Accumulation at the equilibrium-line altitude of glaciers inferred from a degree-day model and tested against field observations

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ABSTRACT. We extrapolate temperature data from a gridded climatology to the equilibrium-line altitude (ELA) of a glacier and tune a degree-day model by adjusting precipitation to give zero mass balance at the ELA. We verify the tuned model by comparing modelled accumulation with winter balance where this has been measured (presently for 180 glaciers). The modelled accumulation naturally depends upon the vertical lapse rate (VLR) for temperature and the degree-day factor (DDF) for snowmelt. Both are somewhat uncertain in high-mountain areas, but modelled accumulation and measured winter balance are in reasonable agreement for most glaciers. The degree-day model predicts a non-linear relation between accumulation and summer temperature at the ELA as assumed by many workers, but we find a family of curves rather than a single universal curve. Maritime glaciers with low annual temperature range have proportionally more accumulation than continental glaciers with high annual temperature range for a similar summer mean temperature. Averages of winter balance for the five main geographical regions where mass-balance data are available agree well with annual accumulation from the degree-day model.

INTRODUCTION

There is widespread concern that global temperatures are rising and that glacier melting will increase and lead to a rise in global sea level over the coming century (Church and others, 2001). Oerlemans and Fortuin (1992) assessed the sensitivity of mass balance to a 1°C temperature change applied throughout the year for 12 glaciers using an energy-balance model to tune modelled mass balance to observed mass balance. The resulting mass-balance sensitivity depends upon the (model-estimated) precipitation on the glacier. Oerlemans and Fortuin (1992) express this dependence by a logarithmic function of precipitation, which they apply to all glacier regions in the world to estimate the temperature sensitivity of global sea-level rise from melting glaciers.

Later work with a degree-day model (Braithwaite and Zhang, 1999, 2000; Braithwaite and others, 2003) confirms the association between mass-balance sensitivity and precipitation regime, especially annual accumulation. For these works, the degree-day model was fitted to observed mass balance at various altitudes (e.g. at 50 or 100 m intervals), but we now calibrate the model to make the mass balance at the equilibrium-line altitude (ELA) of the glacier equal to zero. We have two disposable parameters in the model: (1) the vertical lapse rate (VLR) of temperature, and (2) the degree-day factor (DDF) for melting snow at the ELA. Using pre-chosen values of these parameters we calculate mass balance and climate conditions at the ELA using the gridded climatology of New and others (1999) as a starting point. This means in principle that we can now apply the degree-day model to glaciers without any mass-balance measurements as long as the ELA is known (or can be estimated), but here we apply the model to glaciers with observed mass-balance data, including measured ELA, because we want to verify the model insofar as this is possible.

By their very nature, projections of future impacts of climate change, including sea-level rise from melting ice (Church and others, 2001), cannot be directly verified except by waiting until the projected climate change has actually happened. This is obviously unacceptable to anyone who wants to apply science to the betterment of the human condition. Projections of future climate change, including sea-level rise, can only be made by applying models and we need to somehow generate confidence in these models. We attempt here to justify our degree-day model by showing that it produces reasonably realistic values of snow accumulation on present-day glaciers. A number of outputs from the degree-day model are highly correlated with model accumulation (Table 1), so verification of the model accumulation should raise confidence in other, unverified, parts of the model.

Table 1. Correlation of different outputs from the degree-day model for 276 glaciers with annual accumulation calculated with the model

Output from degree-day model	Linear correlation with annual accumulation at ELA
Sensitivity of mass balance at ELA to +10% precipitation	0.99
Length of melt season at ELA	0.95
Annual precipitation at ELA	0.91
Mass-balance gradient at ELA	0.90
June–August mean temperature at ELA	0.89
Annual mean temperature at ELA	0.76
Sensitivity of mass balance at ELA to +1 K temperature change	–0.89

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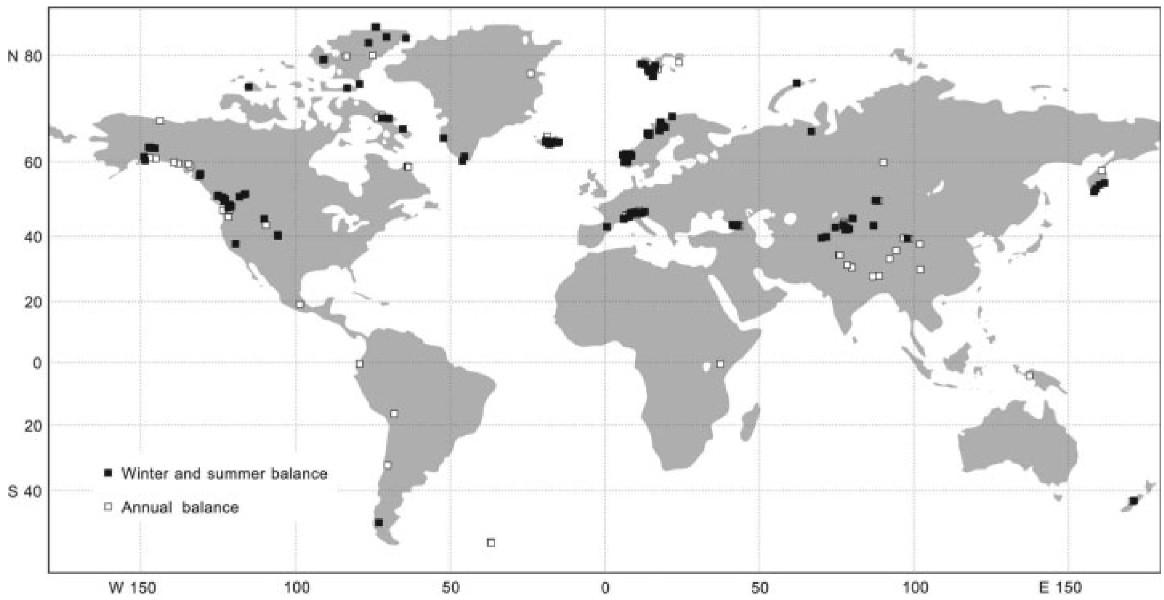

Fig. 1. Location of glaciers with mass-balance data used in the present study. Separate measurements of winter and summer balances are made on 180 glaciers (denoted by filled squares) while only annual balance is measured on other glaciers (denoted by open squares).

