FIGURE 1. Map of the Svalbard archipelago. Screened lines mark boundaries between the 13 regions for which the mass balance has been calculated. Glaciers with mass balance measurements are shown by squares; circles are glaciers with shallow core drillings. K is Kongsfjorden, I is Isfjorden, and H is Hornsund.

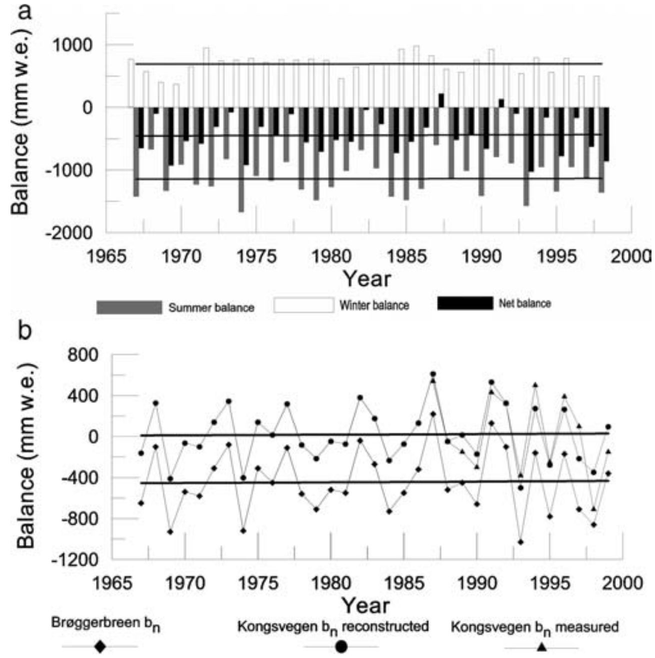

FIGURE 2. The time series of the individual mass balance components on Brøggerbreen (1967–1998) (5 km^2), the longest continuous series in Svalbard (upper). The lower graph shows the net balance on Kongsvegen (1986–1999) (102 km^2) and the good correlation between the net balance (b_n) at the two glaciers and reconstructed series for Kongsvegen. Note that Kongsvegen mean net balance is very close to zero, and that the linear trendlines show no trend in any of the series.

Svalbard (Hagen et al., 1993) (Fig. 1). For each region, a net mass balance per altitude ($b_n(z)$) curve was estimated, representing a mean of the spatial variability within that area. The net balance curves are also time-averaged values, in that they include mass balance and snow accumulation measurements acquired over the last 30 yr or so. Mass balance data from individual glaciers in Svalbard suggest that no temporal trend is present (Hagen and Liestøl, 1990; Lefauconnier et al., 1999), and thus the measurements should represent the present, or recent past, climate. The time series of the individual mass balance components on Brøggerbreen, the longest continuous series in Svalbard, and on Kongsvegen is shown to illustrate this in Figure 2.

The data used to construct the net mass balance/altitude curve in each region of the archipelago are derived from the following data series:

1. Yearly field measurements of winter accumulation, summer melting and net mass-balance at individual glaciers;
2. Point net balance measurements from shallow cores;
3. Snow-distribution maps obtained from depth-probing and ground-penetrating radar;
4. Equilibrium-line altitude (ELA) distribution maps derived from aerial photographs and satellite imagery.

Yearly mass balance components have been measured over periods of different length on a number of glaciers. The set of glaciers where mass balance has been measured systematically (both winter and summer mass balance) includes only about 0.5% of the total ice-covered area of Svalbard (Table 1). Most of these investigations have been carried out on small cirque glaciers at relatively low elevation, and thus they are not fully representative of the area/altitude distribution of the overall ice masses covering higher accumulation areas (Hagen, 1996, Melvold and Hagen, 1998). However, they give reliable estimates of the balance gradients and ELA in their regions and in the altitude interval they cover.

