Seasonal mass-balance gradients in Norway

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ABSTRACT. Previously discovered regularity in vertical profiles of net balance, $b_n(z)$, on ten glaciers in Norway also exists in profiles of both winter, $b_w(z)$, and summer, $b_s(z)$, seasonal balances. All three profiles, unlike those of many glaciers elsewhere in the world, are remarkably linear. Variations of gradients, db_w/dz and db_s/dz, from year to year are small and correlate poorly with glacier-total balances b_w and b_s. Glacier-to-glacier correlation is weak for both gradients but is strongly positive for b_w and b_s. There are two direct consequences of these properties of the gradients that apply to both seasonal balances b_w and b_s. First, because db/dz varies so little from year to year, the difference in balance, Δb, from year to year is nearly the same over the entire glacier, except near the top and bottom of its altitude range. Therefore, balance at a site near the middle of the altitude range of the glacier correlates very well with glacier-total balance. Second, this correlation, combined with the strong positive correlation of balance from glacier to glacier, is the reason balance at one altitude on one glacier correlates well with glacier-total balance at other nearby glaciers.

INTRODUCTION

Glacier net balance b_n is the result of two processes, accumulation and ablation, which correspond approximately to routinely measured winter b_w and summer b_s balances. The altitude (z) variation of net balance b_n at ten glaciers in Norway and two in northern Sweden is markedly linear, and the gradients b'_n (denoting db_n/dz) vary little from year to year (Rasmussen, 2004). Dyurgerov and others (1989) found in a study of balance curves for 13 glaciers, including five in Norway, that there is little variation of gradient from year to year for glaciers in maritime climates, whereas there is significant variation for those in continental climates.

Meier and Tangborn (1965) concluded from seven $b_n(z)$ measured on South Cascade Glacier, Washington State, USA, that the profiles differed from year to year by an amount constant with altitude. Kuhn (1984) found the same for Hintereisferner, Austria, and Lliboutry (1974) founded his linear balance model on that assumption. In contrast, several studies (Oerlemans and Hoogendoorn, 1989; Funk and others, 1997; Dyurgerov and Dwyer, 2000) found steeper $b_n(z)$ in warm years; that is, correlation $r < 0$ between b'_n and glacier-total b_n. For the 12 glaciers in Scandinavia (Rasmussen, 2004), however, the correlation is weak and for six of them $r > 0$.

An issue related to balance gradients is to determine at how many sites on a glacier it is necessary to measure mass balance to obtain a reliable estimate of the glacier-total balance. Fountain and Vecchia (1999) analyzed the relation between uncertainty in the glacier-total b_n and uncertainty in the measurement at a site, concluding that five to ten sites are needed for alpine glaciers $<10\,km^2$. Trabant and March (1999) concluded from work on two glaciers in Alaska, USA, that three sites are needed: one in the ablation zone, one near the equilibrium-line altitude (ELA) and one in the accumulation zone. Funk and others (1997) found that in the Alps one site per km^2 is needed. By contrast, for the 12 glaciers in Scandinavia, correlation between the glacier-total b_n and the value determined at only one site, near the middle of the altitude range of the glacier, was $r \geq 0.97$ (Rasmussen, 2004).

In this paper, we extend the analysis of Rasmussen (2004) to profiles of seasonal balance components $b_w(z)$ and $b_s(z)$ for ten glaciers in Norway (Fig. 1). Our main objective is to examine the properties of the profiles as a first step towards understanding the separate roles of the two processes, accumulation and ablation, in determining $b_n(z)$. A second objective is to determine whether $b_n(z)$ is linear because $b_w(z)$ and $b_s(z)$ are both linear or because their curvatures cancel. Another is to determine whether b_w or b_s at one site on the glacier correlates well with the glacier total. In investigating these questions, we use measured profiles for the glaciers (Table 1).

