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Correlations between glacier properties: finding appropriate parameters for global glacier monitoring

MARK B. DYURGEROV, DAVID B. BAHR
Institute of Arctic and Alpine Research, Campus Box 450, University of Colorado–Boulder, Boulder, Colorado 80309-0450, U.S.A.

ABSTRACT. To develop new strategies for global mass-balance monitoring, data for the period 1961–90 have been compiled for 80 glaciers with a variety of mass-balance and morphological parameters. This dataset is significantly larger than that used in previous studies. This allows us to check the mass-balance data for both strong and weak correlations with different glacier parameters. In many cases, the strong correlations suggest new approaches to monitoring glaciers on a global scale. For example, the mass balance at the terminus is strongly correlated with the difference in elevation between the terminus and the glacier's mean elevation. These easily measured parameters could be particularly useful in assessing maximum ablation and meltwater potential based on altitudes derived from maps and photographs. Good correlations also exist between differences in mass-balance parameters (e.g. net balance minus terminus balance) and several other morphological properties (e.g. elevation range and length). Equally important, the weak correlations demonstrate that some relationships commonly used on individual glaciers are not appropriate when considering global monitoring strategies. For example, the correlation between net mass balance and terminus balance is very poor. Likewise, the correlation between the net mass balance and equilibrium-line altitude is weak, and the correlation between the net mass balance and activity index is almost non-existent. This suggests that although these climatically sensitive parameters may be closely related on individual glaciers, these same relationships are not reliable as tools for monitoring glaciers on a global scale.

INTRODUCTION

Glaciers act as reservoirs, storing and releasing water with changes in local, regional and global climate. As such, tracking a glacier's change in shape and volume with time can provide valuable information about current climatic conditions and the response to previous changes in climate on time-scales of years to centuries (e.g. Meier, 1965; Jóhannesson and others, 1989). The classic link between a glacier and its climate has been the net mass balance (e.g. Meier, 1965), but there are other approaches and key components to monitoring glacier fluctuations. Some parameters used for monitoring, such as glacier tongue position, length, area and elevation, are easy to measure or easy to determine from maps, air photos and satellite images. Many other characteristics, such as the activity index, mass balance and their associated components, are not as easy to determine. Measuring these parameters can be an expensive and laborious task (Østrem and Brugman, 1991).

Several alternative approaches for regional and global glacier monitoring have been developed recently. The theoretical background and some practical recommendations for these new techniques are given in Krenke and Menshutin (1987), Dyurgerov (1988, 1993), Jóhannesson and others (1989), Meier (1993), Haeberli (1995) and Fountain and others (1997). However, many of these new techniques are based on studies using small datasets or even modeled results. More appropriate monitoring strategies could be devised by using a worldwide compilation of all the available data on glacier lengths, areas, activity indices, mass balances, and so forth. Towards this goal, we have used a substantially larger dataset to analyze the relations between a number of commonly monitored characteristics of glaciers: surface area (S), length (x), maximum elevation (Z_{up}, at the glacier head), mean elevation (Z_{m}), minimum elevation (Z_{t}, at the terminus), equilibrium-line altitude (ELA), activity index (E), net or annual mass balances (b_{n}), and mass balances at the glacier's tongue (b_{t}) and head (b_{up}). The data for this analysis have been compiled primarily from volumes of *Fluctuations of Glaciers* (Kasser, 1973; Müller, 1977; Haeberli, 1985; Haeberli and Müller, 1988; Haeberli and Hoelzle, 1993; we refer to them as *FOG*, 1973, 1977, 1985, 1988, 1993), from *Glacier Mass Balance Bulletins* (Haeberli and Herren, 1991; Haeberli and others, 1993, 1994, 1996; abbreviated *GMB*, 1991, 1993, 1994, 1996) and from many other published and unpublished sources with data spanning the period 1961–90 (for details, see Dyurgerov and Meier, 1997).

Special attention is focused here on the terminus balance, b_{t}. This is because b_{t} may be a key parameter in studies of the response time of glaciers to climate change (Jóhannesson and others, 1989). It has also been suggested that measurements of the mass balance at the terminus and at one or two stakes in the vicinity of the ELA may provide a reasonable estimate of the mass balance of an entire glacier, b_{n} (Haeberli, 1995). This has been recommended as part of a future strategy for mass-balance measurements (Haeberli, 1995). However, even though b_{t} is easier to measure than b_{n}, there are few terminus balance data available at present. To estimate b_{t}, measurements of mass balance vs altitude are needed. Of all the glaciers with mass-balance measurements (around 260; see Dyurgerov and Meier, 1997) we found only 80 glaciers worldwide with published data on annual balance vs altitude. Thus, our study has been bounded by this sample (Table 1). (To facilitate future studies, we strongly encourage the publication of annual, winter and summer balance profiles in appropriate media (e.g. issues of *GMB*). These data will have already been collected by anyone measuring net mass balances.)

In the following sections we divide the 80 glaciers into five subsamples based on their general morphological characteristics (e.g. valley glacier vs mountain ice cap). For each subsample, a variety of variables which could be used for monitoring glaciers ($S, x, Z_{\mathrm{up}}, Z_{\mathrm{m}}, Z_{\mathrm{t}}$, ELA, $E, b_{\mathrm{n}}, b_{\mathrm{t}}$ and b_{up}) are correlated with each other. Based on these correlations (which come from a comparatively large possible selection), we suggest what parameters and combinations of parameters might be most useful in monitoring the response of glaciers to changes in climate.

DATA PROCESSING

Country codes and geographical locations have been taken from *FOG* volumes without changes. In order to reduce errors, the periods of mass-balance study, the elevations ($Z_{\mathrm{up}}, Z_{\mathrm{m}}, Z_{\mathrm{t}}$) and the area ($S$) have been taken from *FOG*s and compared with primary sources when possible. The mean specific mass balance (b_{n}) of a mountain glacier has been calculated as a function of altitude:

$$b_{\mathrm{n}} = [\sum b(h_i)s(h_i)]/S. \tag{1}$$

The sum is taken over the entire glacier, where b is the measured or calculated mass balance centered in altitude increments h_i (the index i refers to the altitude range), and where $s(h_i)$ is the area–altitude distribution. The same approach has been used to calculate winter and summer balances (b_{w}, and b_{s}). Data for these have been compiled from *FOG*s and from other sources of original information (see sources in Table 1). The data on vertical variations in annual balance have been used to estimate b_{up} and b_{t}. We also recalculated b_{n} from the seasonal mass-balance components ($b_{\mathrm{n}} = b_{\mathrm{w}} - b_{\mathrm{s}}$) in order to identify and, where possible, correct errors in previous publications. Thus, the data presented in Table 1, all of which are averages over the period of record shown in column G, are somewhat different, in many cases, from those published in the *FOG*s.