The longest series are from the Kongsfjorden area in the northwestern part of Spitsbergen (Fig. 1), where direct yearly measurements have been carried out continuously since 1967 and 1968 on two small glaciers Austre Brøggerbreen and Midre Lovènbreen, (both ca. 5 km^2) by Norwegian scientists (Hagen and Liestøl, 1990). These glaciers cover an altitude range from ca. 100 to 600 m a.s.l. Since 1987, the glacier Kongsvegen (100 km^2) has been measured, covering an altitude range from sea level to ca. 1000 m a.s.l., and thus covering higher altitude accumulation area. In south Spitsbergen, Polish researchers have been making mass balance measurements on Hansbreen since 1988/89, and over shorter periods Russian scientists have studied some glaciers in west Spitsbergen (Troitskiy et al., 1975, Jania and Hagen, 1996). The net balance of the measured glaciers has been generally negative during the ca. 30 yr of observations (Table 1), and no changing trend or increased melting has been observed over the last decades (Fig. 2). The glaciers have probably had a stable negative mass balance since about 1920 (Lefauconnier and Hagen, 1990). The glacier area/altitude distribution is important, however, and the measurements on Kongsvegen indicate that glaciers covering higher accumulation areas are closer to zero balance than the lower lying glaciers (Hagen, 1996).

In addition to systematic direct mass balance measurements, there are several point measurements of mean net balance. Shallow cores have been drilled in a number of places throughout the archipelago (Fig. 1) to detect radioactive reference horizons from the fallout of 1962–1963 nuclear bomb tests and from the early May 1986 Chernobyl nuclear accident (Pinglot et al., 1999). The reference layers could be detected in all cores in the accumulation area of the glaciers. Cores were taken at varying altitudes from the highest part of the accumulation area downward to below the ELA (Fig. 3), thus providing average net accumulation values and the net balance gradient for the ice-mass accumulation areas.

TABLE 1

Mean annual specific net mass balance (in water equivalent units) and ancillary information for the Spitsbergen glaciers at which field observations have taken place.

Glacier	Area (km^2)	N of obs.[a]	Mean net balance (m w.e. yr^{-1})	Standard dev. (mm yr^{-1})	Marine margin[b]
Austre Brøggerbreen	5	32	–0.45	0.32	N
Austre Grønfjordbreen	38[c]	6	–0.63	0.20	Y
Bertilbreen	5	11	–0.72	0.29	N
Bogerbreen	5	12	–0.43	0.36	N
Daudbreen	2	6	–0.36	0.27	N
Finsterwalderbreen	11	9	–0.51	0.59	N
Fridtjovbreen	49	5	–0.25	0.19	Y
Hansbreen	57	7	–0.52[d]	0.39	Y
Kongsvegen	102	12	0.04[d]	0.40	Y
Longyearbreen	4	6	–0.55	0.45	N
Midre Lovenbreen	6	28	–0.30	0.36	N
Vestre Grønfjordbreen	38[c]	4	–0.46	0.16	Y
Vøringbreen	2	18	–0.64	0.37	N

[a] N of obs. is the number of balance years for which measurements have been made (up to 1999).

[b] Y indicates that all or part of the glacier terminus is marine, and N that it ends on land.

[c] area of Grønfjordbreen as a whole.

[d] includes losses by iceberg calving.

On the larger ice caps in eastern Svalbard no mass balance data have been available. For our overall estimates for the whole archipelago it was important to specify the accumulation pattern on at least one of the large ice caps in eastern Svalbard in addition to the smaller ice masses in Spitsbergen. On the ice cap of Austfonna (8120 km^2), the largest ice cap in the archipelago (Fig. 1), an extensive study of the surface mass balance was carried out in the years 1998–2000. During two following years of spring field campaigns the winter accumulation was mapped and 29 shallow ice cores were retrieved (Fig. 3). The Chernobyl layer was located in 19 ice cores, all drilled in the accumulation area, and the nuclear test layer was located in two deeper ice cores (Pinglot et al., 2001). The temporal variation of the mean annual mass balance shows that no variation occurred for the two