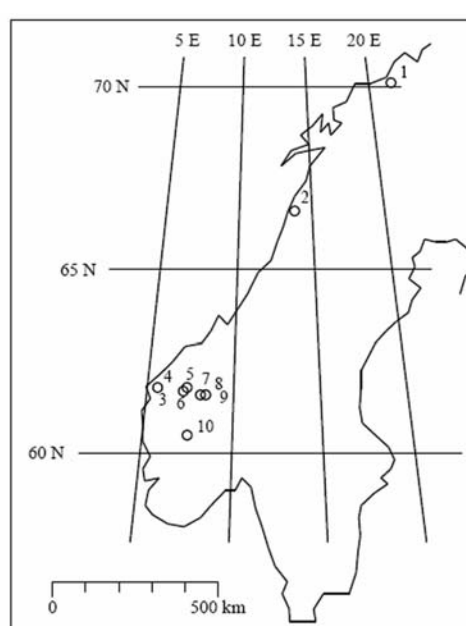

Fig. 1. Glacier locations. See Table 1 for names.

Table 1. Years with $b_w(z)$ and $b_s(z)$ profiles used in this analysis. Altitude interval is 50 m, except for glaciers 1, 2 and 6, where it is 100 m

Glacier	Area km^2	Altitude m a.s.l.	n	Data
1. Langfjordjøkelen	3.7	280–1050	13	1989–93, 1996–2003
2. Engabreen	38.0	40–1594	27	1970–72, 1978, 1981–2003
3. Ålfotbreen	4.5	903–1382	33	1964–72, 1978, 1981–2003
4. Hansebreen	3.1	930–1327	16	1986, 1988–90, 1992–2003
5. Austdalsbreen	11.8	1200–1757	16	1988–2003
6. Nigardsbreen	47.8	320–1960	33	1962, 1965–72, 1978, 1981–2003
7. Hardangerjøkulen	17.1	1020–1865	27	1965–72, 1985–2003
8. Storbreen	5.4	1390–2100	19	1953, 1963, 1987–2003
9. Hellstugubreen	3.0	1465–2200	34	1963–72, 1978, 1981–2003
10. Gråsubreen	2.3	1830–2290	34	1963–72, 1978, 1981–2003

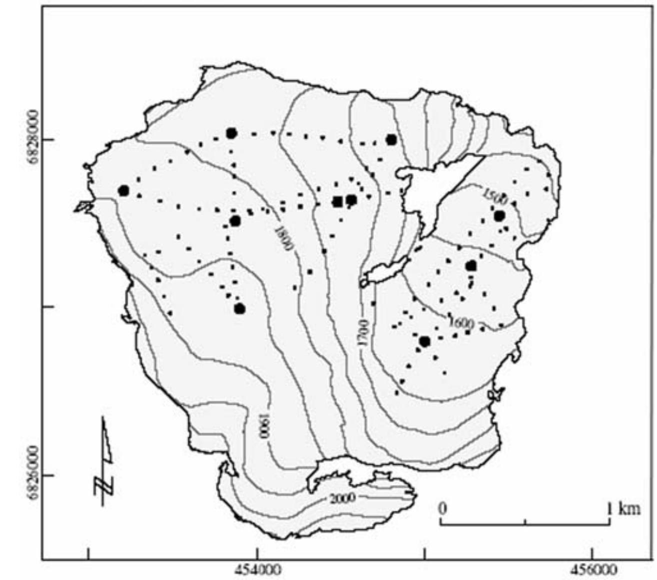

Fig. 2. Storbreen 2003 probing sites (small circles), stakes (large circles) and snow pit (square). Coordinates are Universal Transverse Mercator zone 32 (meters).

NORWEGIAN MASS-BALANCE PROGRAM

A comprehensive review of the variation of glaciers in Norway since 1900 is given by Andreassen and others (in press). Altitude profiles of b_w, b_s and b_n for most years are published in Kjøllmoen (2004) and in previous reports by the Norwegian Water Resources and Energy Directorate (NVE). Profiles for a few other years are available from the NVE archives. Values are given at 50 m altitude intervals for seven glaciers and at 100 m intervals for the other three (Table 1). Methods used to measure mass balance have changed little over the years, except that the fieldwork has become more efficient as more experience has been gained. Mass balance is calculated by the stratigraphic method (Østrem and Brugman, 1991), i.e. between successive 'summer surfaces'. Consequently, the measurements describe the state of the glacier after the end of melting and before fresh snow starts to fall.