For many glaciers, the curves describing the vertical distribution of annual mass balance have complicated shapes. To estimate these profiles, data for vertical profiles of b_{n} on a given glacier have been averaged through time and approximated by power-law, exponential or logarithmic best-fit curves. From these curves, values for the activity index E and ELA have been determined (see Table 1). For the ELAs we tried to use only directly measured values, but in cases where obvious inconsistencies were found, we substituted approximations from the b_{n} profiles.

Each glacier was assigned to one of five groups (1–5 in Table 1) depending on their basic type. *Group 1* contains 31 mountain or outlet glaciers, usually of simple valley-glacier form, with a single accumulation basin and a single lobe (clean or only partly covered by debris). *Group 2* consists of 29 glaciers, similar to group 1, but with two or more separate accumulation basins; these glaciers have more complex shapes and larger surface areas. *Group 3* comprises ten cirque glaciers, or other small glaciers with a single accumulation basin and lobe. *Group 4* includes six dome-shaped ice fields or ice caps (mountain and subpolar). *Group 5* contains four glaciers that calve into sea, a lake or land. We placed these glaciers in a separate group because their length and other morphometric characteristics may be altered by the calving discharge (Meier and Post, 1987).

For consistency, in making this division into five groups we have used the classification scheme (and three digit codes) introduced in *FOG* (see *FOG*, 1985, p. 100–103 and table A). In reality, the differences between groups 1 and 2 are slight and occasionally ambiguous. Dzhankuat and Marukh glaciers (central and western Caucasus), for example, might have been included in group 1, but following the internationally recognized classification (*FOG*, 1985, table A), we include them in group 2. Also, although group 5 contains all calving glaciers, the differences between them can be profound. The tongues of some of these glaciers do not calve substantial amounts of ice, or they calve on land rather than in water (e.g. the Rhonegletscher, Griesgletscher and Bridge Glacier). Each of these might have been included in group 1 or 2. On the other hand, Columbia Glacier (Chugach Mountains, Alaska) in group 5 is a very large but otherwise typical tidewater glacier which loses most of its ice by calving (Meier and Post, 1987). Average properties summarizing each of the five groups are given at the bottom of Table 1.

Due to the morphological differences which distinguish groups 1–5, we might expect some pairs of variables to be correlated differently from one group to another. However, correlations between glacier properties are not possible for the small numbers of glaciers in groups 3–5, so an analysis of the differences in correlations between groups is necessarily preliminary (see below). Instead, we have combined the five distinct groups into five different "samples" that each have enough glaciers to derive meaningful correlations between properties. Sample 1 consists of the 31 simple valley glaciers from group 1. Sample 2 contains the 29 compound valley glaciers from group 2. Sample 3 comprises the 60 glaciers of groups 1 and 2 (i.e. all valley glaciers). Sample 4 has 70 glaciers (including groups 1, 2 and 3; or all the valley and cirque glaciers). Sample 5 contains all 80 glaciers.

As expected, the mean surface area and the length are smallest for the simple valley glaciers in sample 1 (Fig. 1). At the same time, b_{up} and b_{t} are less positive and more negative, respectively, for sample 1 compared with the other samples (Fig. 2). The elevations ($Z_{\mathrm{up}}, Z_{\mathrm{t}}, Z_{\mathrm{m}}$) and the ELA are higher and E is larger in sample 1 than in other samples (Figs 3 and 4 and bottom lines in Table 1). For each of the samples, the next section explores correlations between the various glacier parameters.

RESULTS

Within a given sample, two properties (such as terminus balance and length) were selected for each glacier. Both linear and power-law correlations were calculated between these two parameters. Similar linear and power-law correlations were determined for all other pairs of parameters commonly used in monitoring glaciers (i.e. the previously mentioned $S, x, Z_{\mathrm{up}}, Z_{\mathrm{m}}, Z_{\mathrm{t}}$, ELA, $E, b_{\mathrm{n}}, b_{\mathrm{t}}$, and b_{up}). Correlations were also performed between each of these parameters and potentially useful combinations of para-

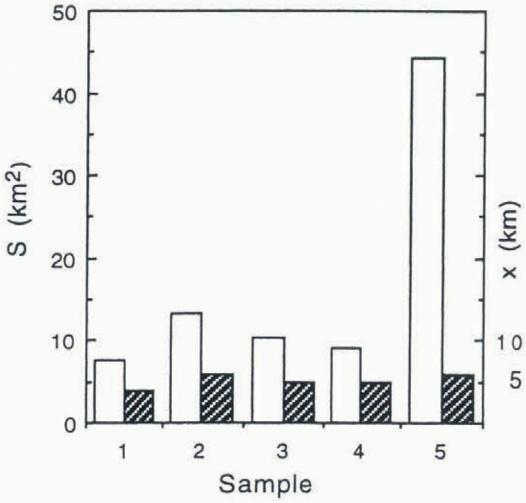

Fig. 1. Histogram of surface area, S, and length, x (along center line), averaged by sample.

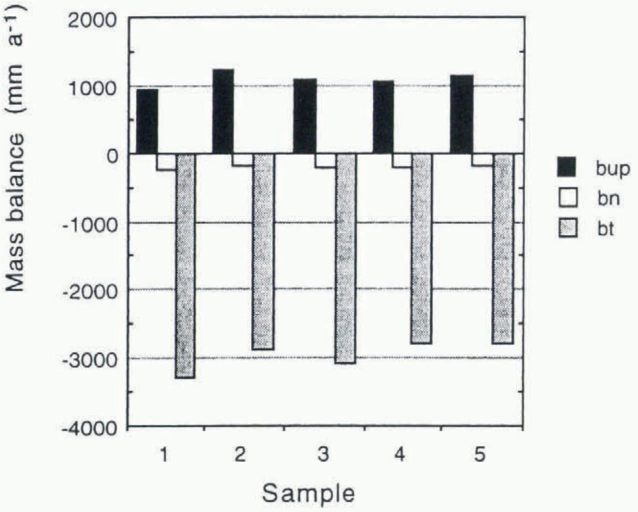

Fig. 2. Histograms of mass balance at the head of the glacier ($b_{\rm up}$), annual or net mass balance ($b_{\rm n}$) and mass balance at the tongue ($b_{\rm t}$), averaged by sample.