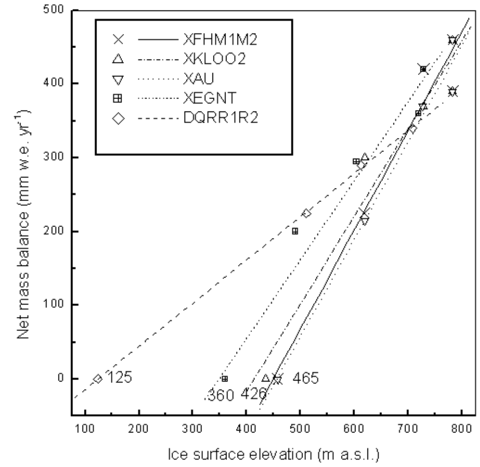

FIGURE 4. Net accumulation gradients and ELA-estimates from shallow cores at different altitudes in the transects shown in Figure 3 on the Austfonna ice cap. The letters refer to core-sites given in Figure 3.

time periods, namely from 1963 to 1986, and from 1986 to 1999. Based on the average net accumulation and the altitude of the core sites Pinglot et al., (2001) established net balance gradients in the accumulation area in five transects radiating from the crest of the ice cap (Figs. 3, 4). These gradients have been used to estimate ELA along the transects. Almost no information exists on the ablation rate in the lower part of Austfonna, we have therefore assumed that the shape of the net balance curves $b_n(z)$ is similar to those found in other parts of Svalbard and used that to extrapolate the net balance curves found in the accumulation area down into the ablation area. However, the net balance curves are steeper in Nordaustlandet than in west Spitsbergen (Fig. 5) indicating that the conditions are drier and colder in the northeastern part of the archipelago. Limited data exist for region 1,7 and 13, and again the linear model was used based on few points, ELA pattern and information from the nearest regions.

On Storøyjøkulen (ca. 30 km^2) on the island of Storøya, east of Nordaustlandet, Swedish glaciologists obtained mass balance information and the accumulation pattern in the years 1976 to 1978

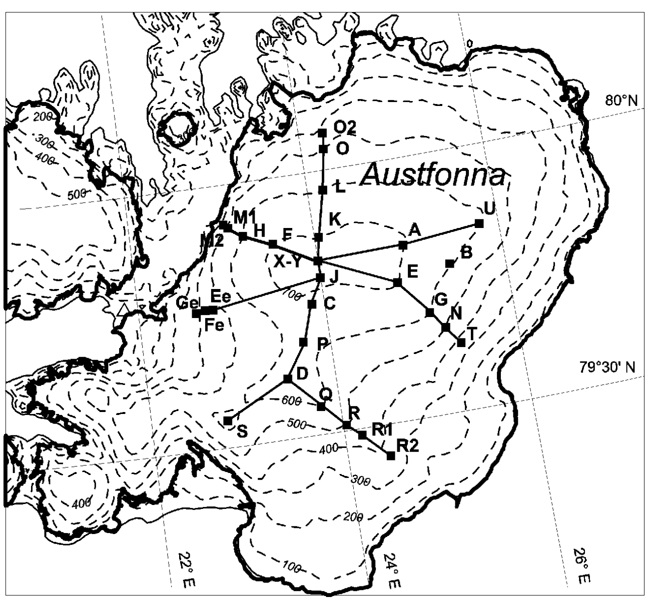

FIGURE 3. Shallow core network (squares) and snow radar survey in transects on the Austfonna ice cap, Nordaustlandet.