Winter balance, which is the accumulated snow during the winter season, is measured each spring by probing to the previous year's summer surface at typically 50–150 sites on each glacier. Snow density is measured utilizing coring and pits dug at one location, or at two locations at different elevations, to determine the water content of the snow. Manual coring is used to verify the location of the summer surface.

Summer balance is obtained from stake measurements. The number of stakes, typically 5–15, varies from glacier to glacier. In general, stake density is highest on the smallest glaciers and declines with increasing glacier size (Andreassen and others, in press).

Net balance is defined as the algebraic sum $b_n = b_w + b_s$ of the seasonal balances, in which b_s is a negative quantity. Melting after the ablation measurements may occur in warm periods late in autumn. On glaciers with large altitude ranges, such as Nigardsbreen and Engabreen, melting after the ablation measurements is commonly observed on the lower parts. This melting will not greatly affect the total specific balance, due to the small area involved, but will influence the lower parts of the profile. Melting after the last ablation measurements and new snow deposited at these measurement sites are considered part of the next year's winter balance.

Table 2. Means and standard deviations of mass-balance components, and r correlations between components (boldface significant at 99%)

Glacier	$\bar{b}_w$ m w.e.	$\bar{b}_s$ m w.e.	$\bar{b}_n$ m w.e.	σ_w m w.e.	σ_s m w.e.	σ_n m w.e.	r_{nw} %	r_{ns} %	r_{ws} %
1. Langfjordjøkelen	2.25	–2.99	–0.74	0.45	0.49	0.76	**78**	**82**	28
2. Engabreen	2.83	–2.35	0.49	0.81	0.72	1.11	**76**	**69**	5
3. Ålfotbreen	3.76	–3.60	0.17	1.11	0.76	1.44	**85**	**64**	15
4. Hansebreen	3.44	–3.97	–0.53	0.98	0.75	1.36	**84**	**71**	22
5. Austdalsbreen	2.24	–2.42	–0.19	0.69	0.77	1.19	**79**	**83**	32
6. Nigardsbreen	2.43	–1.96	0.47	0.64	0.63	1.08	**86**	**85**	**45**
7. Hardangerjøkulen	2.13	–1.95	0.18	0.77	0.62	1.08	**82**	**72**	20
8. Storbreen	1.54	–1.81	–0.27	0.44	0.56	0.85	**80**	**88**	42
9. Hellstugubreen	1.11	–1.44	–0.33	0.27	0.49	0.61	**64**	**90**	24
10. Gråsubreen	0.79	–1.08	–0.29	0.26	0.47	0.59	**61**	**90**	20

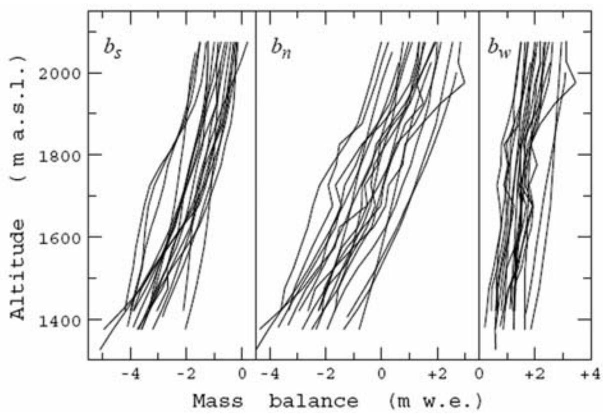

Fig. 3. Storbreen balance profiles for 19 individual years.

