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Mass-balance variability as a base for interpreting ice-core data

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ABSTRACT. The spatial extrapolation of data from ice cores depends on the complexity of the glacier system where the drilling site is located. The correlation between net mass balance, b_n, of a specific point and of the whole glacier is different for each point. Analysis of net mass balance of Tuyuksu glacier in the Tien Shan, central Asia, confirms that the distribution of mass balance with height is more-or-less constant from year to year except in years with extreme values of b_n. Two types of "similarity" are described, additive and multiplicative. The "similarity" changes gradually from additive at the peripheral parts of the Tien Shan to multiplicative in the most continental central and eastern parts. Glacier mass-balance fluctuations of the frontal ridges are connected to the oscillations of accumulation and consequently to precipitation. Where the climate is more continental the mass-balance variability depends much more on the melting conditions than on accumulation. For the spatial interpretation of ice-core drilling results, a special analysis of "similarity type" is necessary. It allows the fixing of the spatial borders of the glacier system for which the drilling site is representative.

INTRODUCTION

Data from accumulation areas of glaciers can give information relevant to different fields of science.

The spatial interpretation of ice-core results depends a lot on the complexity of the glacier system drilled. The most important factor is the location of the drilling site. The spatial variability of mass-balance components in the glacier system is also significant.

LOCATION OF THE DRILLING SITE

Accumulation and precipitation estimated from a mountain glacier ice core are representative only of a limited area around the drilling site. In contrast to Antarctic and Greenland ice sheets, isolines of the mass balance of the mountain glaciers have a complicated character (Haeberli and Herren, 1991), depending on the surface topography, proximity to surrounding ranges and other factors. The simplest mass-balance isolines are found in circular ice caps and domes.

Consider the 35 year record of the Tuyuksu valley glacier in the Tien Shan, central Asia. Mass balance measured in the four upper zones of the glacier (b_{ni}) and over the whole glacier (b_{ng}) were correlated (see Fig. 1). That in the top zone, where steep slopes surround the glacier basin, correlates worst of all with the balance of the whole glacier. Towards the middle part of the glacier (i.e. towards the equilibrium-line altitude), b_{ni} becomes closer to b_{ng} as indicated by the angle of curves in Figure 1. The b_{ni}/b_{ng} correlation coefficient increases at the same time. Mass balance of this zone is equal to the mass balance of the whole glacier.

Such correlations are not identical for every glacier. In each case it is necessary to consider the ratio between b_{ni} at the drilling site and b_{ng} of the whole glacier or glacier system. Two important problems arise:

1. Is there a relation (linear in the simplest case) which allows the transfer of correlations from one field to another, and is the relation stable in time? Researchers analyzing the ice-cores suppose that such similarity occurs.

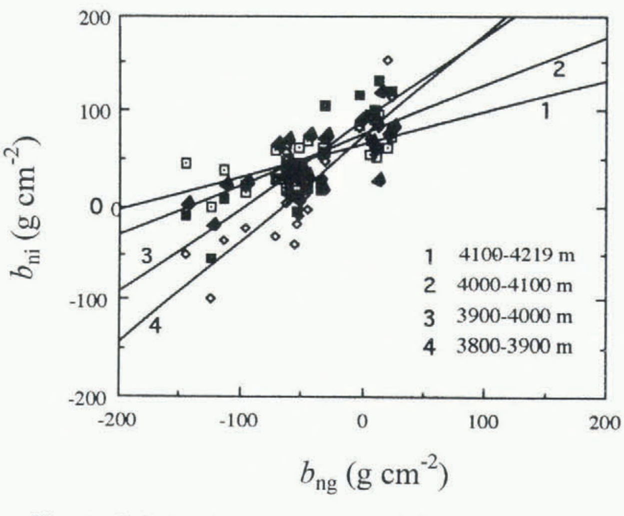

Fig. 1. Relation between net mass balance of different parts of the accumulation area of Tuyuksu glacier, b_{ni}, and average net mass balance of the whole glacier, b_{ng}.

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2. How do the mass-balance components of separate glaciers change within the borders of a glacier system?

SIMILARITY OF MASS-BALANCE FIELDS

Similarity of mass-balance fields (position of isolines of net mass balance at the glacier) was first mentioned by Ahlmann (1948). He found that the annual mass-balance curves (b_n vs altitude) of the southern Norwegian glaciers were parallel in different years. Thus the mass balance for any one year can be determined by observing only one site if the shape of the mass-balance curve is known. Meier (1962) considered the parallel balance curves of South Cascade Glacier to be a common peculiarity of all glaciers. Lliboutry (1974) worked out a more general model and postulated that the temporal variations of mass balance were similar from one point to another. This model was extrapolated to an overall glacier system where the individual glacier data were taken as points (Reynaud, 1980; Reynaud and others, 1986). The same method was applied to compare the temporal variability of glacier mass balance in the Alps, Scandinavia and the Tien Shan (Reynaud and others, 1984). There was an attempt to analyze statistically the annual balance curves and to check the hypothesis on the parallelism of the balance curves. Dyurgerov and others (1989) ascertained that this parallelism does not hold for all glaciers.