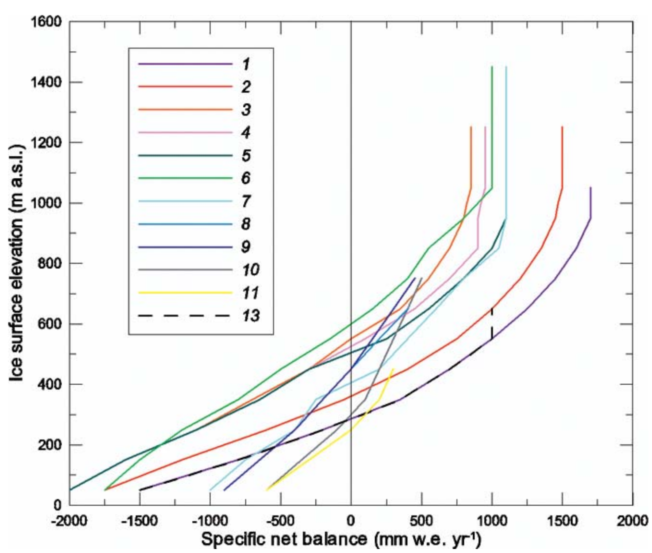

FIGURE 5. Specific net balance/altitude curves $b_n(z)$ *in the thirteen different regions of Svalbard, numbers corresponds to region numbers given in Figure 1.*

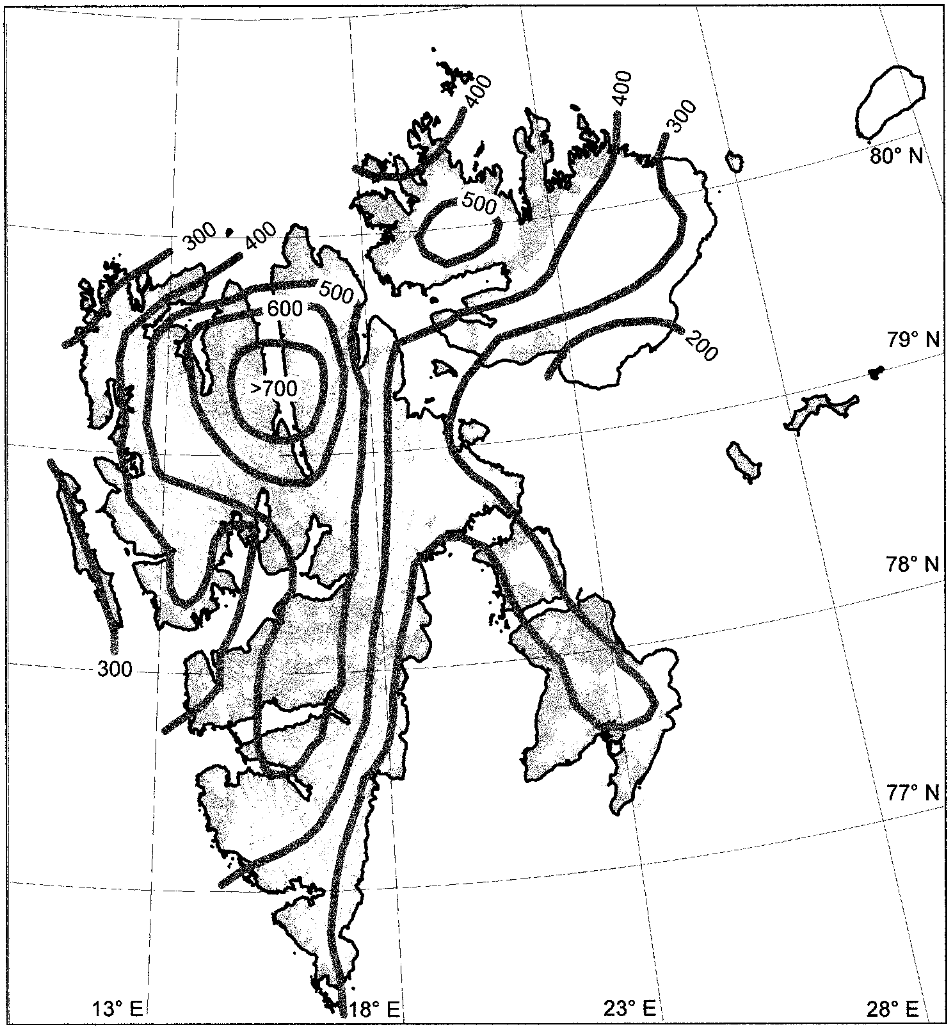

FIGURE 6. Distribution pattern of the equilibrium-line altitude in Svalbard given as 100-m contour intervals.

