only the data of distribution of winter mass balance in dependence of altitude and the values of glacierization square in each basin were used. Such an approach allows one to estimate the changes in ice supply and contribution of glaciers to the river runoff in the large glaciated mountain basins. Exact calculations using experimental data, which can be carried out for individual glaciers, are not possible in these mountain basins.

The highland regions of the Tien Shan represent the source area of the largest Central Asian rivers. For this reason the question of mass-balance estimation and glacier runoff is interesting from the scientific as well as the practical point of view.

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Table 1. Glacier area (km^2) distribution by altitude

Altitude interval m	*Chu*	*Chu upper course*	*Talas*	*Atbashy*	*Chirchik*	*Kara-daria*	*Narin upper course*	*Narin*	*Ily*	*Issik-Kul*	*Sari-Djas*	*Aksu*	*Sum* km^2
7500–7000											0.55	0.17	
7000–6500											4.28	0.20	5.05
6500–6000									0.36		34.08	34.10	34.44
6000–5500						0.12			1.80		122.50	8.59	132.99
5500–5000						4.33	2.03		11.50	0.36	239.80	38.50	296.50
5000–4800	0.23			0.14		13.10	3.99		9.34	0.83	126.40	77.30	231.31
4800–4600	2.34	0.32		1.45		56.60	30.80		11.40	5.74	139.60	194.00	442.40
4600–4400	8.68	1.11		7.26		141.00	139.39	0.26	23.40	28.80	142.00	397.00	890.06
4400–4200	35.90	5.24	1.72	22.35	0.39	237.00	305.63	1.66	65.80	84.80	130.80	597.00	1487.80
4200–4000	120.00	26.52	10.79	45.51	5.59	242.00	324.25	10.29	152.00	179.10	110.70	502.00	1728.50
4000–3800	208.00	55.24	40.67	30.17	32.20	149.00	148.09	33.35	218.00	173.20	76.03	245.00	1474.10
3800–3600	195.00	17.20	62.13	5.95	66.68	75.40	19.24	55.51	183.00	59.63	39.16	69.50	916.07
3600–3400	53.40	0.86	39.00	0.75	50.78	31.20	1.56	29.53	71.40	10.98	20.16	7.92	336.27
3400–3200	9.75		9.22	0.10	19.82	14.40		4.23	8.84	1.39	11.03	0.39	83.79
3200–3000	1.32		1.01		3.29	5.19		1.39	0.68		6.48		20.55
3000–2400	0.62				0.26	2.43		0.40			2.21		5.92
Sum, km^2	635.00	106.49	164.50	113.70	179.01	971.00	974.98	136.60	723.00	703.20	1206.00	3344.00	8051.70

REGIONAL CHARACTERISTICS

Glacierization in the Tien Shan is unequally distributed over the territory and river basins. It is documented, in particular, by the data of distribution of the glacial area altitudes (Table 1). Most of the information on glacierization used in this work is published in the USSR Glacier Inventory (Gidrometeorologicheskoye Izdatel'stvo 1969–1978). The regime of glaciers in the northwest and west parts of the inner Tien Shan has been well studied. Glaciers in these outlying areas have a greater energy balance owing to greater precipitation and more active ablation than in the inner Tien Shan. Considerable ablation values are determined by less absolute altitudes.

There is little information about glacierization in the inner Tien Shan. In the basins of Sarydjaz, Kokshaal, and Aksu rivers are concentrated more than 3000 km^2 of glacier area. But measurements of mass balance in the highest parts of compact glacierization are very scarce (Dekikh, 1982). There are also no meteorological data.

Winter mass balance in these basins was measured in 1991 by an expedition from the Laboratory of Mountain Glaciology of the Institute of Geography and this enabled a calculation to be made for all glacierization of Soviet Tien Shan.

METHOD

The process of glacierization of each basin may be represented as a distribution of altitudinal glaciered area, that is as one hypsographic curve, because the altitude is the main parameter of mass-balance variation.