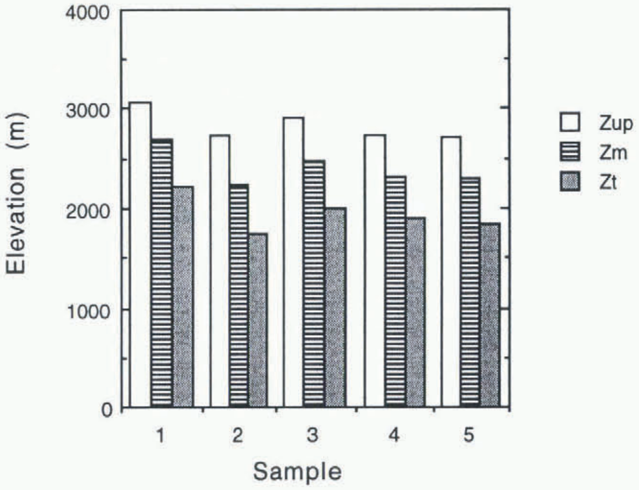

Fig. 3. Glacier minimum ($Z_{\rm t}$) average ($Z_{\rm m}$) and maximum ($Z_{\rm up}$) elevations, averaged by sample.

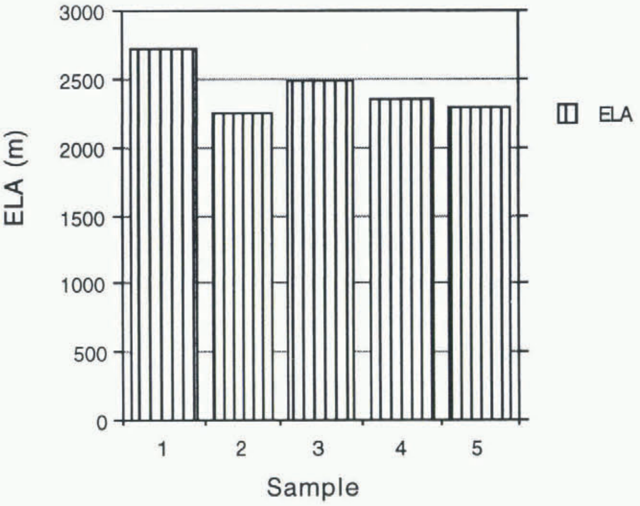

Fig. 4. Equilibrium-line altitude (ELA), averaged by sample.

meters, such as the total range in elevation ($Z_{\rm up} - Z_{\rm t}$) and the range in mass balance ($b_{\rm up} - b_{\rm t}$). We emphasize that all of these correlations are spatial (between many glaciers) and not temporal; each glacier is assigned only one value for each parameter, for example an average ELA and an average net mass balance over the period of observation (Table 1). The correlations for each pair of parameters in each of the five samples are listed in Table 2.

The glaciers in each sample are different in shape and type and reside in many different geographical regions. Thus, correlations between properties apply to all glaciers globally rather than to any individual glacier or mountain range. For example, for individual glaciers, a strong correlation between interannual variations in $b_{\rm n}$ and the ELA is widely recognized (see, e.g., *GMB*, 1991, 1993, 1994, 1996). However, for all 80 glaciers considered simultaneously (using the temporal mean values of $b_{\rm n}$ and ELA for each glacier), the correlation between $b_{\rm n}$ and the ELA is almost non-existent (see Table 2).

For all five samples we have calculated about 130 correlation coefficients (r) for both linear and power-law regressions. In many cases the coefficients of correlation are very weak, but we report them for two reasons. First, our dataset is larger than any other previously analyzed, and it is useful to know that larger datasets do not improve the correlations found in previous analyses with smaller datasets. Second, in addition to recommending strong relationships, we can also note which correlations are not useful for global monitoring programs. Some of these poor correlations may seem obvious, but many others are not. The most important of the possible correlations between combinations of parameters listed in Table 2 are noted here and discussed in the next section.

1. *Net or annual specific mass balance* (for simplicity we do not distinguish between these two balances). The correlation between $b_{\rm n}$ and $b_{\rm t}$ is weak, with $r = -0.4$ for simple valley glaciers and 0.44 for compound valley glaciers. Correlations between $b_{\rm n}$ and E, ELA and all elevations ($Z_{\rm m}$, $Z_{\rm t}$, $Z_{\rm up}$) are also very weak. The correlation between $b_{\rm n}$ and $b_{\rm up}$ is poor for most samples, although significant ($r = -0.72$) for simple valley glaciers (sample 1). On the other hand, a good linear correlation (r = 0.6–0.8) occurs between ($b_{\rm n} - b_{\rm t}$) and other properties, such as length x and differences in elevation ($Z_{\rm m} - Z_{\rm t}$), (ELA $- Z_{\rm t}$) and ($Z_{\rm up} - Z_{\rm t}$).

2. *Terminus balance.* $b_{\rm t}$ is well correlated with the length of glaciers, especially in sample 1 ($r = 0.75$). The correlation coefficient for $b_{\rm t}$ vs $b_{\rm up}$ is 0.65 for simple valley glaciers (sample 1) but is very weak for all other samples, especially for relatively large compound glaciers (sample 2; $r = 0.2$). The correlation coefficients for $b_{\rm t}$ vs (ELA $- Z_{\rm t}$) and ($Z_{\rm m} - Z_{\rm t}$) are large for all samples (r = 0.7–0.8).