(Jonsson, 1982). They found that the ELA was as low as between 100 and 150 m a.s.l., the accumulation pattern was asymmetrical as on the Austfonna ice cap with highest accumulation in southeast. The highest part of the ice cap is only ca. 240 m a.s.l., and superimposed ice was formed all over the ice cap.

Superimposed ice and internal refreezing is formed all over Svalbard. However, when using the net balance data obtained from core data the average net balance should be correct when assuming that the density below the reference horizon is constant over time.

Snow accumulation distribution on Spitsbergen, Svalbard, has been mapped by depth-probing and ground-penetrating radar in some selected east-west profiles following many of the large glaciers in Spitsbergen (Winther et al., 1998) and on Austfonna (Pinglot et al., 2001). The results from Winther et al. confirmed the precipitation pattern with higher accumulation rate and thus lower ELA in the eastern part of Spitsbergen compared to the western part as shown in Figure 6.

The ELA can be derived from aerial photographs and satellite imagery in addition to the altitude given from the direct measured glaciers and the shallow cores. In the *Atlas of Glaciers in Svalbard and Jan Mayen*, Hagen et al. (1993) published a map of the distribution of the ELA in Svalbard. However, very little information was available from the eastern part of the archipelago. The satellite imagery mainly gives information about the snowline, which is at higher altitudes than the actual ELA due to the formation of superimposed ice. No general function has been established between the snowline and the ELA, but the pattern of the ELA distribution is likely to have the same shape as the snowline distribution. This linkage was used by Hagen et al. (1993) for Spitsbergen and by Dowdeswell and Bamber (1995) on the islands Barentsøya and Edgeøya in eastern Svalbard to give information about the ELA pattern. The ELA map in Figure 6 shows the pattern of the current ELA. The map reflects the precipitation pattern in Svalbard; the higher the ELA, the lower is the snow accumulation.

In the calculations of the surface net balance we estimated the average net balance gradient ($\delta b_n/\delta z$) or change in net balance per unit change in altitude in each of the 13 regions of Svalbard (Fig. 5). Hypsometric data for each region were taken from digital elevation models with a 100 m horizontal resolution, produced from Norsk Polarinstitutt topographical maps at a scale of 1:100,000 (contour interval 50 and 100 m). From the net balance curves $b_n(z)$ and the altitude models $A(z)$ we obtained the specific net balance b_{ni} and the surface area A_i for each altitude interval. Thus, the total net balance per year (B_n) in each region can be given from:

$$B_n = \sum_{i=1}^{k} b_{ni} \cdot A_i \,[\mathrm{km}^3\ \mathrm{yr}^{-1}] \qquad (2)$$

where i is altitude interval $i = 1$ (0–100 m a.s.l.) $i = 2$ (100–200) ... $i = k$. The total overall net surface balance, Q_n, combining all 13 regions ($Q_n = \sum B_{nj}, j = 1, \ldots, 13$), was found to be slightly negative:

$Q_n = -0.5 \pm 0.1$ km^3 yr^{-1}. The mean specific surface net mass balance can then be given for the overall ice masses by: $b_n = Q_n/A$, giving $b_n = -14 \pm 3$ mm yr^{-1}. The overall area/altitude distribution of specific ($b_n(z)$) and total net balance ($Q_n(z)$) is shown in Fig. 7.

