Mass balance of three Svalbard glaciers reconstructed back to 1948

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Abstract

A simple model using upper-air meteorological variables in the NCEP-NCAR Reanalysis database is used to model seasonal components of mass balance of three glaciers in Svalbard. The model was originally developed for glaciers in North America, and has been applied to glaciers in Norway, Sweden and Iceland. Over the period for which mass balance data are available for the three Svalbard glaciers, the model fit yields r^2 values ranging from 0.46 to 0.61 for winter balance B_w and from 0.56 to 0.59 for summer balance B_s. Sensitivity to +1°C warming was about −0.36 m yr^{-1} water equivalent (w.eq.), caused mainly by increased ablation and secondarily by shift of precipitation from snow to rain. Sensitivity to a 10% increase in precipitation was about +0.06 m yr^{-1} w.eq. The model, calibrated over the period of observations, was used to extend the mass balance series back to 1948. At annual resolution, observed mass balance of the three glaciers correlates poorly with both the North Atlantic Oscillation (NAO) and with glaciers in Norway. Over two multiyear periods, the strongly positive NAO period 1990–1996 and the period afterward, glaciers in both Svalbard and especially Norway showed a pronounced decline in B_w. However, B_s for Svalbard glaciers was not more strongly negative after 1996, in contrast to glaciers in Norway.

Glacier volume changes fundamentally in response to climate change. Glacier volume changes over long timescales amount to changes in glacier thickness or, equivalently, in the surface elevation, and can be studied using comparison of maps or digital elevation models. On shorter timescales, mass balance measurements are used to characterize changes. Glacier mass balance is the quantity of snow and ice either lost or gained on a particular glacier, and represents the material flux through the glacier surface over an interval of time.

Although volume change estimates for glaciers arguably go as far back as the 1700s, in the form of front position measurements (Oerlemans 2001), the longest continuous annual mass balance measurements only date back to the 1940s. The latter are for glaciers in Scandinavia; in the Arctic, mass balance time series are even shorter, only going back to the early 1960s. The three glaciers considered in this paper, Austre Brøggerbreen, Midre Lovénbreen and Kongsvegen in western Svalbard (Fig. 1) have some of the longest time series (1967–present, 1968–present and 1987–present, respectively) in the High Arctic. A detailed description of the glaciers can be found in Lefauconnier et al. (1999).

Previous workers have sought to extend the mass balance record for these glaciers. Hagen & Leistol (1990) used meteorological measurements at Ny-Ålesund in a positive degree day (PDD) model of summer balance B_s at Midre Lovénbreen. Lefauconnier & Hagen (1990) used multivariable linear regression between Ny-Ålesund observations and Austre Brøggerbreen net or annual mass balance B_n. DeWoul & Hock (2005) applied a PDD model of ablation, using daily observations of temperature at Ny-Ålesund, and linear regression between precipitation observations there and accumulation for each of the three glaciers.

In this paper we extend the mass balance using a simple model driven by upper-air meteorological variables in the NCEP-NCAR Reanalysis database. The database has the advantage that it is global in extent, has 6-h temporal resolution, is free from missing observations and is main-

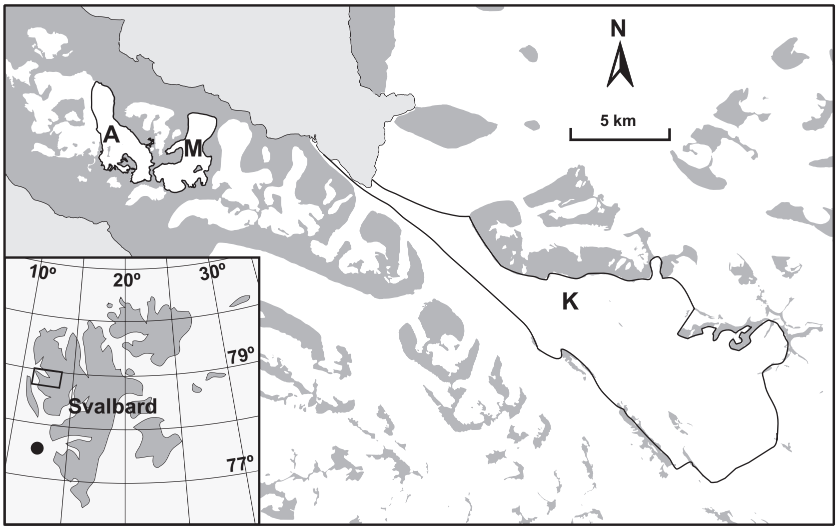

Fig. 1 Map showing the three study glaciers: Austre Brøggerbreen (A), Midre Lovénbreen (M) and Kongsvegen (K). Upper-air conditions are taken at the NCEP-NCAR Reanalysis gridpoint nearest the glaciers at 77.5 °N, 12.5 °E (filled circle).