Table 1. *Characteristics of glaciers used for correlations*

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
					km^2			mm w.e.	mm w.e.	mm w.e.	m	mm m^{-1}	km	m	m	m	
Laika Glacier	75°53′ N	79°10′ W	431	1	4.28	1974–75	2	−513	−1705	315	420	7	3.8	520	360	20	[2, 7]
Alexander Glacier	57°06′ N	130°49′ W	538	1	5.834	1981–84	4	−666	−2625	205	1770	5.1	5	1820	1670	1190	[3–5]
Yuri Glacier	56°58′ N	130°41′ W	638	1	3.58	1981–84	9	−629	−1682	625	1850	4.2	3	2010	1645	1390	[3–5]
Bench Glacier	51°26′ N	124°55′ W	638	1	10.509	1981–85	5	−630	−4388	1500	1875	5.4	8	2740	2000	1480	[4, 5]
Place Glacier	50°26′ N	122°36′ W	538	1	3.7	1965–89	19	−730	−2600	1190	2270	6	4.2	2610	2089	1860	[1–5]
Sentinel Glacier	49°54′ N	122°59′ W	530	1	1.74	1966–89	18	331	−1842	1620	1860	7.5	2	2105	1990	1660	[2–4]
Sykora Glacier	50°52′ N	123°35′ W	418	1	25.351	1981–85	5	14	−4154	2000	2215	3.2	9.2	2750	2050	1520	[2–5]
Zavisha Glacier	50°48′ N	123°25′ W	636	1	6.49	1981–85	5	−252	−1048	480	2340	2.2	3.1	2500	2200	2010	[3, 4]
South Cascade Glacier	48°22′ N	121°03′ W	538	1	2.5	1965–80	16	−323	−4970	800	1875	15.7	3.1	2140	1920	1630	[8]
Ghiacciaio de Caresér	46°27′ N	10°42′ E	638	1	4.83	1967–90	24	−530	−1314	215	3210	6.44	2.2	3350	3092	2857	[1–4, 10, 11]
Kesselwandferner	46°50′ N	10°48′ E	638	1	4.713	1967–90	14	10	−4167	700	3105	12.8	4.2	3490	3180	2720	[2–5, 12]
Langtalerferner	46°48′ N	11°01′ E	538	1	3.049	1963–70	8	−192	−3043	1330	2855	8.9	5.1	3420	2910	2450	[1, 2, 12]
Engabreen	66°39′ N	13°51′ E	438	1	38.02	1970–90	15	810	−9155	2700	1090	9.5	11.5	1524	1220	40	[2–5, 10, 11]
Gråbreen	61°30′ N	6°48′ E	438	1	9.55	1974–75	2	435	−1195	1360	1380	5.7	5	1660	1510	1040	[2]
Hardangerjøkulen	60°32′ N	7°22′ E	438	1	17.18	1965–90	14	278	−5356	1000	1585	9.3	8.1	1850	1740	1050	[1–5, 10, 11]
Nigardsbreen	61°43′ N	7°08′ E	438	1	48.2	1964–90	22	381	−10283	2500	1515	8.1	9.6	1950	1618	355	[1–5, 10, 11]
Vestre Memurubre	61°32′ N	8°30′ E	638	1	8.96	1968–72	5	−479	−1754	810	1915	6	4	2200	1880	1570	[1, 2]
Vesledalsbreen	61°30′ N	7°16′ E	438	1	4.18	1967–72	4	265	−2330	950	1390	11	3	1730	1450	1130	[1, 2]
Leviy Aktru, Lednik	50°05′ N	87°44′ E	536	1	6.24	1988–89	2	196	−2140	1220	3130	2	5.9	4043	3250	2561	[4, 5, 11, 25]
Maliy Aktru, Lednik	50°05′ N	87°45′ E	536	1	2.86	1970–89	7	83	−4320	740	3270	1.5	4.4	3714	3200	2229	[2–5, 11, 22, 25]
Praviy Aktru, Lednik	50°05′ N	87°44′ E	536	1	4.8	1988–89	2	210	−4290	1350	3080	4.9	5.3	3750	3000	2500	[5, 25]
Kozelskiy, Lednik	53°16′ N	158°49′ E	539	1	1.8	1988–90	3	−1321	−5083	200	1730	8.3	4.6	2050	1590	880	[21]
Golubina, Lednik	42°27′ N	74°30′ E	538	1	6.215	1981–90	10	−307	−3516	600	3850	7.5	5.1	4437	3970	3250	[18]
No. 131	41°51′ N	77°46′ E	538	1	0.51	1988–89	2	−533	−1462	200	4330	3.3	1.28	4433	4151	3864	[18]
Sary-Tor (No. 356), Lednik	41°50′ N	78°11′ E	536	1	3.614	1984–89	5	−132	−1694	950	4250	5	4.48	4800	4252	3860	[18]
Shumskiy, Lednik	45°05′ N	80°14′ E	536	1	2.82	1967–89	23	−73	−2251	850	3700	6.5	3.58	4463	3407	3126	[1]
Suyok Zapadniy, Lednik	41°47′ N	77°47′ E	538	1	1.25	1981,89	2	−930	−1280	470	4325	6.4	2.5	4496	4187	3895	[18]
Tsentral'nyy Tuyuksu, Lednik	43°00′ N	77°06′ E	536	1	2.75	1965–90	26	−465	−1727	500	3820	7.9	3.2	4219	3760	3401	[15, 16, 18]
Lewis Glacier	0°09′ S	37°18′ E	533	1	0.205	1981–95	14	−922	−2489	−118	4927	2.95	0.95	4962	4850	4611	[3, 5, 10, 11, 23]
Carstensz Glacier	4°06′ S	137°10′ E	538	1	0.9	1973	1	−81	−3800	950	4580	28	1.8	4800	4600	4380	[2]
Meren Glacier	4°05′ S	137°10′ E	536	1	1.94	1973	1	−512	−3800	1000	4585	28	2.1	4860	4610	4260	[2]
White Glacier	79°27′ N	90°40′ W	515	2	38.7	1960–91	29	−98	−1836	300	1050	1.3	15.4	1780	1160	80	[6]
Andrei Glacier	56°56′ N	130°59′ W	428	2	92.147	1981–84	4	−394	−4500	1300	1505	5.7	22	2190	1280	660	[3–5]
Helm Glacier	49°58′ N	123°00′ W	626	2	1.411	1982–89	8	−859	−1662	360	2090	5.9	2.4	2150	1900	1770	[3–5]
Tiedemann Glacier	51°20′ N	125°03′ W	529	2	62.67	1981–85	5	−824	−8658	2570	1940	3.8	24	3800	1950	700	[4, 5]
Peyto Glacier	51°40′ N	116°32′ W	528	2	12.88	1966–90	24	−498	−3375	1900	2685	7.3	5.3	3185	2635	2125	[1–5]
Woolsey Glacier	51°07′ N	118°03′ W	628	2	3.92	1966–74	8	−211	−1960	1600	2265	7.7	2.9	2670	2240	1920	[1, 2]
Hintereisferner	46°48′ N	10°46′ E	518	2	8.984	1964–90	27	−311	−4637	840	2990	5.2	7.7	3710	3050	2391	[2–5, 12]
Jamtalferner	46°42′ N	10°10′ E	526	2	3.85	1989–90	2	−436	−2900	200	2875	3.1	2.8	3160	2810	2408	[9–11, 12]
Limmerngletscher	46°49′ N	8°59′ E	627	2	2.39	1976–85	10	−27	−1258	1110	2865	3.1	2.9	3421	2760	2260	[2–4, 9–11, 26]
Silvrettagletscher	46°51′ N	10°05′ E	626	2	3.15	1960–90	29	64	−2632	1040	2740	5.9	3.5	3160	2780	2439	[5, 10, 11]
Sonnblickkees	47°08′ N	12°36′ E	606	2	1.72	1964–78	15	208	213	700	2720	10.2	1.5	3030	2790	2500	[2–5, 10, 11]
Vernagtferner	46°53′ N	10°49′ E	626	2	9.052	1966–90	22	−120	−2599	390	3115	4	3.3	3627	3187	2748	[1–5, 13, 27]