The result depends of the accuracy of the net balance curves $b_n(z)$. The error bars are only based on a qualified assessment. It is difficult to give quantified estimates of the error in these curves. The altitude of the ELA is fairly good. The error of individual mass balance measurements on monitored glaciers can be given by statistical methods and error analysis to assess and quantify the accuracy, but no consensus appears on error estimates even for glaciers on which traditional mass balance measurements are carried out. The reason for that is that there are a number of possible error sources. In our case, where we extend data from few areas and points to cover large areas, it is the representativness of the points that brings in the largest error. It is a matter of subjective evaluations and experience when we combine all available data to obtain the net balance curves. The result from many shallow cores taken in different altitudes is that they can be used to give the net balance curve with fairly good accuracy. This has been shown on Kongsvegen where good correlation was found between core data and direct measurements of the net balance per altitude, $b_n(z)$, based on annual measurements of accumulation and ablation (Lefauconnier et al. 1994a). The errors in the lower ablation areas are probably larger than in the accumulation areas since they are based on fewer points and in many parts just on the linear model. However, we believe that this crude estimate and extrapolation of data to obtain the overall net balance is far better than former estimates based on only individual glaciers. Since the curves $b_n(z)$ are based on direct measurements of the net balance the uncertainty in total overall net surface balance is less than in the estimates of the individual accumulation and ablation volumes.

The annual surface accumulation (Q_a) and the annual surface melting (Q_m) roughly estimated over the Svalbard archipelago and based on a subset of the data for the net balance calculations, give a total of close to 25 ± 5 km^3 yr^{-1} for both the accumulation and the ablation without calving. This corresponds to a specific value of 680 ± 140 mm yr^{-1}.

Iceberg Production

The ice flux at the marine glacier margins of Svalbard is the product of terminus velocity, ice thickness at the calving front, and the horizontal width of the ice front. The average thickness of the 1000-km-long calving front in the archipelago is estimated to be about 100 m, although many outlet glaciers have no ice-penetrating radar or marginal bathymetric data. All margins are grounded. Many of these ice fronts are relatively slow-moving or stagnant with velocities of less than 10 m yr^{-1}, although some relatively fast-flowing outlet glaciers flow at 50 to 100 m yr^{-1} and sometimes a little more (e.g., Dowdeswell and Collin, 1990; Lefauconnier et al., 1994b). The bigger iceberg producers are dominant. There are few glaciers where surface velocity measurements and calving estimates have been carried out. Lefauconnier et al. (1994b) tracked ice-surface features on sequential SPOT imagery to calculate ice velocity, which was combined with field measurements of terminus thickness of Kronebreen (ca. 700 km^2) in Kongsfjorden in northwest Spitsbergen to yield a calving rate of 0.25 km^3 yr^{-1}. Kronebreen is by far the fastest-flowing glacier in Svalbard with a velocity of about 2 m d^{-1} at the front. Field surveys of changing ice-cliff height, calving events and surface velocity at its marine margin have allowed the rate of mass loss to be estimated at Hansbreen (57 km^2), in south Spitsbergen (Jania and Kaczmarska, 1997). A calving rate of ca. 0.02 km^3 yr^{-1} was found, which is an important part of the mass loss (ca. 30%), equivalent to ca. 0.35 mm yr^{-1} water equivalent on the glacier surface. In Basin 5, a 670 km^2 drainage basin of the ice cap Austfonna, Dowdeswell and Drewry (1989) found a velocity of ca. 40 m yr^{-1} at the calving terminus. On Austfonna, flow velocities have also been measured from remote sensing data by interferometry (Dowdeswell et al., 1999), but a full calculation of mass loss by calving awaits the associated marginal ice-thickness data.