tained as an integral part of a major scientific enterprise. The model was developed with data from South Cascade Glacier (48.4° N, 121.1° W): first for winter balance B_w (Rasmussen & Conway 2001) and then for B_s (Rasmussen & Conway 2003). It was successfully applied to glaciers in Alaska (Rasmussen & Conway 2004), Scandinavia (Rasmussen & Conway 2005) and Iceland (Rasmussen 2005).

Data

US National Centers for Environmental Prediction and US National Center for Atmospheric Research (NCEP-NCAR) Reanalysis data (Kalnay et al. 1996; Kistler et al. 2001) give values of meteorological variables at many levels in the atmosphere at 10 512 gridpoints spanning the entire globe, at integral multiples of 2.5° in both latitude and longitude. Data for 1948–2005 at the 1000- and 850-hPa levels were downloaded from East Anglia University, UK (http://www.cru.uea.ac.uk/cru/data/ncep).

Variation of mean September–May upper-air variables with wind direction at the Reanalysis gridpoint (77.5° N, 12.5° E; Fig. 1) is shown in Fig. 2. Their seasonal variation is shown in Fig. 3, along with the precipitation flux F and snow flux f (Eqns 1–3) calculated from direction $\phi' = 210°$. Both figures show that f is strongest when the wind is from the south-west.

The glacier mass balance data used are winter, summer and net balances B_i, where i = winter, summer and net for the years 1967–2005 (Austre Brøggerbreen), 1968–2005 (Midre Lovénbreen) and 1987–2005 (Kongsvegen) (Hagen et al. 2003; Kohler, unpubl. data). Standard deviations of the seasonal balance components are shown in Table 1. The correlations r_{ns} of B_n with B_s are larger than

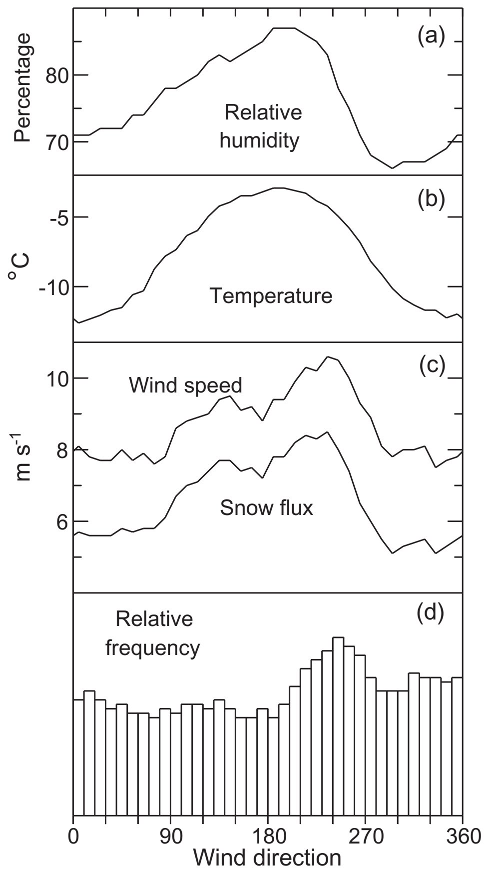

Fig. 2 Variation with wind direction of mean September–May conditions over the period 1948–2005 at the NCEP-NCAR Reanalysis gridpoint (77.5 °N, 12.5 °E): (a) relative humidity RH, (b) temperature T, (c) wind speed and snow flux $\bar{f}_w$ and (d) frequency distribution of wind direction. RH and wind are at 850 hPa; T and $\bar{f}_w$ are at 200 m.

r_{nw} (B_n with B_w), in rough proportion to the amount by which σ_s is larger than σ_w, because the correlation r_{ws} between B_w and B_s is so small (see Eqn 13 of Rasmussen & Conway 2001). The r_{ws} are small, as is the case for glaciers elsewhere in the world (see fig. 6 of Dyurgerov & Meier 1999; and fig. 5 of Braithwaite & Zhang 1999). Glacier to glacier correlation of B_s and of B_w are both coherent spatially (Table 2).