Ålfotbreen	61°45′ N	5°39′ E	436	2	4.815	1965–93	24	398	−1119	1330	1155	7.4	2.9	1380	1230	890	[2–5, 2, 3]
Austre Memurubre	61°33′ N	8°26′ E	627	2	8.77	1968–72	5	−585	−2922	1010	2095	3.5	4	2280	1940	1630	[1, 2]
Bondhusbreen	60°02′ N	6°20′ E	438	2	10.416	1977–80	4	−408	−9762	890	1535	10.2	6	1635	1450	450	[3, 4]
Høgtuvbreen	66°27′ N	13°39′ E	528	2	2.598	1971–77	7	41	−2620	1350	880	9	2.7	1160	940	588	[2, 3]
Hellstugubreen	61°34′ N	8°26′ E	518	2	2.981	1965–90	21	−283	−2716	1760	1900	5.5	3.4	2130	1900	1470	[1–5, 10, 11]
Gråsubreen	61°39′ N	8°36′ E	676	2	2.199	1965–90	21	−277	−640	270	2185	4.8	2.6	2300	2060	1850	[1–5, 10, 11]
Rabots glaciär	67°54′ N	18°33′ E	528	2	3.74	1986–90	5	−81	−2159	2570	1395	4.1	4.1	1700	1350	1071	[4, 5, 10, 11]
Storbreen	61°34′ N	8°08′ E	526	2	5.26	1990	1	1249	−1350	2500	1530	7	2.9	1970	1440	1380	[1–5, 10, 11]
Storglaciären	67°54′ N	18°34′ E	528	2	3.03	1971–90	15	54	−1300	2770	1460	7	3.7	1828	1400	1125	[2–5, 10, 11, 14]
Storsteinsfjellbreen	68°13′ N	17°55′ E	528	2	6.12	1965–68	4	−79	−2300	1135	1370	4.7	5.3	1850	1380	930	[1, 2]
Trollbergdalsbreen	66°43′ N	14°27′ E	538	2	1.82	1971–75	5	−301	−850	600	1090	13.5	2.1	1300	1050	900	[2, 11]
Tunsbergdalsbreen	61°36′ N	7°03′ E	428	2	49.86	1966–72	7	−246	−5389	2070	1440	5.5	18.5	1930	1530	540	[1, 2]
Dzhankuat, Lednik	43°12′ N	42°46′ E	528	2	3.126	1968–90	23	−64	−3617	2100	3200	8.2	3.2	4018	3250	2700	[1–5, 10, 11]
Garabashi, Lednik	43°18′ N	42°28′ E	8	2	4.47	1987–89	3	236	−1607	420	3760	6.2	5.8	5000	3880	3316	[4, 5, 10, 11]
Marukh, Lednik	43°05′ N	41°10′ E	528	2	3.33	1967–82	16	−589	−2900	1900	2885	12.4	4	3160	2785	2490	[1–4, 20]
Abramova, Lednik	39°39′ N	71°38′ E	528	2	22.5	1968–94	23	−508	−4150	990	4221	6.8	9.4	4960	4200	3620	[17, 28]
Davidov, Lednik	41°50′ N	78°12′ E	526	2	11.43	1984–85	2	−430	−2073	320	4351	2.6	6.13	4980	4280	3780	[18]
Abraham Glacier	58°56′ N	63°32′ W	648	3	0.73	1982–84	3	−190	−2250	1250	985	12	1.2	1150	900	690	[4]
Hidden Glacier	58°56′ N	63°33′ W	648	3	0.853	1982–84	3	−419	−1417	1080	927	8.2	1.5	1090	920	790	[4]
Minaret Glacier	58°53′ N	63°43′ W	648	3	0.86	1982–84	3	35	−250	1030	1295	9.4	1.9	1505	1250	1020	[4]
Superguksoak Glacier	58°57′ N	63°47′ W	649	3	1.395	1982–84	3	−153	−331	860	920	8.7	2	1080	820	660	[4]
Ram River Glacier	51°51′ N	116°11′ W	648	3	1.8	1966–74	9	−385	−1819	540	2815	7	2.1	3020	2750	2560	[1, 2]
Plattalvagletscher	46°50′ N	8°59′ E	656	3	0.86	1976–85	10	129	−283	790	2720	3.15	1.1	2980	2740	2550	[1–5, 9–11, 26]
Nördlicher Schneeferner	47°25′ N	10°59′ E	648	3	0.33	1967–68	2	600	209	870	no data	3	0.9	2820	2688	2556	[1]
Blåisen	68°20′ N	17°51′ E	648	3	2.18	1965–68	4	−363	−1258	440	1080	8.4	2.18	1240	1040	860	[1]
IGAN, Lednik	67°40′ N	65°48′ E	648	3	0.9	1960–77	18	−239	−1000	1250	981	5.6	1.4	1217	1100	830	[19]
Obrucheva, Lednik	67°43′ N	65°42′ E	648	3	0.3	1960–77	18	−208	−1300	1580	528	10.5	0.6	660	500	390	[19]
Devon Ice Cap	75°25′ N	83°15′ W	303	4	1695.1	1961–90	30	−40	−1059	214	1125	0.7	50	1890	1200	0	[1–5]
Laika Glacier and Ice Cap	75°53′ N	79°10′ W	230	4	9.82	1975	1	−624	−2050	30	500	2.8	3.8	520	370	20	[2]
Cainhavarrebreen	68°06′ N	18°00′ E	238	4	0.683	1965–68	4	−165	−465	320	1470	3.4	1.4	1540	1410	1210	[1]
Grigoryev, Lednik	41°50′ N	78°09′ E	–	4	9.35	1987–88	2	−36	−658	580	4410	3.2	3	4609	4350	4150	[18]
No. 125 (Vodopadniy)	50°06′ N	87°42′ E	303	4	0.93	1988–89	7	134	−680	500	3160	6	1.4	3550	3100	3025	[6, 11, 25]
Glacier Gl, Deception Island	63°00′ S	60°35′ W	–	4	0.43	1969–71	3	−293	−1913	480	310	14.8	0.8	400	250	0	[2]
Columbia Glacier	60°00′ N	147°06′ W	514	5	1090	1978	1	360	−7000	8000	1160	4.2	66.6	3353	2000	0	[3]
Bridge Glacier	50°49′ N	123°34′ W	414	5	88.101	1981–85	5	−460	−5300	2000	2200	4.2	18.2	2900	2100	1400	[4]
Griesgletscher	46°26′ N	8°20′ E	534	5	6.194	1962–94	33	−305	−2866	1080	2780	3	6.2	3373	2920	2370	[24]
Rhonegletscher	46°37′ N	8°24′ E	514	5	17.38	1980–82	3	200	−5420	4340	2810	9.4	10.2	3620	2940	2125	[5]
Group 1				31	7.7		9	−232	−3273	942	2713	7.9	4.5	3077	2689	2219	
Group 2				29	13.4		13	−186	−2872	1251	2251	6.3	6.2	2740	2228	1749	
Group 3				10	1		7	−119	−970	969	1361	7.6	1.5	1676	1471	1290	
Group 4				6	286.1		8	−171	−1138	354	1829	5.2	10.1	2084	1780	1401	
Group 5				4	300.4		11	−51	−5146	3855	2238	5.2	25.3	3312	2490	1474	

For each group, the glaciers are arranged in alphabetical order within the following regions: Arctic Islands, Labrador, Alaska, mainland U.S.A. and Canada, Alps, Scandinavia, Altai, Caucasus, Kamchatka, Polar Ural, Pamir, Tien Shan, Oceania, Africa, Antarctica.