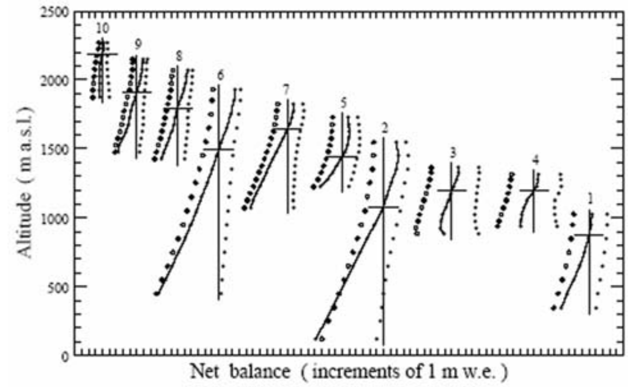

Fig. 4. Mean altitude profiles b_s (open circles), b_w (solid circles) and b_n (connected solid circles). Vertical line is $b = 0$, and horizontal line is ELA. See Table 1 for glacier names and period of record.

Profiles are made by plotting point measurements of winter and summer balance vs altitude, and their mean values for each 50 or 100 m elevation interval are determined (Fig. 2). Snow probing and stake locations are chosen to sample the glacier area overall, and their readings are extrapolated to the lower and upper parts. Another approach, however, was used until the 1980s when hand-contoured maps of accumulation and ablation were made from the observations. The areas within each height interval (50 or 100 m) were measured using a planimeter, and the total amount of accumulation and ablation was calculated for each height interval. Profiles $b_w(z)$, $b_s(z)$ and $b_n(z)$ were thus created. There was no appreciable change in the linearity of the profiles between the earlier and later periods.

MEAN GLACIER BALANCE

Mean and variance of the seasonal components b_w and b_s are given in Table 2 along with their correlation with net balance r_{nw} and r_{ns}. For the maritime glaciers (numbered 1–7) interannual variation of b_w is larger than for b_s, so $r_{nw} > r_{ns}$, and for continental glaciers (8–10) it is smaller, so $r_{ns} > r_{nw}$. The ratio r_{nw}/r_{ns} differs slightly from that of the standard deviations σ_w/σ_s because of the small correlation r_{ws} between the two seasonal components (Rasmussen and Conway, 2001). The r_{ws} are consistent with those of Dyurgerov and Meier (1999), although their r are negative because they defined b_s to be positive, and with those of Braithwaite and Zhang (1999). The r_{ws} are all positive, but only one is significant at 99%.

BALANCE PROFILES

Because $b_n = b_w + b_s$, their profiles are also related by $b_n(z) = b_w(z) + b_s(z)$. From any of the profiles, the glacier-total balance b is obtained as a linear combination of the values at several discrete altitudes. If the profiles from year to year differ only by an amount Δb that is constant with altitude, *regardless of the shape of those profiles*, the glacier-total balance also will differ from year to year by Δb.

Various curves of $b_w(z)$ and $b_s(z)$ have been made over the years, and curves from prior years have often been used as a guide, especially for years with few or questionable observations. The 19 years of profiles at Storbreen are shown in Figure 3. The $b_w(z)$ are quite linear, with little variation of gradient from year to year, but there is slight ($d^2 b_s/dz^2 < 0$) curvature in the $b_s(z)$.

Mean values over the period of record of the three profiles are shown in Figure 4 for each of the glaciers. For each glacier, the sets of $b_w(z)$ for all the years were fit with two different functions: (1) a separate linear function each year, and (2) a family of parallel linear functions. The same was done with $b_s(z)$ and $b_n(z)$. With only a few exceptions, which will be noted below, the profiles are fit very well by the linear functions (Table 3). Calculation of the goodness of fit r^2 is detailed in Rasmussen (2004).

Balance gradients, as approximated by slopes of the individual linear functions fit to the $b(z)$ profiles, vary little from year to year (Table 4). Here gradients are denoted b'_w for db_w/dz, etc. Gradients of net balance are greatest (6.4–8.7 m w.e. km^{-1}) at maritime glaciers, as noted by Oerlemans (2001), and lowest (2.0–6.1) at more continental glaciers. The ratio $\sigma/\bar{b}'$ does not vary systematically from west to east in southern Norway for b_n, b_w or b_s. Gråsubreen is unusual, in that distributions of both accumulation and ablation are strongly dependent on glacier geometry, with the result that the mean $b'_w < 0$ (Fig. 4).