Recent variations

Although mass balance at the three Svalbard glaciers correlates poorly with the mass balance at glaciers in northern and maritime Norway (Rasmussen, in press), they do share some longer-term characteristics. Correlations of B_n and B_s between the two regions are positive but small. Correlations of B, and of B_3 between the two regions are positive but small, and those of B_w are negative but small. The only exceptions are $r(B_n) = 0.69$ between Kongsvegen and Langfjordjøkelen (70.1° N, 21.8° E) and $0.47 < r(B_s) < 0.50$ for the three glaciers with Engabreen (66.6° N, 13.8° E). Correlation with three different measures of the North Atlantic Oscillation (NAO) that are significant at annual resolution for glaciers in Norway with $r(B_n) > 0$ and $r(B_w) > 0$ are negligible for all three glaciers in Svalbard. Low correlation with the NAO was also found by Pohjola & Rogers (1997), Nesje et al. (2000) and Washington et al. (2000). There were some similar changes in the two regions, however, over multi-year periods in phase with the NAO regime. At ten glaciers in Norway the mean change in the mass balance components δB_i (in units of m w.eq.) obtained from comparing the strong NAO period 1990–1996 with the following period 1997–2004 was $\delta B_n \approx -1.0$, consisting of changes $\delta B_w \approx -0.4$ and $\delta B_s \approx -0.6$ (Andreassen et al. 2005). At the glaciers in Svalbard, changes between 1990–1996 and 1997–2005 were $-0.29 < \delta B_w < -0.18$, all significant at 99%, but changes in summer balance $-0.13 < \delta B_s < +0.03$ were weaker.

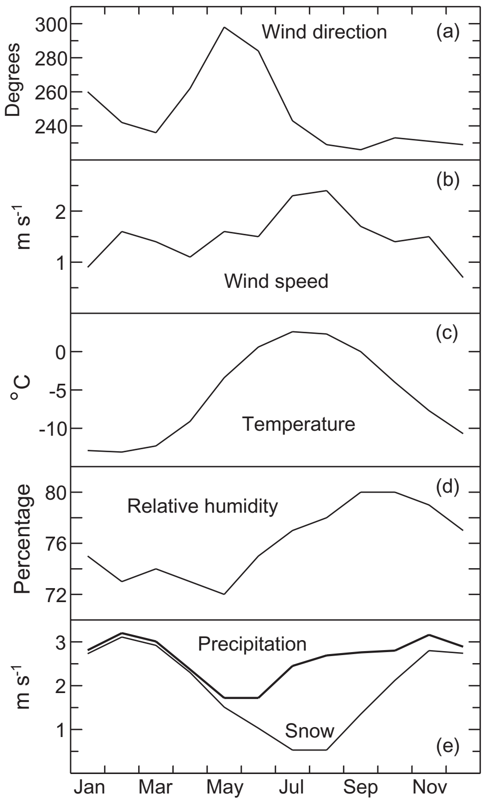

Fig. 3 Seasonal variation of mean conditions over the period 1948–2005 at the NCEP-NCAR Reanalysis gridpoint (77.5 °N, 12.5 °E). (a) Wind direction at 850 hPa, (b) wind speed at 850 hPa, (c) temperature T interpolated at 200 m, (d) percentage relative humidity RH at 850 hPa and (e) precipitation flux F calculated from Eqns (1) and (2) using $\phi' = 210°$ and snow flux f, the part of F when $T < +2$°C at 200 m. Monthly resolution.

Upper-air model

Precipitation at the glacier is assumed to be proportional to the precipitation flux F at the 850-hPa level. It is estimated from measurements of wind and humidity by the relation

$$F = \begin{cases} U\ \mathrm{RH} & (U \geq 0) \\ 0 & (\text{otherwise}). \end{cases} \tag{1}$$

Table 2 Glacier to glacier correlation (percentage r, significant at 99%) of winter balance B_w (above the diagonal) and summer balance B_s (below the diagonal) over the common period of observations. Values on the diagonal are for both B_w and B_s.