A, glacier; B, latitude; C, longitude; D, code (see *FOG*, 1985, 1988, 1993); E, group number; F, surface area; G, period of study (only when vertical distributions of mass balance are available); H, number of years; I, J, K, average values of b_n, b_t, and b_{up}, respectively, over the period of record shown in column G; L, ELA; M, E; N, x; O, Z_{up}; P, Z_t; Q, Z_m; R, sources.

Sources: 1. *FOG* (1973); 2. *FOG* (1977); 3. *FOG* (1985); 4. *FOG* (1988); 5. *FOG* (1993); 6. Cogley and others (1995); 7. Blatter and Kappenberger (1988); 8. Krimmel (1995); 9. *GMB* (1991); 10. *GMB* (1993); 11. *GMB* (1994); 12. G. Markl (personal communication, 1996); 13. O. Reinwarth (personal communication, 1994); 14. Holmlund and others (1996); 15. Dyurgerov and others (1996); 16. Makarevich and others (1984); 17. Glazyrin and others (1993); 18. Mikhalenko and others (1995); 19. Voloshina (1987); 20. Krenke and others (1988); 21. Vinogradov and Murav'yev (1992); 22. Galakhov and others (1987); 23. Hastenrath (1991); 24. Funk and others (1997); 25. Narozhnyy (1991); 26. Chen Jiyang (1991); 27. Moser and others (1986); 28. Pertziger (1996).

Table 2. Correlation coefficients between glacier properties. In each column the linear correlation coefficients are given first and power-law correlations second