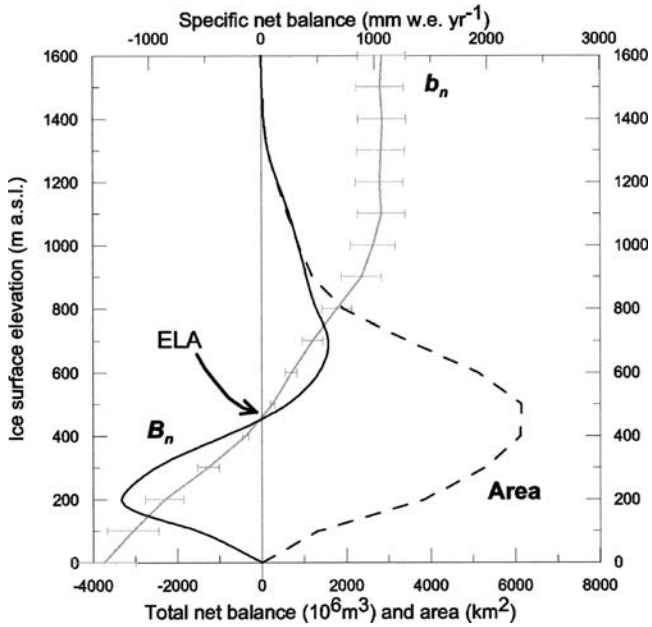

FIGURE 7. Average specific net balance with elevation $b_n(z)$*, total net balance* $Q_n(z)$ *and area with altitude for Svalbard ice masses showing that the equilibrium line is very close to the peak of the hypsometric curve.*

Over the last nearly 100 yr the glacier fronts in Svalbard have been generally retreating, thus giving larger calving rates than in a steady state situation. In the Hornsund fjord (Fig. 1) the tidewater glacier fronts have retreated and an area of about 90 km^2 have been deglaciated over the last 90yr (0.1 km^3 yr^{-1}) (Jania, 1988). Any advance or retreat of the ice front must also be considered when calving rates are estimated.

Compiling the available information together, an initial estimate of the average velocity of calving fronts through the archipelago is about 20 to 40 m yr^{-1}. Thus, with an average margin thickness of 100 m and 1000 km length, the current calving ice flux is estimated to be about 3 ± 1 km^3 yr^{-1}. In addition to this the retreat of the calving glacier fronts is estimated to give 1 km^3 yr^{-1}. This estimate does not take into account the annual height change from melting. The total calving loss Q_c is thus estimated to be about 4 ± 1 km^3 yr^{-1}.

An additional complication to the assessment of the rate of iceberg calving within Svalbard, is that a number of glaciers and ice-cap drainage basins undergo periodic surges (Hagen et al., 1993; Hamilton and Dowdeswell, 1996). Between the active surge advances, the termini of these ice masses are largely stagnant, contributing little to mass loss through iceberg production (Melvold and Hagen, 1998). In years when major Svalbard tidewater outlet glaciers surge, several cubic kilometers of ice can be released to the adjacent seas, and thus in years with such events the above estimate of calving rate can be far too low. The general retreat of calving and surging glaciers over the last hundred years has been mapped along the east coast of Spitsbergen by Lefauconnier and Hagen (1991). The largest surge observed was at Bråsvellbreen in 1936 to 1938 (Liestøl, 1969). This outlet from the Austfonna ice cap is about 1100 km^2 and is grounded in water in a 30 km long glacier front. During the surge the front advanced up to 20 km (Schytt 1969). Negribreen in the inner part of Storfjorden, east Spitsbergen, surged in 1935 to 1936 and advanced about 12 km in less than a year along a 15-km-long section of the front. That is an average speed of 35 m d^{-1} (Liestøl, 1969). The 1250 km^2 Hinlopenbreen surged in 1970 and calved about 2 km^3 of icebergs in a single year (Liestøl, 1973). Synoptic satellite SAR investigations of ice-surface velocities on Svalbard ice caps and glaciers will eventually provide, together with airborne ice-penetrating radar measurements of ice thickness, a more complete dataset on iceberg calving (Dowdeswell et al., 1999).