Glacier	1	2	3
1 Austre Brøggerbreen	100	94	76
2 Midre Lovénbreen	96	100	80
3 Kongsvegen	90	84	100

Table 1 Mean and standard deviation (both in m water equivalent [m w.eq.]) and correlation (percentage r) of seasonal mass balance components over the period of record of observations (n years). All r_{nw} and r_{ns} are significant at 99%.

Glacier	°N	°E	n	$\overline{B}_w$	$\overline{B}_s$	σ_w	σ_s	r_{nw}	r_{ns}	r_{ws}
Austre Brøggerbreen	78.9	11.8	39	0.67	–1.16	0.15	0.30	43	89	–3
Midre Lovénbreen	78.9	12.1	38	0.70	–1.09	0.17	0.29	40	84	–16
Kongsvegen	78.8	13.0	19	0.71	–0.79	0.19	0.28	74	89	36

Here, $0 \le \mathrm{RH} \le 1$ is the relative humidity, and U is the component of the 850-hPa wind in the empirically determined critical direction ϕ'. That is,

$$U = |\vec{V}_{850}|\cos(\phi_{850} - \phi'), \tag{2}$$

in which ϕ_{850} is the wind direction and $|\vec{V}_{850}|$ is its speed in ms^{-1}. Although precipitation indeed might occur with the wind in the opposite direction to ϕ', empirical results show it correlates most strongly with the U component. Moreover, the simple model described here obtained better results (Hayes et al. 2002) in a direct comparison with a sophisticated mesoscale precipitation model.

Precipitation is assumed to fall as snow if the temperature at elevation $z_1 = 200$ m is less than the critical temperature T'

$$f = \begin{cases} F & (T(z_1) \le T') \\ 0 & \text{(otherwise)}. \end{cases} \tag{3}$$

Here f is termed the snow flux, $T(z_1)$ is interpolated between the 1000- and 850-hPa levels in the NCEP-NCAR Reanalysis data, and $T' = +2°\mathrm{C}$ is the rain–snow discriminator (Oerlemans 1993; Rasmussen et al. 2000; Forland & Hanssen-Bauer 2003; Kohler & Aanes 2004). The physical basis for using +2°C as the discriminator is that precipitation forming at high altitude as snow requires a layer of air with T > 0°C to change to rain; at the average wet adiabatic lapse rate of −6°C km^{-1}, +2°C corresponds to a layer thickness of ≈300 m.

The model estimates winter balance B_w^* by

$$B_w^* = \alpha_w \bar{f}_w + \beta_w \tag{4}$$

Coefficients α_w and β_w are obtained by linear regression of observed winter balance B_w and $\bar{f}_\mathrm{w}$, which is the September–May average of f. Because RH is dimensionless, both F and f have the same units as U (ms^{-1}), so α_w has units to convert to m w.eq.

The quantity $\alpha_\mathrm{w}\bar{f}_\mathrm{w}$ corresponds most closely to actual snowfall, but is higher by about a factor of two than the September–May precipitation measured at Ny-Ålesund, which might reflect either higher precipitation on the glaciers caused by orographic lifting or undercatch in the precipitation gage (e.g. Forland & Hanssen-Bauer 2000).

The model estimates summer balance B_s^* by

$$B_s^* = \alpha_s \bar{T} + \beta_s, \tag{5}$$

in which $\bar{T}$ is the June–August average of temperature interpolated at altitude $z_2 = 500$ m between the 1000- and 850-hPa levels, considering only $T' > T''$, where T'' is the degree-day temperature threshold, here taken to equal 0°C. Coefficients α_s and β_s are obtained by linear regression of the observed summer balance B_s with $\bar{T}$.