To estimate the mass balance, data of measurements of winter mass balance, b_w, on the glaciers, snow accumulation over the snow measuring routes and meteorological data were used (Table 2). this information served for dependencies plotting $b_w(Z)$ in the river basins.

The computation was produced according to the data of the USSR Glacier Inventory (Gidrometeorologicheskoye Izdatel'stvo 1969–1979). The Tien Shan area was divided into five main basins: Lake Issikkul, Lake Balkhash, the Aral Sea, the Talas and Chu rivers, and the river Aksu. To estimate the mass balance, 240 minor river basins within five main basins were originally chosen from the Glacier Inventory (Kuz'michenok, 1989). They were then classified on the basis of two indices:

- similarity of hypsographic curves of glacierization;
- distribution of snow accumulation, depending on altitude (Getker, 1985).

These two indices are used in the estimation. As a result, 12 river basins with homogeneous mass balance conditions (Fig. 1, Table 1) were selected.

Thus each basin is described by two curves: $b_w(Z)$ and $b_s(Z)$ (at 100 m altitude intervals). Basin glacierization is considered as a single glacier with complete collection of exposition, as established in previous studies (Dyurgerov, 1984, 1988; Mikhalenko, 1990).

Table 2. Winter mass-balance distribution by equilibrium line altitude

Altitude m	Chu, upper course	Chu	Talas	Atbashy	Chirchik	Kara-daria	Narin	Narin, upper course	Ily	Issyk-Kul	Aksu	Sari-Djas
4850											840	816
4750								850			670	695
4650								850			650	565
4550								845			326	452
4450								845			120	324
4350								510			170	252
4250	410	450						470			100	180
4150	390	430		700			930	415	430	340	80	216
4050	350	400	500	650			900	350	510	330	60	200
3950	295	365	420	490			850	250	705	315	35	180
3850	240	315	360	430	1330		810	180	880	300	15	150
3750	190	275	310	380	1300		770	120	630	290	10	120
3650	150	235	270	330	1260	1140	725	70	505	275	5	90
3550	130	200	240	300	1200	1020	675	30	450	260	3	80
3450	120	170	220	270	1125	910	620	20	380	240	3	70
3350		145	195	240	1055	800	560		355	225		60
3250		120	175		990	700	495		335			50
3150		100	95		940	620	425		320			40
3050		90	80		900	550	350		310			30
2950		85			830	495	280					20
2850		75				445						10
2750		65				405						
2650						375						
2550						350						
2450						320						