	Properties	*Sample 1*		*Sample 2*		*Sample 3*		*Sample 4*		*Sample 5*	
1	b_n vs b_{up}	−0.72	−0.45	−0.20	−0.10	−0.46	−0.29	−0.42	−0.30	−0.38	−0.18
2	b_n vs b_t	−0.40	−0.01	0.44	0.32	−0.02	0.16	0.04	0.20	0.01	0.32
3	b_n vs x	−0.50	−0.06	0.31	0.19	0.02	−0.01	0.04	0.05	0.11	−0.05
4	$b_n - b_t$ vs x	0.76	0.59	0.58	0.60	0.54	0.58	0.58	0.64	0.41	0.60
5	b_n vs Z_{up}	0.21	−0.30	0.20	0.10	0.21	−0.07	0.17	0.02	0.10	−0.04
6	b_n vs Z_{up}	0.31	−0.22	0.06	0.12	0.22	0.00	0.18	0.03	0.14	−0.07
7	b_n vs Z_m	0.23	−0.27	0.16	0.09	0.21	−0.04	0.17	0.04	0.11	−0.02
8	b_n vs ELA	0.28	−0.27	0.20	0.14	0.25	−0.01	0.22	0.06	0.17	0.01
9	b_n vs E	−0.04	−0.28	−0.10	0.28	−0.04	0.07	−0.01	0.04	−0.01	0.19
10	$b_n - b_t$ vs $Z_m - Z_t$	0.83	0.71	0.74	0.62	0.78	0.65	0.81	0.69	0.75	0.69
11	$b_n - b_t$ vs ELA − Z_t	0.69	0.42	0.78	0.60	0.72	0.51	0.75	0.58	0.72	0.59
12	$b_n - b_t$ vs $Z_{up} - Z_t$	0.62	0.57	0.63	0.66	0.58	0.60	0.63	0.67	0.64	0.68
13	b_t vs b_{up}	0.65	0.47	0.23	0.29	0.39	0.35	0.38	0.26	0.46	0.35
14	b_t vs x	0.72	0.55	0.60	0.63	0.56	0.56	0.60	0.61	0.40	0.56
15	b_t vs Z_t	−0.40	−0.29	−0.25	−0.12	−0.31	−0.21	−0.21	−0.10	−0.21	−0.09
16	b_t vs Z_{up}	−0.24	−0.08	0.10	0.25	−0.07	0.08	0.06	0.25	0.08	0.22
17	b_t vs Z_m	−0.25	−0.10	−0.04	0.15	−0.13	0.03	−0.02	−0.02	−0.01	0.16
18	b_t vs $Z_m - Z_t$	0.82	0.70	0.76	0.68	0.78	0.68	0.80	0.68	0.74	0.68
19	b_t vs E	0.24	0.34	−0.01	0.02	0.17	0.21	0.16	0.12	0.15	0.16
20	b_t vs ELA	−0.29	−0.15	−0.03	0.15	−0.16	0.00	−0.03	0.17	−0.04	0.12
21	b_t vs ELA − Z_t	0.71	0.51	0.81	0.72	0.76	0.62	0.78	0.65	0.74	0.65
22	b_t vs $b_{up} - b_n$	0.52	0.42	0.45	0.42	0.43	0.40	0.44	0.35	0.50	0.49
23	b_{up} vs x	0.76	0.54	0.20	0.16	0.36	0.32	0.35	0.22	0.59	0.27
24	b_{up} vs Z_{up}	−0.28	0.01	−0.20	−0.20	−0.26	−0.10	−0.23	−0.13	−0.02	0.14
25	b_{up} vs Z_t	−0.43	−0.13	−0.32	−0.09	−0.40	−0.11	−0.38	−0.13	−0.29	0.12
26	b_{up} vs Z_m	−0.33	−0.02	−0.32	−0.27	−0.35	−0.15	−0.32	−0.18	−0.14	0.09
27	b_{up} vs $Z_{up} - Z_t$	0.57	0.42	0.16	0.12	0.33	0.26	0.32	0.19	0.57	0.31
28	b_{up} vs $Z_m - Z_t$	0.59	0.37	0.05	0.00	0.30	−0.15	0.29	0.11	0.56	0.21
29	b_{up} vs ELA	−0.38	−0.10	−0.32	−0.27	−0.37	0.20	−0.34	−0.18	−0.21	0.01
30	b_{up} vs E	0.08	0.11	0.17	0.40	0.06	0.21	0.07	0.21	0.03	0.27
31	$b_{up} - b_n$ vs x	0.57	0.44	0.34	0.22	0.42	0.29	0.41	0.28	0.60	0.34
32	$b_{up} - b_t$ vs x	0.78	0.65	0.59	0.59	0.58	0.60	0.61	0.56	0.53	0.59
33	$b_{up} - b_t$ vs $Z - Z_t$	0.82	0.73	0.68	0.46	0.75	0.57	0.77	0.62	0.78	0.62
34	$b_{up} - b_t$ vs $Z_{up} - Z_t$	0.63	0.61	0.61	0.54	0.60	0.56	0.64	0.62	0.70	0.64
35	$b_{up} - bt$ vs ELA − Z_t	0.69	0.47	0.73	0.57	0.71	0.53	0.73	0.62	0.70	0.57
36	$b_{up} - b_n$ vs $Z_{up} - Z_t$	0.43	0.39	0.29	0.07	0.35	0.18	0.35	0.20	0.58	0.32
37	$b_{up} - b_n$ vs $Z_m - Z_t$	0.35	0.27	0.21	0.05	0.25	0.11	0.27	0.15	0.54	0.28
38	ELA vs Z_m	1.00	0.99	1.00	0.99	1.00	0.99	1.00	0.99	0.99	0.99
39	ELA vs Z_t	0.98	0.90	0.96	0.83	0.98	0.87	0.98	0.84	0.97	0.86
40	ELA vs Z_{up}	0.98	0.99	0.95	0.95	0.97	0.97	0.97	0.98	0.96	0.97
41	ELA vs x	−0.51	−0.46	0.15	−0.07	−0.28	−0.28	−0.14	0.03	−0.19	0.02
42	E *vs* x	−0.19	−0.07	−0.31	−0.38	−0.21	−0.22	−0.21	−0.21	−0.22	−0.32
43	Z_{up} vs Z_m	0.98	0.99	0.96	0.95	0.97	0.97	0.97	0.98	0.97	0.98
44	Z_{up} vs Z_t	0.96	0.87	0.86	0.69	0.92	0.80	0.92	0.78	0.89	0.81
45	Z_t vs Z_m	0.98	0.90	0.96	0.81	0.97	0.85	0.97	0.83	0.96	0.86
46	S vs x	0.85	0.90	0.96	0.94	0.93	0.92	0.93	0.94	0.85	0.95
47	S vs Z_t	−0.55	−0.51	−0.37	−0.42	−0.42	−0.47	−0.34	−0.32	−0.26	−0.28
48	S vs Z_{up}	−0.40	−0.46	0.01	0.15	−0.16	−0.21	−0.06	0.07	−0.03	0.12
49	S vs $Z_m - Z_t$	0.75	0.60	0.64	0.67	0.65	0.62	0.66	0.70	0.54	0.73
50	S vs $Z_{up} - Z_t$	0.54	0.57	0.68	0.77	0.65	0.68	0.67	0.76	0.43	0.78
51	S vs ELA − Z_t	0.67	0.49	0.72	0.76	0.68	0.61	0.68	0.70	0.43	0.72
52	S vs Z_m	−0.42	−0.49	−0.20	−0.06	−0.29	−0.33	−0.19	−0.04	−0.12	0.00
53	S vs ELA	−0.45	0.53	−0.19	−0.06	−0.29	−0.35	−0.19	−0.04	−0.17	−0.05
54	S vs E	−0.08	−0.02	−0.26	−0.38	−0.15	−0.18	−0.15	−0.18	−0.18	−0.34
55	S vs b_n	−0.53	−0.09	0.28	0.21	−0.04	−0.03	−0.02	0.02	−0.12	−0.13
56	S vs b_{up}	0.77	0.54	0.16	0.13	0.36	0.34	0.36	0.23	0.32	0.22
57	S vs b_t	0.78	0.40	0.51	0.63	0.55	0.48	0.57	0.56	0.09	0.47
58	S vs $b_n - b_t$	0.82	0.48	0.49	0.63	0.55	0.53	0.57	0.61	0.11	0.52
59	S vs $b_{up} - b_n$	0.55	0.36	0.29	0.19	0.38	0.25	0.38	0.26	0.30	0.27
60	S vs $b_{up} - b_t$	0.84	0.52	0.50	0.55	0.57	0.52	0.59	0.58	0.19	0.50
61	x vs Z_t	−0.61	−0.47	−0.37	−0.44	−0.42	−0.44	−0.31	−0.28	−0.34	−0.23
62	x vs Z_m	−0.48	−0.42	−0.15	−0.06	−0.26	−0.26	−0.13	0.03	−0.12	0.08
63	x vs Z_{up}	−0.40	−0.36	0.08	0.17	−0.10	−0.11	0.03	0.16	0.03	0.20
64	x vs $Z_m - Z_t$	0.79	0.76	0.79	0.72	0.72	0.72	0.75	0.79	0.80	0.81
65	x vs $Z_{up} - Z_t$	0.74	0.78	0.82	0.83	0.77	0.81	0.81	0.86	0.79	0.87
66	x vs ELA − Z_t	0.68	0.64	0.82	0.82	0.73	0.74	0.75	0.80	0.68	0.81

3. *Mass balance at the head of the glacier.* b_{up} correlates best with length x ($r = 0.76$). In general, b_{up} correlates well (around 0.6) with all measures of elevation (Z_{m}, $(Z_{\mathrm{m}} - Z_{\mathrm{t}})$ and $(Z_{\mathrm{up}} - Z_{\mathrm{t}})$).

4. *ELA.* The ELA is best correlated with the mean elevation Z_{m} ($r = 0.99$). The correlation between the ELA and Z_{t} and Z_{up} is also >0.95 for all samples.

5. *Surface area.* S is strongly correlated with many parameters, especially the length x ($r = 0.82$–0.95 for all samples) and various mass balances such as $b_{\mathrm{t}}, b_{\mathrm{up}}$, $(b_{\mathrm{up}} - b_{\mathrm{t}})$, and $(b_{\mathrm{n}} - b_{\mathrm{t}})$ (with r around 0.8 for sample 1). S is somewhat correlated with elevations (e.g. $(Z_{\mathrm{up}} - Z_{\mathrm{t}})$ and $(Z_{\mathrm{m}} - Z_{\mathrm{t}})$), and is more weakly correlated with the ELA and Z_{m} ($r \approx 0.4$). The correlation of S with the activity index E is very weak.

6. *Length.* x is well correlated with many parameters, particularly Z_{t} and differences in elevation such as $(Z_{\mathrm{up}} - Z_{\mathrm{t}})$. This is expected since x is well correlated with the surface area, which is also well correlated with many other parameters.