The mass-balance field is determined mainly by the accumulation field which is determined by the glacier surface topography. The ablation field is more regular and depends mainly on altitude. There can be two representations ("similarity types") of the mass-balance field according to Kunakhovitch (1991). The "additive similarity" is typical of relatively low glaciers and maritime glaciers. Its characteristic is parallelism of the mass-balance curves. The "multiplicative similarity" is typical of continental glaciers and those which occupy a large altitude range. Figure 2 shows examples of both.

The "additive similarity" from year to year of the mass-balance field of Tuyuksu glacier can be seen in Figure 3. However, as mentioned by Kuhn (1986), in some extreme years the character of additivity is broken. The correlation coefficient r between the balance curves for different years was used as a criterion of additive similarity (Table 1). Values of r less than 0.900 were taken as extreme cases. Examples are years with extremely negative mass balance (1978, 1984) or extremely positive mass balance (1969, 1981). They correspond well with Kuhn's conclusion.

VARIABILITY IN A GLACIER SYSTEM

It is difficult to find a glacier system where the mass-balance field is uniform over all glaciers. Glaciers in different parts of a mountain region react variously to climate changes. For example, warming in southern Norway led to positive balances for coastal glaciers from 1961 till 1990 but to negative balances for inland glaciers (Dyurgerov and Mikhalenko, 1989).

Four glaciers in the Tien Shan have been observed for more than 30 years (see Fig. 4). The observations allow both the temporal variability of accumulation and ablation and changes in spatial characteristics to be considered.

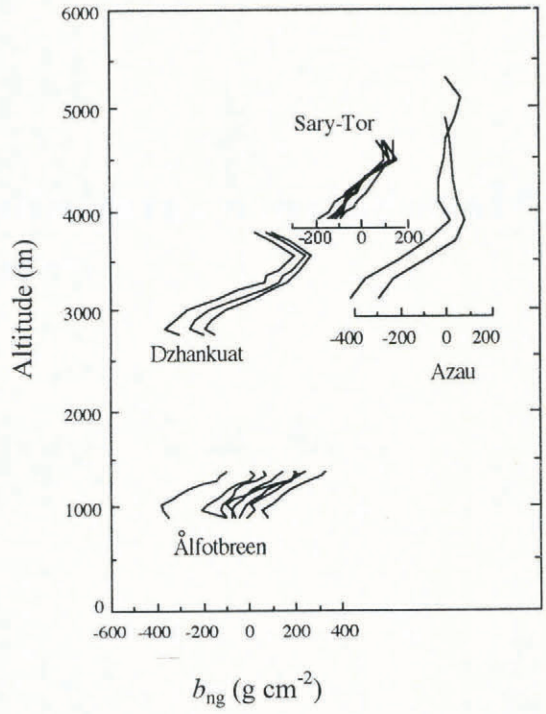

Fig. 2. Typical mass-balance curves for Ålfotbreen (southern Norway), Dzhankuat (central Caucasus), Azau (Elbrus massif, central Caucasus) and Sary-Tor (Tien Shan interior) glaciers.

The largest negative mass balances and annual variability are along the ridges in the northern and western Tien Shan which have the greatest precipitation (Table 2). The relation between accumulation and ablation for the three glaciers observed the longest is shown in Figure 5. They have had a negative balance for the last 30 years. The absolute mass balance decreases gradually towards the centre, reaching the minimum negative value at glacier No. 1. This is because summer precipitation increases as one goes towards glaciers which are more continental. Also, the "similarity type" changes from "additive" to "multiplicative" as the glaciers become more continental.

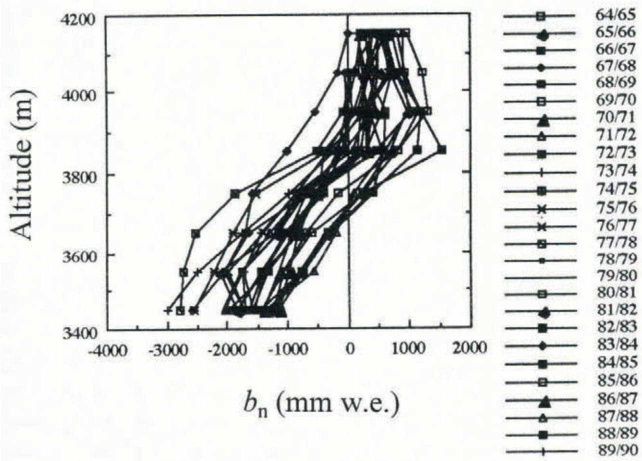

Fig. 3. Mass-balance curves for Tuyuksu glacier, 1964–90.