Correlation r_{nn} between b'_n and b_n is weak and of varying sign from glacier to glacier. Correlation r_{ww} between b'_w and

Table 3. Results of fitting $b_n(z)$, $b_w(z)$ and $b_s(z)$ profiles for n individual years. The fit of individual linear functions with generally different gradients each year is r_1^2, and the fit of a family of linear functions with the same gradient each year is $\bar{r}_1^2$. All r^2 are significant at 99%

Glacier	n	b_n r_1^2 %	b_n $\bar{r}_1^2$ %	b_w r_1^2 %	b_w $\bar{r}_1^2$ %	b_s r_1^2 %	b_s $\bar{r}_1^2$ %
1. Langfjordjøkelen	13	96	95	94	90	95	92
2. Engabreen	27	98	94	95	89	96	93
3. Ålfotbreen	33	97	91	97	89	98	94
4. Hansebreen	16	96	94	90	85	98	95
5. Austdalsbreen	16	91	89	87	85	94	91
6. Nigardsbreen	33	98	97	95	89	97	96
7. Hardangerjøkulen	27	98	96	94	90	97	94
8. Storbreen	19	98	95	96	93	96	92
9. Hellstugubreen	34	96	95	89	83	97	95
10. Gråsubreen	34	93	87	88	78	97	92

Table 4. Means $\bar{b}'$ and standard deviations σ of vertical gradients of balance b'_n, b'_w and b'_s in m w.e. per km of altitude. Correlation of b'_n with b_n is r_{nn}, of b'_w with b_w is r_{ww}, of b'_s with b_s is r_{ss}, of b'_w with b_n is r_{wn} and of b'_s with b_n is r_{sn} (boldface significant at 99%)

Glacier	$\bar{b}'_n$	σ_n	r_{nn}	$\bar{b}'_w$	σ_w	r_{ww}	r_{wn}	$\bar{b}'_s$	σ_s	r_{ss}	r_{sn}
	m w.e. km^{-1}	m w.e. km^{-1}	%	m w.e. km^{-1}	m w.e. km^{-1}	%	%	m w.e. km^{-1}	m w.e. km^{-1}	%	%
1. Langfjordjøkelen	6.8	1.0	28	2.5	0.6	33	22	4.3	0.9	46	15
2. Engabreen	8.7	1.7	25	3.3	1.0	**67**	**59**	5.4	1.2	**–49**	–12
3. Ålfotbreen	6.4	2.8	21	1.1	2.0	32	20	5.4	1.5	5	1
4. Hansebreen	8.2	2.0	21	2.3	2.0	47	40	5.9	1.6	13	–27
5. Austdalsbreen	8.3	1.6	–46	2.8	0.7	22	–2	5.4	1.2	–51	–54
6. Nigardsbreen	7.8	0.7	24	2.0	0.5	**73**	**56**	5.9	0.7	–16	–19
7. Hardangerjøkulen	8.5	1.2	–30	2.1	0.7	37	27	6.5	1.1	–42	**–51**
8. Storbreen	6.1	1.3	5	1.8	0.5	25	18	4.3	1.1	4	–3
9. Hellstugubreen	5.7	0.9	–39	1.5	0.5	**44**	30	4.1	0.8	**–68**	**–63**
10. Gråsubreen	2.0	1.3	**–48**	–0.6	0.8	–13	5	2.6	1.0	**–64**	**–61**

b_w is generally positive, and r_{ss} between b'_s and b_s is generally negative. Because $b'_n = b'_w + b'_s$, these two relations generally tend to counteract each other to weaken correlation between b_n and b'_n. Beniston and others (2003) found that increase in snowfall amount with altitude in the Swiss Alps is greater in warm than in cold winters.

If $b_n < 0$ is caused by b_s being more negative than normal, it will make b'_s more positive and thus strengthen b'_n. If $b_n < 0$ is caused by b_w being less positive than normal, it will make b'_w less positive and thus weaken b'_n. The opposite occurs when $b_n > 0$ is caused by either b_w being more positive than normal, strengthening b'_n, or b_s being less negative than normal, weakening b'_n.