DISCUSSION

Based on experience, simple physical arguments and previous analyses, many of the strong correlations are expected. For example, the correlations between many morphological properties (such as upper and lower elevations, the range in elevation, length and surface area) have obvious physical explanations: the larger a glacier's area, the greater its length (Bahr, 1997); and the higher Z_{up} (the higher the mountains), the larger the size and length of glaciers. Nevertheless these strong correlations may be helpful for global monitoring because only one of the three parameters (area, length or elevation) is available in many cases.

A similarly reasonable and strong correlation between the ELA and the mean elevation has been suggested (personal communication from A. Ruddel, 1997). When averaged over long time-spans, the ELA is always close to Z_{m} and will also have a strong correlation with Z_{t}. Likewise, longer glaciers are expected to be strongly correlated with b_{up} and b_{t}, because the greater length implies a greater range in altitude and a greater span in climate conditions. An obvious reason for some of the weak correlations between the net mass balance and other parameters, such as elevation and area, is that $b_{\mathrm{n}} \approx 0$ for all glaciers that are in or nearly in a steady state, regardless of the size of the glacier.

However, many of the correlations are not expected or do not have an immediate physical explanation. For example, the correlations between differences in mass balance $(b_{\mathrm{up}} - b_{\mathrm{t}}, b_{\mathrm{n}} - b_{\mathrm{t}}, b_{\mathrm{n}} - b_{\mathrm{up}})$ and any other properties are consistently better than the correlations between simple mass-balance measurements $(b_{\mathrm{up}}, b_{\mathrm{t}}, b_{\mathrm{n}})$ and these other properties. In fact, the good correlation between these differences in mass balance and glacier length, surface area and range in altitude $(Z_{\mathrm{up}} - Z_{\mathrm{t}})$ suggests that these parameters would be good for global glacier monitoring.

On the other hand, there is a very weak correlation between the ELA and glacier mass balance for all samples. On individual glaciers, the ELA is known to correlate very strongly with b_{n} (*GMB*, 1991, 1993, 1994, 1996). However, the global spatial correlation between net mass balances is very poor (Dyurgerov, 1994; Cogley and others, 1995) because glaciers occur in a wide variety of climatic zones from polar to temperate. We expect, therefore, that the ELA would also have a poor spatial correlation, and it is not too surprising that the correlation between the net mass balance and the ELA is poor.

Similar arguments suggest that the activity index, E, would be a poor tool for global glacier monitoring. Likewise, the very weak correlation between b_{n} and b_{t} for all samples prevents the net balance from being replaced by simpler measurements of the balance at the terminus. Measuring b_{t} (and one or two stakes in the vicinity of the ELA) is not a good strategy for global mass-balance monitoring (Haeberli, 1995).

The simple valley glaciers (sample 1) frequently have stronger correlations than other samples. The reasons for this are unclear, although sample 1 is the most homogeneous in size and type. However, in several cases, the correlations in sample 5 (all glaciers) are at least as large as the correlations in other samples. This is true, in particular, for power-law correlations and for parameters that are common in routine glaciological work (e.g. surface area, length, ranges in elevation and ranges in mass balance such as $b_{\mathrm{up}} - b_{\mathrm{n}}$ and $b_{\mathrm{n}} - b_{\mathrm{t}}$). The global properties of such parameters may be observed and studied without differentiation by groups or samples.

CONCLUSIONS AND RECOMMENDATIONS

Net mass balance is typically used to monitor, understand and predict fluctuations in glacier volume, size and length. This relatively difficult-to-measure property (b_{n}) might be replaced by other parameters (e.g. $S, x, Z_{\mathrm{up}}, Z_{\mathrm{m}}, Z_{\mathrm{t}}$, ELA, E, b_{t} and b_{up}), as long as the new parameters are well correlated with b_{n}. Using a substantially larger dataset than in previous studies, we have calculated a large number of correlations to demonstrate which glacier properties might be useful as substitutes and which other properties would be less helpful (Table 2).

Most notably, correlations between net mass balance b_{n} and the terminus balance b_{t} are poor. Likewise the correlation between b_{n} and b_{up} is poor. Thus, despite previous suggestions, neither b_{t} nor b_{up} should be used as a replacement for b_{n} in global monitoring strategies. On the other hand, the terminus balance is well correlated with $(Z_{\mathrm{m}} - Z_{\mathrm{t}})$. Because b_{t}, Z_{m} and Z_{t} are easy to measure in the field and to derive from maps or remotely acquired images (in contrast to b_{n} or the ELA), this relationship could be helpful in estimating the maximum ablation rate and total meltwater production over large regions. Ranges in mass balance (e.g. $b_{\mathrm{up}} - b_{\mathrm{n}}, b_{\mathrm{n}} - b_{\mathrm{t}}$ and $b_{\mathrm{up}} - b_{\mathrm{t}}$) are also well correlated with many other parameters (e.g. ranges in elevation) and are usually better correlated than b_{up}, b_{n} or b_{t}. Thus, the ranges in mass balance could be particularly useful in any of the global monitoring programs which have previously used only the direct measurements of mass balance ($b_{\mathrm{up}}, b_{\mathrm{n}}$ or b_{t}).

The correlations between the activity index and mass balances ($b_{\mathrm{up}}, b_{\mathrm{n}}$ and b_{t}) are weak. This implies that the activity index is a unique property of individual glaciers and most likely reflects local and/or regional climate and topography, rather than global climate. Similarly, the correlations between ELAs and glacier mass balances ($b_{\mathrm{up}}, b_{\mathrm{n}}$ and b_{t}) are very weak. If necessary, though, the ELA may be replaced by Z_{m}, Z_{t} or Z_{up}, as it is strongly correlated with each of these. This gives a nice technique for replacing a harder-to-measure climatically sensitive parameter with an easily measured altitude

Although, in many cases, the correlations between different glacier parameters are poor (Table 2), there are enough strong relationships to suggest that global mass-balance monitoring can be based on a relatively small subset of glacier properties. Some of these parameters (e.g. $Z_{\mathrm{m}}, Z_{\mathrm{t}}, Z_{\mathrm{up}}, S, x$) may be extracted from glacier inventories or determined from remotely sensed images (e.g. the difference between the ELA and $Z_{\mathrm{m}}, Z_{\mathrm{t}}, Z_{\mathrm{up}}$). Other properties (e.g. $b_{\mathrm{t}}, b_{\mathrm{up}}, b_{\mathrm{n}}$) have to be measured in the field on benchmark glaciers or calculated in models (e.g. Tangborn, 1980; Oerlemans, 1993). The relationships (suggested by the strong correlations in Table 2) between these easy- and hard-to-measure parameters can help estimate glacier mass balances in entire mountain ranges or on a global scale.

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