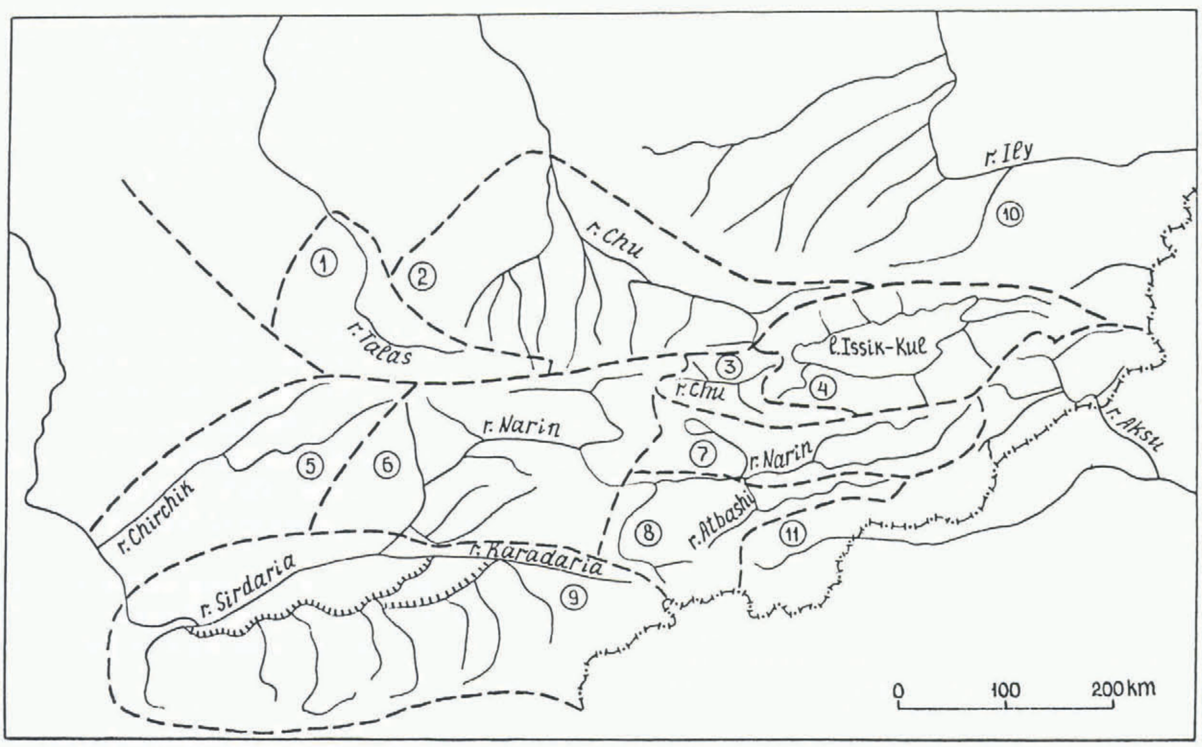

Fig. 1. Sketch map of Tien Shan glacier regions: 1: Talas; 2: Chu; 3: Chu upper course; 4: Chirchik; 5: Issik-Kul; 6: Narin; 7: Narin upper course; 8: Karadaria; 9: Atbashy; 10: Ily; 11: Aksu.

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These curves also serve for computation of snow ablation and for definition of ELA on the glacier.

The ablation curve form, or b_s (summer mass balance), is stable for the distinct morphographical glacier types (Krenke and Menshutin, 1987) and appears as a concave curve (Khodakov, 1965). Normalized ablation values (0 to 1) for each moment, j, are described by the exponential $b_{s_{ij}} = a_j e^{-h_i}$, where a_j is a coefficient, and h_i is normalized (0 to 10) altitude:

$$h_i = 10\left[\frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}}\right],$$

where $Z_{\min}$, $Z_{\max}$ represent the upper and lower lines of Tien Shan glacierization and represented the mean quantity of each altitude interval. This calculation method was described by Kunakhovitch (1991).

Then b_s of altitude interval i may be represented as

$$b_{s_{ij}} = a_j \mathrm{e}^{-10\left[\frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}}\right]}.$$

Coefficient a_j in each moment j is constant for the whole basin (but coefficient a_j is changing during the ablation season) and is calculated according to the altitude interval i, supposing that the equilibrium line is located there. Under this condition $b_{n_i} = b_{s_i} + b_{w_i} = 0$, so $b_{s_i} = b_{w_i}$ and $a_j = b_{w_i}/\mathrm{e}^{-h_j}$.

As an example, Figure 2 shows the computed variation b_s with altitude for Golubina glacier according to measurement data for five years (Haeberli and Müller, 1988).

The mass-balance values $b_{n_{ij}}$ in each interval i were estimated for each ELA by the formula:

$$b_{n_{ij}} = b_{w_i} + a_j \mathrm{e}^{-10\left[\frac{X_i - Z_{\min}}{Z_{\max} - Z_{\min}}\right]}.$$