Conversely, if b_w is more positive than normal and b_s is more negative than normal in the same balance year, they will both tend to strengthen b'_n. If b_w is less positive and b_s less negative, they will weaken b'_n. The first case is high turnover $b_t = b_w - b_s$, and the second is low turnover, so b'_n will correlate better, positively, with b_t than with b_n (Rasmussen, 2004).

The foregoing cancellation effect is illustrated by Figure 5, showing two years with $b_n > 0$ (1989, 1990) and two with $b_n < 0$ (2002, 2003) at Hellstugubreen, which has strong r_{ww} and r_{ss} compared with other glaciers (Table 4). In both $b_n > 0$ years, b_w was more positive than normal and b_s less negative, whereas in both $b_n < 0$ years b_w was less positive than normal and b_s more negative. The b_s gradient increases from $\sim$4 m w.e. km^{-1} in the $b_n > 0$ years to $\sim$5 m w.e. km^{-1} in the $b_n < 0$ years, and the b_w gradient decreases from $\sim$2 m w.e. km^{-1} to $\sim$1 m w.e. km^{-1}, but the b_n gradient remains at $\sim$6 m w.e. km^{-1}.

Glacier-to-glacier correlations of balance gradients are weak, whereas correlations of balance itself are generally strong and are positive for b_n, b_w and b_s (Fig. 6). For b_n, 35 of the 45 correlations are significant at 95%; for b'_n, only 5 of the 45 correlations are significant at 95%, and 16 are negative. For b_w, 33 are significant at 95%; for b'_w, only 8 are significant at 95%, and 12 are negative. For b_s, 39 are significant at 95%; for b'_s, only 2 are significant at 95%, and 14 are negative. In all 15 cases in which the b' correlations are significant at 95%, they are positive.

Glacier-to-glacier correlation of b is positive for b_w, b_n and b_s and is a generally decreasing function of the distance D between the glaciers (Fig. 6). The correlations of b_w with D and of b_s with D are both $r = -0.76$. Correlations of gradients b' are of both signs and are poorly correlated with D.

GLACIER-TOTAL BALANCE FROM BALANCE AT ONE ALTITUDE

For all glaciers, the altitude where the published b_w correlates best with the glacier-total b_w is near the ELA,

Table 5. Altitude z_n where reported balance $b_n(z_n)$ has best correlation r^2_{nn} with glacier-total balance b_n, and similarly for z_w, r^2_{ww} and z_s, r^2_{ss}. Correlation of $b_w(z_n)$ with b_w is r^2_{wn} and of $b_s(z_n)$ with b_s is r^2_{sn}. All r^2 are significant at 99%

Glacier	ELA	z_n	r^2_{nn}	z_w	r^2_{ww}	r^2_{wn}	z_s	r^2_{ss}	r^2_{sn}
	m a.s.l.	m a.s.l.	%	m a.s.l.	%	%	m a.s.l.	%	%
1. Langfjordjøkelen	870	750	96	650	96	91	850	98	94
2. Engabreen	1080	1250	96	1250	99	99	1250	97	97
3. Ålfotbreen	1190	1275	98	1175	99	98	1225	99	97
4. Hansebreen	1190	1125	98	1175	96	95	1125	99	99
5. Austdalsbreen	1440	1425	98	1575	99	99	1525	96	95
6. Nigardsbreen	1490	1650	98	1650	99	99	1650	97	97
7. Hardangerjøkulen	1640	1725	99	1725	98	98	1725	99	99
8. Storbreen	1790	1775	97	1625	98	96	1775	95	95
9. Hellstugubreen	1910	1875	97	1925	94	92	1925	96	96
10. Gråsubreen	2180	2025	99	2075	97	94	2025	99	99