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Table 1. Correlation coefficients of mass balance vs altitude curves for the Tuyuksu glacier for 1965–1990 (b_n, annual net mass balance, mm w.e.)

	b_n	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
1965	–50	1.000																									
1966	40	0.970	1.000																								
1967	230	0.971	0.995	1.000																							
1968	–780	0.973	0.988	0.986	1.000																						
1969	210	0.943	0.973	0.987	0.958	1.000																					
1970	110	0.988	0.987	0.979	0.987	0.939	1.000																				
1971	–360	0.987	0.944	0.937	0.962	0.902	0.978	1.000																			
1972	130	0.962	0.978	0.962	0.976	0.934	0.977	0.962	1.000																		
1973	–290	0.989	0.979	0.970	0.971	0.944	0.987	0.981	0.986	1.000																	
1974	–620	0.967	0.899	0.895	0.933	0.847	0.954	0.989	0.917	0.945	1.000																
1975	–450	0.949	0.934	0.916	0.964	0.866	0.967	0.977	0.964	0.953	0.967	1.000															
1976	–720	0.956	0.895	0.881	0.924	0.818	0.953	0.978	0.918	0.939	0.992	0.972	1.000														
1977	–1100	0.977	0.923	0.914	0.947	0.875	0.964	0.996	0.955	0.972	0.989	0.974	0.982	1.000													
1978	–1480	0.967	0.897	0.893	0.932	0.850	0.947	0.987	0.924	0.947	0.993	0.960	0.982	0.993	1.000												
1979	–520	0.977	0.940	0.926	0.957	0.879	0.972	0.986	0.968	0.976	0.975	0.975	0.979	0.992	0.983	1.000											
1980	–630	0.983	0.970	0.979	0.975	0.975	0.967	0.964	0.957	0.974	0.932	0.929	0.911	0.950	0.935	0.949	1.000										
1981	110	0.917	0.975	0.974	0.974	0.953	0.945	0.881	0.942	0.921	0.837	0.899	0.836	0.861	0.840	0.894	0.937	1.000									
1982	–690	0.985	0.944	0.945	0.961	0.913	0.970	0.980	0.939	0.964	0.977	0.957	0.971	0.974	0.970	0.974	0.976	0.902	1.000								
1983	–550	0.964	0.961	0.947	0.981	0.906	0.978	0.974	0.979	0.968	0.956	0.991	0.961	0.970	0.953	0.982	0.958	0.938	0.972	1.000							
1984	–1250	0.891	0.788	0.772	0.835	0.706	0.869	0.937	0.842	0.869	0.969	0.924	0.975	0.956	0.967	0.942	0.837	0.715	0.920	0.900	1.000						
1985	–550	0.942	0.936	0.911	0.958	0.850	0.967	0.964	0.969	0.954	0.950	0.992	0.966	0.965	0.949	0.979	0.910	0.905	0.940	0.986	0.913	1.000					
1986	–520	0.992	0.957	0.958	0.972	0.929	0.981	0.988	0.952	0.975	0.979	0.964	0.969	0.980	0.973	0.977	0.983	0.912	0.998	0.976	0.913	0.947	1.000				
1987	–340	0.994	0.957	0.965	0.967	0.950	0.981	0.984	0.950	0.979	0.964	0.939	0.940	0.974	0.967	0.963	0.989	0.903	0.980	0.953	0.882	0.920	0.989	1.000			
1988	–610	0.988	0.963	0.960	0.984	0.928	0.985	0.992	0.970	0.979	0.978	0.982	0.969	0.986	0.977	0.985	0.979	0.925	0.988	0.989	0.913	0.968	0.994	0.985	1.000		
1989	–460	0.983	0.964	0.958	0.979	0.929	0.981	0.987	0.973	0.980	0.968	0.979	0.964	0.979	0.963	0.981	0.981	0.925	0.990	0.991	0.905	0.965	0.993	0.979	0.996	1.000	
1990	–960	0.984	0.982	0.971	0.989	0.933	0.996	0.983	0.985	0.987	0.959	0.982	0.960	0.973	0.955	0.982	0.971	0.946	0.977	0.993	0.887	0.980	0.985	0.971	0.992	0.992	1.000
mean	–374																										