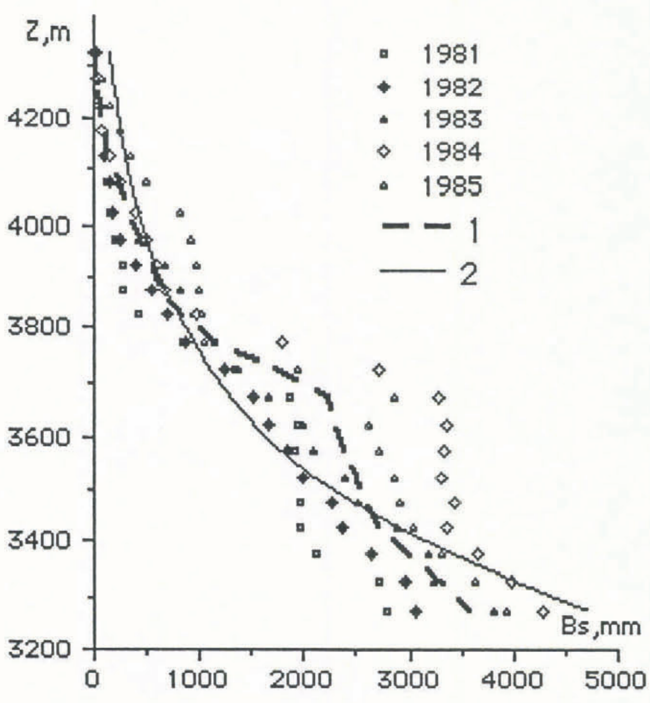

Fig. 2. Annual ablation of Golubina Glacier versus altitude: 1: mean experimental values for 5 years; 2: calculated values.

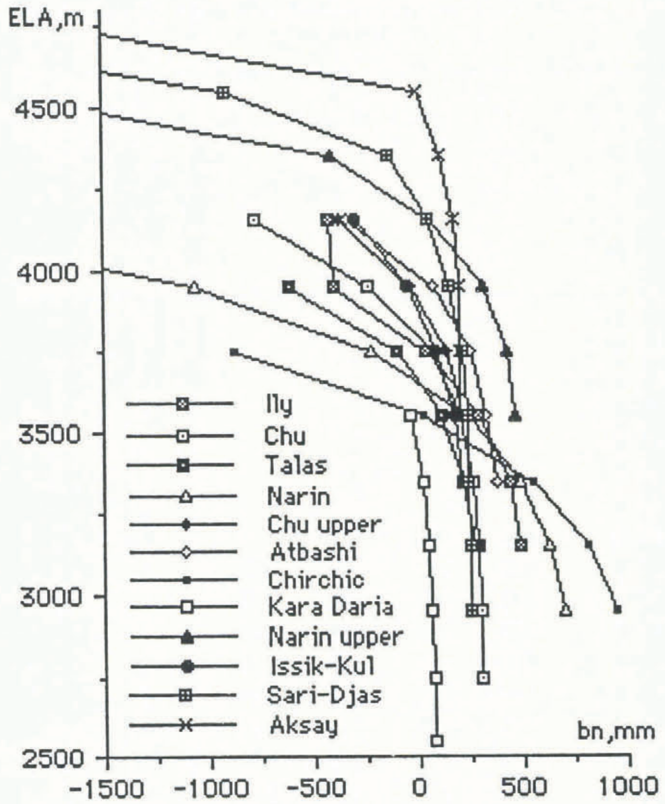

Fig. 3. Calculated curves of the mass balance–equilibrium line altitude relation ELA(b) for 12 regions.

Then a specific mass balance of all glacierization b_{n_j} is computed as:

$$b_{n_j} = \sum_{i=1}^{n}\left(b_w(Z) + a_j \mathrm{e}^{-10\left[\frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}}\right]}\right)\frac{s_i}{S},$$

where S is the total glaciated area, represented by the hypsographic curve, s_i is the area of every altitude zone, and n is the number of altitude intervals.

Thus, from the data for the two curves $b_w(Z)$ and $b_s(Z)$, $b_n = f(\mathrm{ELA})$ for each basin (Fig. 3, Table 3).

RESULTS

The spatial mass-balance variations are considerable. As it is demonstrated in Table 3, the mass balance is positive in all basins until an ELA altitude of 3450 to 3500 m a.s.l. and it is negative, when the ELA is higher than 4200 m a.s.l. The zero b_n value corresponds to average long-term equilibrium line altitude, ELA. Three regions can be distinguished according to the ELA meanings.