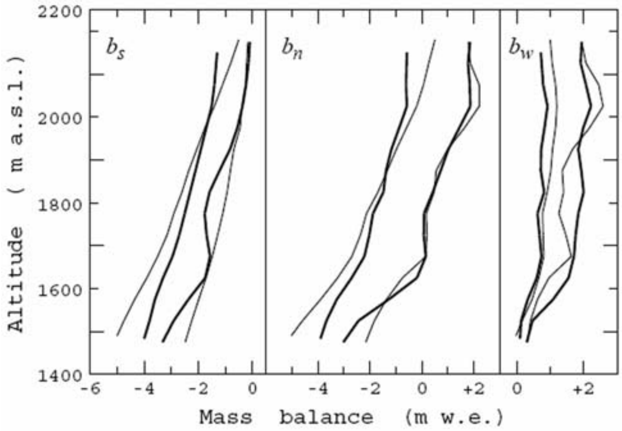

Fig. 5. Hellstugubreen $b(z)$ profiles for four extreme years. In each panel, the more positive curves are 1990 (thick) and 1989 (thin); the more negative curves are 2003 (thick) and 2002 (thin).

rather than in the middle of the accumulation zone (Table 5). The altitude where the published b_s correlates best with the glacier-total b_s is also near the ELA, rather than in the middle of the ablation zone. Using b_s from the optimum altitude for using b_n has nearly as good a correlation as using that from the optimum altitude for b_s, and for b_w it is nearly as good as using that from the optimum altitude for b_w except for Langfjordjøkelen.

These results are a direct consequence of the properties of the balance gradients. Because linear functions all with the same gradient fit the observed profiles so well ($\bar{r}_1^2$ in Table 3), change in balance from one year to the next is much the same at all altitudes. Change in the glacier-total balance is then approximately the same.

A related issue arises from the combination of correlation of b between glaciers (Fig. 6) and correlation between b at one altitude and glacier-total b (Table 5). Published balance at 1650 m on Nigardsbreen is used here to illustrate the relations for all three components (Table 6). Comparable results would occur if balance at z_n (Table 5) for any other glacier in southern Norway were used to estimate glacier-total balance at the other glaciers.

DISCUSSION

Balance profiles were created by different workers during the NVE mass-balance program, which may have increased their variation over the years. Conversely, objective measurements were supplemented by glaciological judgment, including using profiles from previous years as a guide, especially in years with few or uncertain measurements, which may have decreased their variation over the years. In view of the very high spatial density of measurements, however, it is unlikely that methodological inconsistencies have introduced significant spurious variation in the published profiles.

Variation of the gradient b'_n of net balance is weak, with an apparently large random component. For most of the glaciers (Table 4), positive correlation of b'_w with b_w counteracts negative correlation of b'_s with b_s so that correlation of b'_n with b_n is weak. Year-to-year variations of all three gradients are poorly correlated from glacier to glacier, whereas the variations of the balance itself are strongly positively correlated for b_w, b_s and b_n.

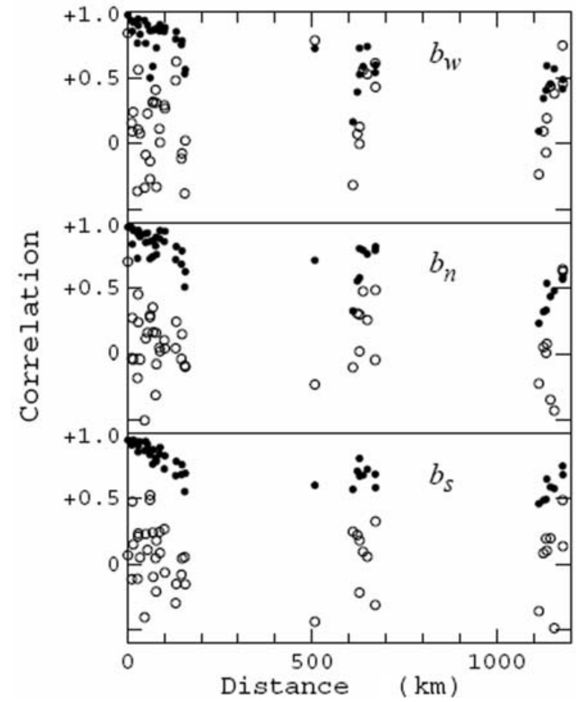

Fig. 6. Glacier-to-glacier correlation of balance b (solid circles) and of its gradient b' (open circles) vs distance D between the glaciers.