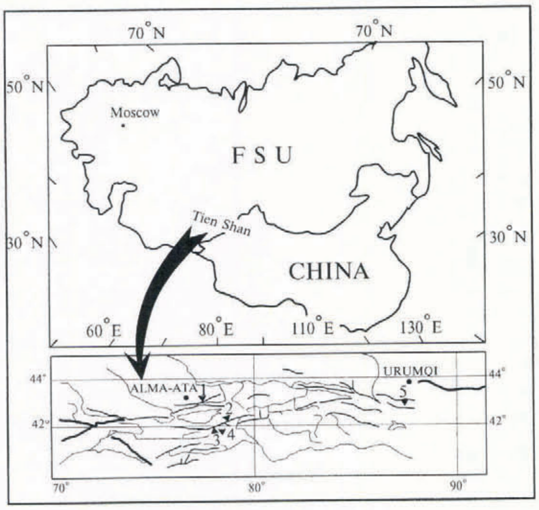

Fig. 4. Locations of the investigated glaciers: 1, Tuyuksu; 2, Karabatkak; 3, Gregoriev; 4, Sary-Tor; 5, glacier No. 1.

Table 2. Mass-balance components of the Tien Shan glaciers: c_t annual net accumulation; a_t annual net ablation; b_n annual net mass balance (mm w.e.)

	Tuyuksu			Karabatkak			Glacier No.1		
Year	c_t	a_t	b_n	c_t	a_t	b_n	c_t	a_t	b_n
1957	1070	−1220	−150	548	−579	−31			
1958	1250	−920	330	728	−666	62			
1959	970	−1390	−420	737	−1081	−344	543	−456	87
1960	1090	−1190	−100	666	−957	−291	608	−796	−188
1961	920	−1480	−560	474	−1280	−806	630	−663	−33
1962	870	−1560	−690	656	−742	−86	624	−791	−167
1963	1290	−850	440	666	−706	−40	633	−399	235
1964	1320	−800	520	893	−749	144	589	−587	2
1965	1160	−1210	−50	711	−752	−41	650	−276	375
1966	1120	−1080	40	879	−1035	−156	511	−885	−374
1967	1280	−1050	230	796	−786	10	608	−678	−69
1968	810	−1590	−780	613	−1265	−652	545	−1001	−457
1969	1210	−1000	210	665	−665	0	647	−499	148
1970	1130	−1020	110	619	−801	−182	539	−852	−313
1971	980	−1340	−360	722	−574	148	625	−523	102
1972	970	−840	130	610	−557	53	669	−407	262
1973	1010	−1300	−290	496	−1249	−753	503	−1211	−707
1974	790	−1410	−620	632	−683	−51	606	−720	−24
1975	950	−1400	−450	505	−980	−475	747	−459	306
1976	780	−1500	−720	444	−1285	−841	517	−488	29
1977	850	−1950	−1100	371	−1235	−864	714	−534	180
1978	790	−2270	−1480	406	−1582	−1176	441	−551	−110
1979	930	−1450	−520	573	−1074	−501	462	−546	−76
1980	880	−1510	−630	670	−1034	−364	390	−725	−337
1981	1100	−990	110	577	−1024	−447	536	−1188	−655
1982	890	−1580	−690	323	−1107	−784	656	−701	−49
1983	1170	−1720	−550	211	−1159	−948	668	−568	96
1984	710	−1960	−1250	235	−1807	−1572	455	−538	−83
1985	770	−1320	−550	263	−1555	−1292	478	−1090	−612
1986	1130	−1650	−520	663	−1055	−392	482	−1151	−669
1987	930	−1270	−340	432	−1114	−682	474	−650	−175
1988	1090	−1700	−610	791	−1247	−456	463	−1106	−644
1989	820	−1280	−460	691	−1087	−396	578	−473	108
1990	920	−1880	−960	730	−1508	−778	596	−544	52
1991							456	−1162	−706
1992							605	−587	18
Mean	999	−1373	−374	762	−1160	−398	565	−704	−135
S.d.	169	349	48	175	314	435	88	262	308
C_v	0.17	−0.25	−0.13	0.23	−0.27	−1.09	0.16	−0.37	−2.27

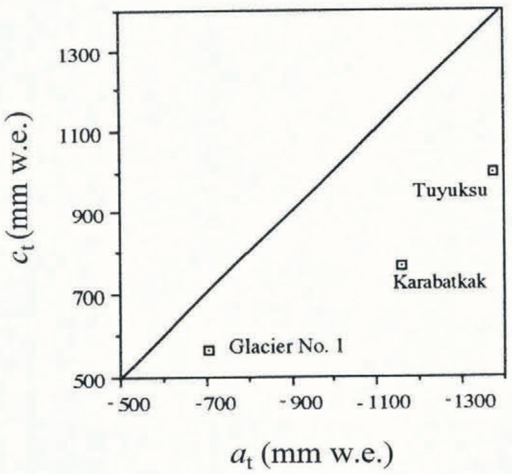

Fig. 5. Relation between annual net accumulation c_t and annual net ablation a_t of the Tien Shan glaciers, 1959–90.