Both B_w^* and B_s^* are estimated from upper-air conditions at the NCEP-NCAR Reanalysis gridpoint 77.5° N, 12.5° E. Mean winter conditions for the period 1948–2005 are shown in Fig. 2. The only model parameter that was varied experimentally to optimize the model results was the critical direction ϕ' (Table 3). All the other parameters, the altitudes $z_1 = 200$ m and $z_2 = 500$ m, the critical temperatures $T' = +2°\mathrm{C}$ and $T'' = 0°\mathrm{C}$, and the seasons September–May and June–August, were held constant. For each glacier, model parameters α and β were determined by the regressions of Eqns (4) and (5) fitted to the observed B. For all three glaciers $\beta_\mathrm{w} \approx 0.05$ so that $\alpha\bar{f}_\mathrm{w}$ accounts for almost all of B_w^*.

Model results

Model estimates of seasonal components, both of which are identified by the calendar year in which the balance year ends, are illustrated in Fig. 4. As pointed out by von Storch (1999), the variance of regression results is smaller than that of the variable being fitted (unless the regression fits it exactly).

Goodness of fit (Bevington 1969) is expressed by the coefficient of determination

$$r^2 = 1 - \left(\frac{\mathrm{rms}}{\sigma}\right)^2. \tag{6}$$

Here, rms is the root mean square of the differences between the model estimates B^* and the measured values B, and σ is the standard deviation of B. Results are shown in Table 3. They are generally much better for B_w and slightly worse for B_s compared with those obtained by deWoul & Hock (2005).

Table 3 Model results (percentage r^2 and m water equivalent [m w.eq.], per year rms) over the period of record using critical direction ϕ' with upper-air model and $\hat{r}_w^2$ and $\hat{r}_s^2$ from deWoul & Hock (2005). Models: (1) upper-air model, (2) correlation with Austre Brøggerbreen, (3) average of models (1) and (2).

Glacier	Model	ϕ'	r_w^2	r_n^2	r_s^2	rms_w	rms_n	rms_s	$\hat{r}_w^2$	$\hat{r}_s^2$
Austre Brøggerbreen	1	210	49	55	56	0.11	0.23	0.20	<15	61
Midre Lovénbreen	1	210	46	52	56	0.12	0.21	0.19	<15	76
Kongsvegen	1	235	61	68	59	0.12	0.22	0.18	67	68
Kongsvegen	2		58	80	80	0.13	0.18	0.13		
Kongsvegen	3		67	80	77	0.11	0.17	0.14		

Hagen & Leistøl (1990) obtained linear relations between Lovénbreen B_s and Ny-Ålesund meteorological observations with $r = 0.75$ for June–August temperature and $r = 0.88$ for June–September PDD. Lefauconnier & Hagen (1990) used multivariable linear regression to relate Brøggerbreen B_n to Ny-Ålesund observations, obtaining $r^2 = 0.77$ with July–August PDD and October–May precipitation, whereas with PDD taken separately for four individual summer periods, r^2 increased to 0.81.

Our model results are only weakly sensitive to values of model parameters z_1 and z_2 as well as to the period of days over which averages are formed. If the period of forming $\bar{f}_w$ is extended into June, for instance, it will be lower because f decreases in June (Fig. 3); in the regression of Eqn (4), however, the coefficient α_w will tend to increase so as to match the observed B_w as well as possible with the smaller $\bar{f}_w$. Varying z_2 has little effect because $\bar{T}$ appears linearly in Eqn (5) and $T(z)$ is roughly linear, so that α_s will be adjusted during the regression by an amount roughly proportional to the product of the lapse rate dT/dz and the difference in z_2, so as to match the observed B_s as well as possible.

The values for the critical direction ϕ' are slightly different for Kongsvegen and the two smaller glaciers Austre Brøggerbreen and Midre Lovénbreen. This might reflect local topographic effects as the accumulation area of the smaller glaciers is protected from southerly winds by surrounding mountains, whereas snowfall on the more exposed Kongsvegen is more susceptible to wind redistribution. On the other hand, the differences in critical direction ϕ' are relatively small, so this may simply reflect random errors in the data.