Concluding Remarks

The actual total net surface balance, Q_n, combining all regions of Svalbard, was found to be slightly negative: $Q_n = -0.5 \pm 0.1$ km^3 yr^{-1}. The calving loss, Q_c, was estimated to be $-4 \pm 1 km^3$ yr^{-1}. The overall net balance of Svalbard ice masses is then:

$$\partial V / \partial t = Q_n + Q_c = -4.5 \pm 1\,\mathrm{km}^3\ \mathrm{yr}^{-1} \quad (3)$$

giving a specific net balance $b_n = -120 \pm 30$ mm yr^{-1} in water equivalent. The contribution of the ice caps and glaciers on Svalbard to global sea-level change is then $\partial h / \partial a \approx \partial V / (\partial a\ A_{sea})$ ≈ 0.01 mm yr^{-1} as an average value over the last 30 yr. This is less negative than earlier estimates based on net mass balance data for individual glaciers where stake measurements of accumulation and ablation have taken place (Dowdeswell et al., 1997).

The use of regionally derived net balance gradients and hypsometries is of particular importance because the overall mass balance of Svalbard can then be calculated in regionally representative height intervals of 100 m instead of using the mean specific values given for a small number of individual glaciers. Due to the area/altitude distribution of the measured glaciers, the negative mass balance values of these glaciers have usually given an overestimated sea-level contribution. Recent 10-yr- interval repeated GPS profiling over some large ice fields in Spitsbergen has also indicated that the higher accumulation areas are more stable and do not show the same shrinking as the smaller cirque and valley glaciers at lower altitudes (unpublished data).

Our analysis shows how important the area/altitude distribution within the archipelago is for the sensitivity of the glacier mass balance to climate changes. A diagram of the total net balance and area per altitude increment shows that the present equilibrium line is very close to the bulk of the glacier area (Fig. 7). Thus, the net surface balance of Svalbard glaciers and ice caps is sensitive to quite small changes in the equilibrium line altitude, with a shift of a few tens of meters up or down having a large effect on the total mass balance due to the nature of the hypsometric distribution. The analysis also indicates that it is important to monitor the mass balance per altitude and give these values in addition to the mean specific mass balance of a glacier.

The net loss of mass through iceberg calving appears to be a very important component of the net mass loss from Svalbard ice masses, even though the ice velocities at the 1000-km-long calving front are for the most part quite low and are certainly rather poorly specified. The total surface accumulation and melting was estimated to be close to 25 ± 5 km^3 yr^{-1}. This corresponds to a specific runoff value of 680 ± 140 mm yr^{-1}. The yearly calving volume of 4 ± 1 km^3 is thus only about 16% of the volume lost by melting. In spite of that, it is an important part of the net balance calculations. In the colder conditions of Severnaya Zemlya, 1600 km east of Svalbard, iceberg calving accounts for 35 to 40% of total mass loss from the 5500 km^2 Academy of Sciences Ice Cap (Dowdeswell et al., 2002). Calving is likely to be increasingly important in colder glacial environments.

We derived a value of 0.01 mm yr^{-1} as our best estimate of the contribution of Svalbard ice masses to sea-level rise. Svalbard is about 15% of the total for the Arctic islands, as calculated by Dyurgerov and Meier (1997a). However, we have indicated that although our value is derived not just from net mass balance observations at a set of glaciers, but also from other measurements of accumulation and the way that it varies spatially across the archipelago and with altitude, it is still an imperfect estimate. We need better spatial information about the ablation rate in lower altitudes where ice core measurements cannot give any net balance data. Almost all Svalbard glaciers have been observed to retreat in the time since the end of the LIA about 80 to 90 years ago. This is a convincing indication that the glacier mass balance over the archipelago has been generally negative over this period. The mass loss from iceberg calving is clearly a very important part of the overall mass balance equation for the very many Arctic glaciers and ice-cap outlets that end in the adjacent seas. It has, however, been calculated for a very small number of Arctic glaciers and ice caps.

Acknowledgments

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