The characteristic mass-balance curves for some glaciers are shown in Figure 6. The "additive similarity" is observed at all altitudes for Tuyuksu glacier. For the Gregoriev ice cap in the Tien Shan interior, the additive similarity is observed in the ablation zone, and the multiplicative similarity in the accumulation zone. The similarity type becomes closer to the additive in years of negative mass balance and to the multiplicative in years of positive mass balance.

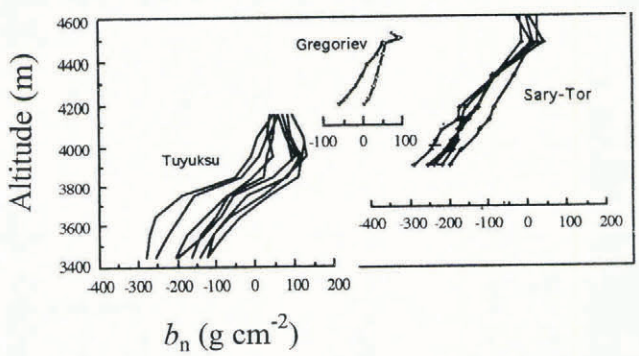

Fig. 6. Change of similarity type of mass-balance field of the Tien Shan glaciers from the periphery to the interior part of the mountain system.

In general, it can be said that all maritime glaciers are "additive", while continental glacier systems can be a mixture of "additive" and "multiplicative" glaciers. Therefore, correlations between maritime glaciers will be stronger (and operate over larger areas) than will the correlations associated with continental glaciers (Table 3).

The contribution of ablation variation to the annual mass balance is greatest for glacier No. 1 and is typical of the continental eastern Tien Shan. It is shown by the correlation triangle of Figure 7. The lengths of its sides are proportional to the standard deviation of the corresponding values. The cosine of the angle between any two sides is equal to the correlation coefficient r. For example, the cosine of the angle opposite to the base is equal to the correlation between accumulation and ablation. The

Table 3. Correlation coefficients of annual net mass balance of the Tien Shan glaciers, 1959–90

Glacier	*Tuyuksu*	*Karabatkak*	*Glacier No. 1*
Tuyuksu	1.000		
Karabatkak	0.743	1.000	
Glacier No. 1	0.075	0.238	1.000

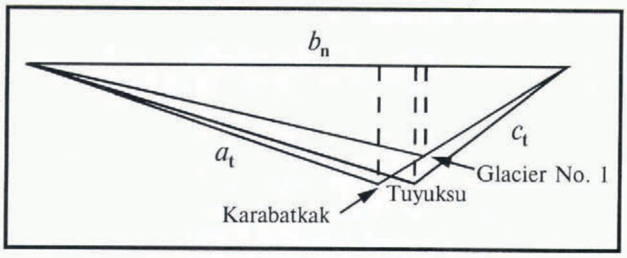

Fig. 7. Input of variability of net accumulation c_t and net ablation a_t of the Tien Shan glaciers into variability of mass balance for the period 1959–91.

apex projection on the base defines the ratio of accumulation and ablation variabilities contributing to the total mass-balance variability.

In summary, ablation variability is most significant for glacier No. 1, is less for Tuyuksu glacier and is least for Karabatkak glacier (see Fig. 7). The heavier the annual precipitation and the less the input of summer accumulation, the lower is the correlation between annual accumulation and ablation. Nevertheless, the close correlation between accumulation and ablation is typical for all Tien Shan glaciers as both processes occur simultaneously, with the maximum rate in the warm season (Dyurgerov and others, 1994).

CONCLUSIONS

For the spatial interpretation of ice cores, a special analysis of the "similarity type" of mass balance is necessary. This allows fixing the spatial borders of the glacier system for which the drilling site is representative. Such analyses require special drilling in regions where there are long records of temperature, precipitation and mass balance. These are few. In the former Soviet Union they are the Katyn and Karaugom plateaus in the Caucasus, the Gregoriev and It-Tysh ice caps in the central Tien Shan and the Pamir firn plateau in the central Pamir at an altitude above 6000 m.

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