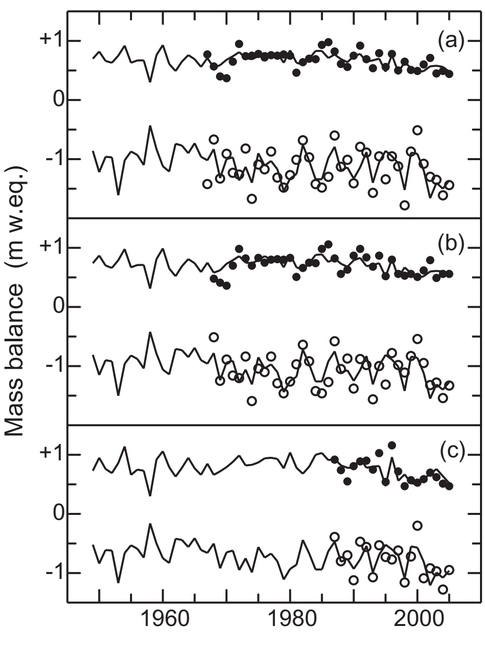

Fig. 4 Model (line) and observed seasonal mass balance components (●, winter balance [B_w]; ○, summer balance [B_s]). (a) Austre Brøggerbreen, (b) Midre Lovénbreen, (c) Kongsvegen.

Sensitivities of calculated B_w and B_s to hypothetical warming ΔT or increased precipitation ΔF are shown in Table 4. Sensitivities to ΔT are less than those found by deWoul & Hock (2005), and sensitivities to ΔF are about the same. A possible explanation of the lower B_s sensitivities compared with those of deWoul & Hock (2005) is that the upper-air model has arbitrarily fixed dates, and might therefore miss some ablation occurring in May or September.

Reconstructed mass balance, 1948–2005

For each glacier, coefficients of Eqns (4) and (5) obtained over the period of record (POR) of observations were applied to upper-air data from prior to the POR back to 1948. Cumulative B_n^* for Brøggerbreen and Lovénbreen is formed from $B_n^* = B_w^* + B_s^*$ for the years before the POR, and from observed B_n during the POR. For Kongsvegen, however, the model was used for 1948–1966, but for 1967–1987 B_n^* was taken to be the average of the model estimate and that of the linear correlation with Brøggerbreen.

As was the case for all seven glaciers in southern Norway, where the record from Storbreen spanned the entire period of model results, the average of the model and the linear correlation with Storbreen was a more accurate estimator than either the model alone or the correlation alone. For Kongsvegen, the rms error for the model was 0.22, and for the correlation with Brøggerbreen the rms error was 0.18. For the average of the model and the correlation it was 0.17.

Cumulative balance before 2005 (Fig. 5) is defined by

$$B_j = -\sum_{j}^{2004} B_{j+1}^*. \tag{7}$$

Here, B_j is the value of B_n^* in year j and B_{2005} is defined to be zero.

Table 4 Sensitivity (m water equivalent [m w.eq.]) to +1°C temperature change and to a 10% increase in precipitation flux F, from the upper-air model and from deWoul & Hock (2005).

	Upper-air			deWoul & Hock		
Glacier	dB_w/dT	dB_s/dT	dB_n/dF	dB_w/dT	dB_s/dT	dB_n/dF
Austre Brøggerbreen	−0.06	−0.33	+0.06		−0.47	
Midre Lovénbreen	−0.06	−0.30	+0.07		−0.56	
Kongsvegen	−0.06	−0.29	+0.07	−0.02	−0.41	+0.05

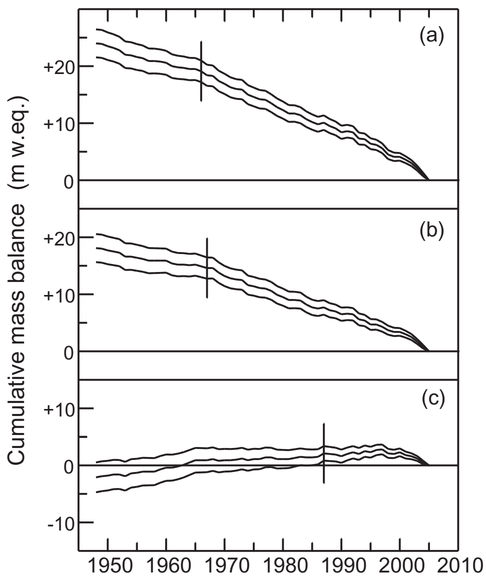

Fig. 5. Reconstructed mass balance (m water equivalent [m w.eq.]) prior to 2005, which is adopted as the datum according to Eqn 7. The error band is shown as $\pm 1\sigma$ (Eqn 9). The short vertical line indicates the start of observations. (a) Austre Brøggerbreen, (b) Midre Lovénbreen and (c) Kongsvegen.