1. Outlying districts of west and northwest Tien Shan (basins of Chirchik, Talas and Karadarya rivers, Chu River middle course), with ELA at 3500 to 3800 m a.s.l.;

2. Inner Tien Shan (basins of Atbashi, Ili Rivers, Issikkul lake, Narin River middle course, Chu River upper course) with ELA at 3800 to 4000 m a.s.l.;

Table 3. Mass-balance distribution (cm W.E.) by equilibrium line altitude

Altitude m	*Chu*	*Chu upper course*	*Talas*	*Atbashy*	*Chirchik*	*Kara-daria*	*Narin upper course*	*Narin*	*Ily*	*Issik-Kul*	*Sari-Djas*	*Aksu*
4950												−4227
4850											−4372	−2452
4750							−3711				−2777	−1732
4650							−2745				−1642	−525
4550							−1987				−915	3
4450							−1420				−393	−10
4350							−409			−135	110	
4250	−1166	−577					−154		−630		37	148
4150	−775	−376		−332			45	−2587	−427	−305	53	173
4050	−468	−194	−1116	−142			193	−1736	−342	−162	109	191
3950	−237	−43	−616	78			316	−1058	−397	−49	152	201
3850	−55	67	−306	178	−1522		383	−578	−359	34	186	203
3750	63	143	−103	247	−869		423	−223	43	92	210	204
3650	146	191	28	298	−366	−77	446	42	229	138	226	205
3550	200	216	113	330	28	−32	459	240	290	172	232	205
3450	236	2231	166	353	328	0	462	386	409	198	237	
3350	260		207	371	545	24		493	441	215	241	
3250	276		234		700	42		572	465		243	
3150	286		269		809	53		628	483		245	
3050	292		278		887	62		668	495		246	
2950	295				950	67		695			246	
2850	298					72					247	
2750	300					74						
2650						76						
2550						78						

3. The highland part of glacierization of the central Tien Shan (basins of Sari-Djas, Aksay rivers, Narin river upper course) with ELA 4200 to 4500 m a.s.l.

These three regions have great differences in $b_n = f(\text{ELA})$ curves (Fig. 3). The first district line has considerable inclination. The differences are determined by the variations of snow accumulation and ablation. The west Tien Shan has a more humid and warm climate, because of the influence of strong west winds and lower altitude.

The most stable conditions are in the highland part of compact glacierization of the central Tien Shan. The b_n gradient here is small with the ELA at 4400 m, then it becomes greater, because of larger accumulation.

In the middle group the mass turnover is minimum, owing to the continental climate of this area.

The ELA is lower than average long-term ELA, determined by Kurovskiy's method for about 100 m. Thus b_n is negative, when the ELA is equal to Kurovskiy's altitude that testifies the trend to a reduction in glacierization. In this case we have $b_n = -48$ mm, so the additional glacial runoff related to negative balance corresponds to about 3.88 km^3 a^{-1} from an area of about 8000 km^2.

Mass-balance variations between basins are not large when the mass-balance values are positive (or with low position of ELA). In warm and dry years we may expect the biggest variations of ELA and b_n altitudes in different basins.

DISCUSSION

The applied method of estimation permits computation not only of the average multi-annual values, but also the annual ones of mass balance with the ELA data.

As it is shown in Figure 3, in the altitudinal range of ELA equal to 3200–3800 m a.s.l., all relation points of $\text{ELA} = f(b_n)$ may be approximated as linear, but in general the dependencies are not linear. In previous studies (Dyurgerov, 1988; Mikhalenko, 1990; Kunakhovitch, 1991), it was shown that the relation of $\text{ELA} = f(b_n)$ may be approximated by hypsographical curves, if the linear relation $\text{AAR} = f(b_n)$ holds. The superimposition of the curves $\text{ELA} = f(b_n)$ on the hypsographical ones (Fig. 4) shows that, for the Tien Shan regions, this is correct. The convergence degree of estimated data of $\text{ELA} = f(b_n)$ with hypsographical curves may serve as an index of computational quality and used for basic data with $b_w = f(Z)$ initially.