Absence of curvature in $b_s(z)$ might result from solar radiation not accounting for as much ablation in this cloudy, maritime climate as in other regions. Its effect is non-linear with altitude largely because of the altitude distribution of mean seasonal albedo. Solar radiation is more important at the eastern glaciers (numbered 8–10), but not as important as in strongly continental regions such as in the Alps or central Asia.

Turbulent fluxes might then dominate even in the low-albedo ablation zone of the glacier. Because temperature is a generally linear function of altitude and because wind speed might be relatively constant with altitude, as found by Greuell and Smeets (2001) on Pasterzenkees, Austria, the effect of the turbulent fluxes would also be roughly linear

Table 6. The r correlation between (1) balance at 1650 m on Nigardsbreen and (2) glacier-total balance at each glacier over n years of common record. The rms error is from the regression of (2) on (1). All r are significant at 99% except Langfjordjøkelen

Glacier	n	b_n r %	b_n rms m w.e.	b_w r %	b_w rms m w.e.	b_s r %	b_s rms m w.e.
1. Langfjordjøkelen	13	42	0.68	43	0.41	60	0.39
2. Engabreen	27	77	0.71	58	0.66	67	0.53
3. Ålfotbreen	32	89	0.65	87	0.54	81	0.44
4. Hansebreen	18	79	0.82	85	0.49	80	0.47
5. Austdalsbreen	16	96	0.35	93	0.26	92	0.30
6. Nigardsbreen	33	99	0.14	99	0.07	99	0.10
7. Hardangerjøkulen	32	92	0.40	87	0.38	92	0.23
8. Storbreen	33	89	0.28	90	0.17	92	0.20
9. Hellstugubreen	33	79	0.29	86	0.14	90	0.22
10. Gråsubreen	33	92	0.38	71	0.18	84	0.27

with altitude. The fact that the ten glaciers have little southern exposure would also contribute to the dominance of turbulent fluxes.

Linearity of $b_w(z)$ might be the result of two factors. One is that mountains in Norway are not so high that there is pronounced decrease of precipitation at higher altitude, which would impart $d^2b_w/dz^2 < 0$ curvature. Another is that winters are so cold that precipitation generally falls as snow over the entire altitude range of a glacier. Altitudinal variation of accumulation would then follow that of precipitation, which Oerlemans (1992) found to be linear at glaciers 3, 6 and 9.

If strongly negative b_s is produced by summers that are uncommonly sunny, the amount of solar radiation received by the glacier will be increased. Because surface albedo is lower in the ablation zone, the increase in melt there is expected to be greater than the increase higher on the glacier. This resulting steepening of the $b_s(z)$ profile contributes to the negative correlation between b_s and b'_s. No mechanism is apparent, however, for why b'_w correlates positively with b_w.

CONCLUSIONS

At the ten glaciers in Norway with long records, vertical profiles of seasonal mass balance are remarkably linear. The gradients of both b_w and b_s have little variation from year to year. A direct consequence of this property is that balance near the ELA correlates strongly with the glacier-total balance. This property, in combination with the strong correlation from glacier to glacier in the glacier-total balance, results in the strong correlation of seasonal balance near the ELA on one glacier with the glacier-total seasonal balance of other nearby glaciers.

It does not follow, however, that the regularity of the profiles is a basis for making a major reduction in the number of stakes used in the monitoring program. Stakes often disappear during winter due to heavy precipitation, as well as being prone to sinking and bending, and they sometimes melt out in summer due to the large mass turnover. Although Norway is better covered by glacier measurements than other glacierized regions, long-term mass-balance measurements exist for only 10 out of about 1600 glaciers. Continuing to monitor profiles of seasonal mass balance is also important for detecting deviations that might occur in extreme years or in a changed climate.

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