For the years when B_n was measured, uncertainty is taken to be $\Delta_{obs} = 0.3$ m w.eq., and for years when it was not,

$$\Delta = \sqrt{\Delta_{obs}^2 + \Delta_{est}^2}, \tag{8}$$

in which the rms_n values from lines 1, 2 and 5 of Table 3 are used for Δ_{est}. On the assumption that errors in the combined reconstructed–observed series are uncorrelated from year to year, the uncertainty in the cumulative value B_j is

$$\sigma_j = \sqrt{\sum_j^{2004} \Delta_j^2}. \tag{9}$$

The cumulative curves in Fig. 5 are shown with a $\pm 1\sigma$ band. If there are systematic errors in the B_n^* series, however, the true σ_j will be larger.

Between the periods 1948–1967 and 1968–2005, net balance B_n became more negative, as shown by the change of mean slope of the cumulative curves in Fig. 5. This was caused by B_s becoming more negative, whilst B_w was little changed. For Austre Brøggerbreen between these periods, the mean $\overline{T}$ (Eqn 5) increased from 1.19 to 1.64°C, but the mean $\bar{f}_w$ (Eqn 4) declined only from 2.41 to 2.36 m s^{-1}.

Lefauconnier & Hagen (1990) used multivariable linear regression to relate B_n at Brøggerbreen to the July–August temperature and the September temperature at Longyearbyen over the period 1967–1988 with $r^2 = 0.52$. They obtained cumulative changes of −18 m over 1912–1948 and −9 m over 1948–1967. The 1948–1967 cumulative change from the upper-air model (Fig. 5) was −6 m.

Linear regression over the period of measurements of B_n at the three glaciers had $r = 0.96$ between Brøggerbreen and Lovénbreen and 0.90 between Brøggerbreen and Kongsvegen (see also Table 2). When these regression coefficients are applied to the −18 m cumulative change found by Lefauconnier & Hagen (1990), at Brøggerbreen, the 1912–1948 changes are −15 m at Lovénbreen and −2 m at Kongsvegen. Combined with the 1948–2005 changes (Fig. 5), the 1912–2005 changes are –42 m at Brøggerbreen, −33 m at Lovénbreen and 0 m at Kongsvegen.

Conclusions

The upper-air model gives a good fit to the observed balances, is substantially better than another published model for B_w at two glaciers, and is moderately worse for B_s. Its sensitivity of B_s to warming is less than that calculated by the other model, and its sensitivity of B_n to increased precipitation is about the same. The upper-air model has the advantage of using a database maintained as an integral part of an ongoing major scientific enterprise as its input. Calculations can therefore easily be extended as future mass balance measurements become available. Moreover, the model can also be used to estimate mass balance for years in which it is not measured. It could also be easily applied to mass balance records for other glaciers in Svalbard. Using upper-air data only at 0 Coordinated Universal Time (UTC) would probably give results that would be nearly as good as those obtained here by using upper-air values four times a day.

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References

Andreassen L.M., Elvehøy H., Kjøllmoen B., Engeset R. & Haakensen N. 2005. Glacier mass balance and length variations in Norway. *Annals of Glaciology 42*, 317–325.

Bevington P.R. 1969. *Data reduction and error analysis for the physical sciences*. New York: McGraw Hill.

Braithwaite R.J. & Zhang Y. 1999. Relationships between interannual variability of glacier mass balance and climate. *Journal of Glaciology 45*, 456–462.

deWoul M. & Hock R. 2005: Static mass balance sensitivity of Arctic glaciers and ice caps using a degree-day approach. *Annals of Glaciology 42*, 217–224.

Dyurgerov M.B. & Meier M.F. 1999. Analysis of winter and summer glacier mass balance. *Geografiska Annaler 81A*, 541–554.

Forland E.J. & Hanssen-Bauer I. 2000. Increased precipitation in the Norwegian Arctic: true or false? *Climate Change 46*, 485–509.

Forland E.J. & Hanssen-Bauer I. 2003. Past and future climate variations in the Norwegian Arctic: overview and novel analyses. *Polar Research 22*, 113–124.