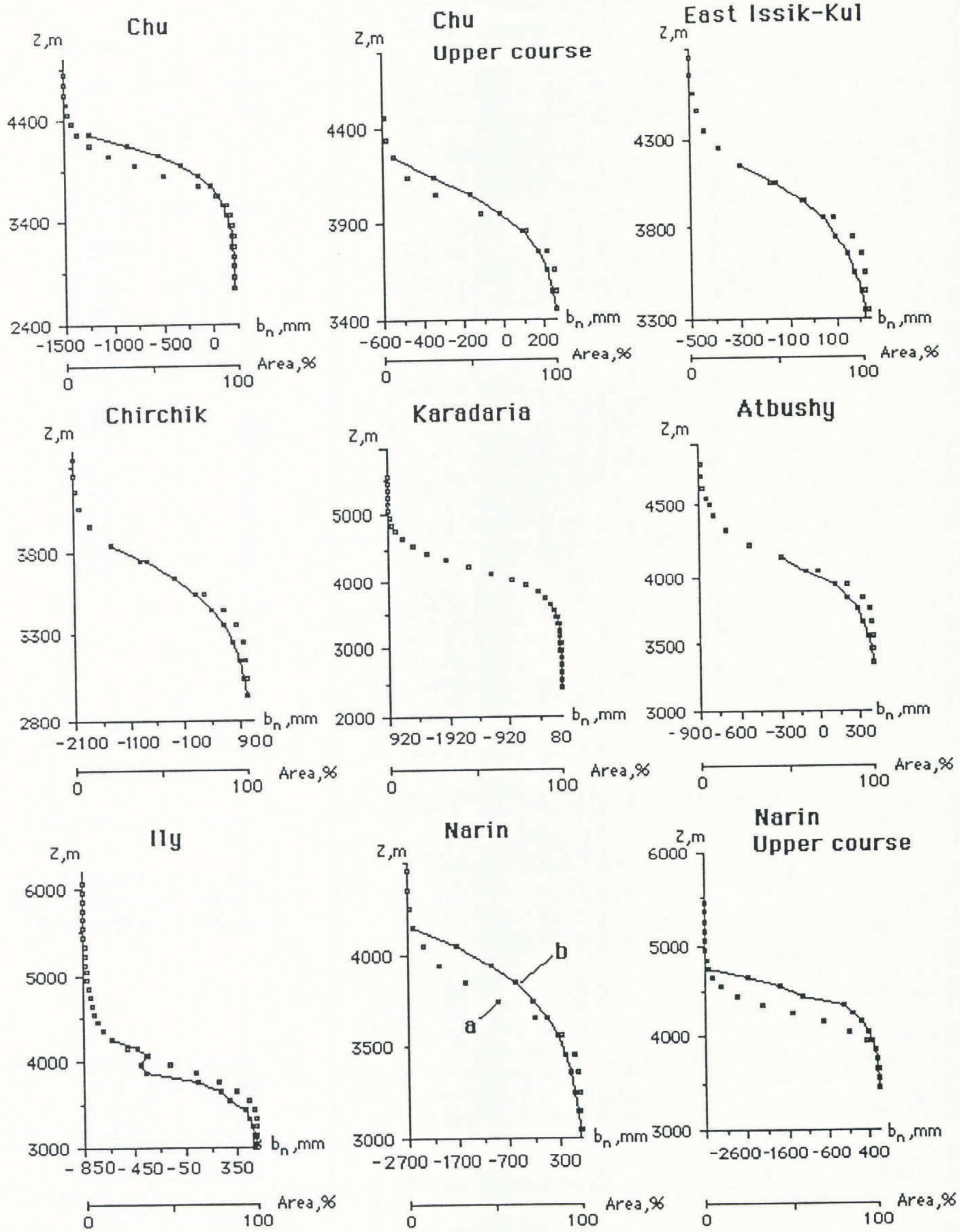

Fig. 4. Hypsographic and ELA(b) curves for 9 regions: a, hypsographic curve; b, ELA(b).

The completeness and reliability of knowledge about glacierization regime and mass balance of the Tien Shan in general, depends on information on the ELA and most high parts of the glaciated area in the basins of the Sari-Djas, Kokshaal and Aksu rivers.

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