Hagen J.O., Kohler J., Melvold K. & Winther J.-G. 2003. Glaciers in Svalbard: mass balance, runoff and freshwater flux. *Polar Research 22*, 145–159.

Hagen J.O. & Leistøl O. 1990. Long-term glacier mass-balance investigations in Svalbard, 1950–88. *Annals of Glaciology 14*, 102–106.

Hayes P.S., Rasmussen L.A. & Conway H. 2002. Estimating precipitation in the central Cascades of Washington. *Journal of Hydrometeorology 3*, 335–346.

Kalnay E., Kanamitsu M., Kistler R., Collins W., Deaven D., Gandin L., Iredell M., Saha S., White G., Woollen J., Zhu Y., Chelliah M., Ebisuzaki W., Higgins W., Janowiak J., Mo K.C., Ropelewski C., Wang J., Leetma A., Reynolds R., Jenne R., Joseph D. 1996. The NCEP-NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society 77*, 437–471.

Kistler R., Kalnay E., Collins W., Saha S., White G., Woollen J., Chelliah M., Ebisuzaki W., Kanamitsu M., Kousky V., vanden Dool H., Jenne R., Fiorino M. 2001. The NCEP-NCAR 50-year Reanalysis: monthly means CD-ROM and documentation. *Bulletin of the American Meteorological Society 82*, 247–267.

Kohler J. & Aanes R. 2004. Effect of winter snow and ground-icing on a Svalbard reindeer population: results of a simple snowpack model. *Arctic, Antarctic, and Alpine Research 30*, 333–341.

Lefauconnier B. & Hagen J.O. 1990. Glaciers and climate in Svalbard: statistical analysis and reconstruction of the Brøggerbreen mass balance for the last 77 years. *Annals of Glaciology 14*, 148–152.

Lefauconnier B., Hagen J.O., Ørbaek J.B., Melvold K. & Isaksson E. 1999. Glacier balance trends in the Kongsfjorden area, western Spitsbergen, Svalbard, in relation to the climate. *Polar Research 18*, 307–313.

Nesje A., Lie O. & Dahl S.O. 2000. Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records? *Journal of Quaternary Science 15*, 587–601.

Oerlemans J. 1993. A model for the surface balance of ice masses: Part 1. Alpine glaciers. *Zeitschrift für Gletscherkunde und Glazialgeologie 27–28*, 1991–1992, 63–83.

Oerlemans J. 2001. *Glaciers and climate change*. Exton, PA, USA: A.A. Balkema.

Pohjola V.A. & Rogers J.C. 1997. Atmospheric circulation and variations in Scandinavian mass balance. *Quaternary Research 47*, 29–36.

Rasmussen L.A. 2005. Mass balance of Vatnajökull outlet glaciers reconstructed back to 1958. *Jökull 55*, 139–146.

Rasmussen L.A. in press. Spatial extent of influence on glacier mass balance of North Atlantic circulation indices. *Terra Glacialis*.

Rasmussen L.A. & Conway H. 2001. Estimating South Cascade Glacier (Washington, U.S.A.) mass balance from a distant radiosonde and comparison with Blue Glacier. *Journal of Glaciology 47*, 579–588.

Rasmussen L.A. & Conway H. 2003. Using upper-air conditions to estimate South Cascade Glacier (Washington, U.S.A.) summer balance. *Journal of Glaciology 49*, 454–462.

Rasmussen L.A. & Conway H. 2004. Climate and glacier variability in western North America. *Journal of Climate 17*, 1804–1815.

Rasmussen L.A. & Conway H. 2005. Influence of upper-air conditions on glaciers in Scandinavia. *Annals of Glaciology 42*, 402–408.

Rasmussen L.A., Conway H. & Hayes P.S. 2000. The accumulation regime of Blue Glacier, U.S.A., 1914–96. *Journal of Glaciology 46*, 326–334.

von Storch H. 1999. On the use of "inflation" in statistical downscaling. *Journal of Climate 12*, 3505–3506.

Washington R., Hodson A., Isaksson E. & MacDonald R. 2000. Northern Hemisphere teleconnection indices and the mass balance of Svalbard glaciers. *International Journal of Climatology 20*, 473–487.