DEGREE-DAY MODEL

In the degree-day model (Braithwaite and Zhang, 1999, 2000; Braithwaite and others, 2003) the sum of positive temperature and the probability of freezing temperature are calculated from monthly mean temperature assuming that temperature is normally distributed within the month (Braithwaite, 1985). Snow accumulation is obtained as the product of monthly precipitation and monthly probability of freezing and is summed to give annual accumulation. The melting of snow and ice is calculated from the annual sum of positive temperature using different DDFs for ice and snow (Braithwaite, 1995). For low annual temperature, meltwater is allowed to refreeze within the pore spaces of snow until the glacier surface layer reaches the density of ice (Braithwaite and others, 1994), while meltwater runs straight off for higher annual temperatures.

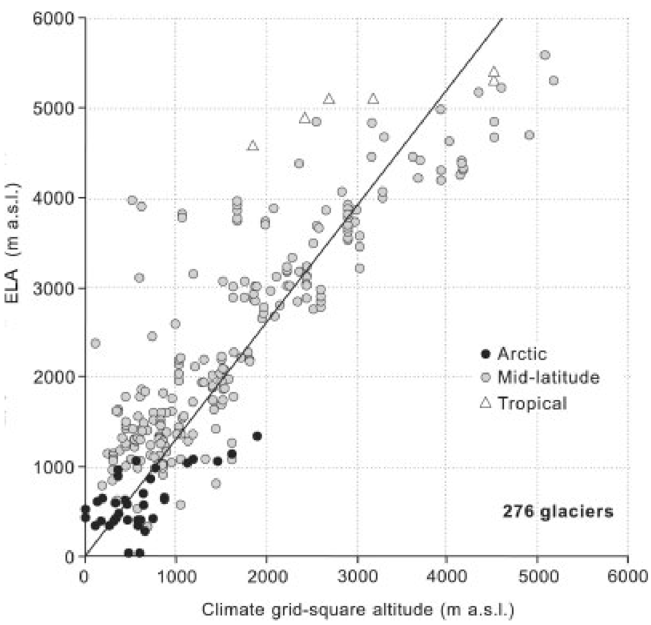

Fig. 2. ELA of 276 glaciers vs the altitude of the 0.5° grid square in which the glaciers lie.

When we apply the model to the ELA, the annual accumulation is equal to the annual melt less any refrozen meltwater. Aside from relocating the model to the ELA, the only change from earlier work is to invoke refreezing of meltwater at slightly lower values of annual air temperature than previously. The degree-day model involves several main sources of error:

Uncertainty in the DDF linking snowmelt to temperature sum on the glacier (Braithwaite, 1995; Braithwaite and Zhang, 2000; Hock, 2003).

Uncertainty in the VLR used to extrapolate temperature from the gridded climatology (New and others, 1999) to the ELA of the glacier

Possible errors in the gridded climatology (Briggs and Cogley, 1996; New and others, 1999)

Mismatch between the time coverage of the gridded climatology (1961–90) and the period for which ELA data are available (1 or more years in the period 1946–99).

MASS-BALANCE DATA

We assembled mass-balance data (1946–99) from all over the world by combining and updating data from Braithwaite (2002) and Dyurgerov and others (2002). We do not have ELAs for all 309 glaciers with mass-balance data, and not all glaciers are included in the topographic mask of New and others (1999). Figure 1 shows the location of 276 glaciers with measured mass-balance data, and Figure 2 compares the ELAs with the altitude of the 0.5° climate grid square in which the glacier is located. We split the glaciers into three classes: arctic (arctic islands of Canada, Svalbard and Russia), tropical (within the astronomical tropics) and mid-latitude (any glacier not included in the previous classes).

For arctic glaciers, the ELA and climate grid-square altitude are generally similar (Fig. 2), reflecting the high

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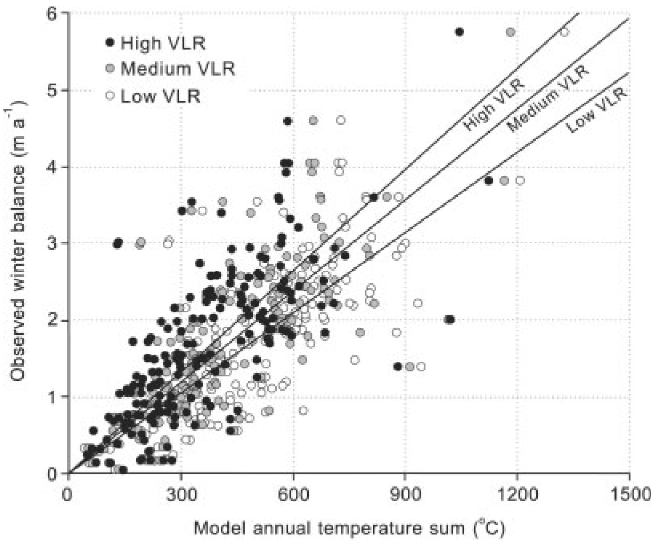

Fig. 3. Observed winter balance of 180 glaciers vs modelled annual temperature sum at the ELA. Temperature is extrapolated from the gridded climatology of New and others (1999) with three different values of VLR.

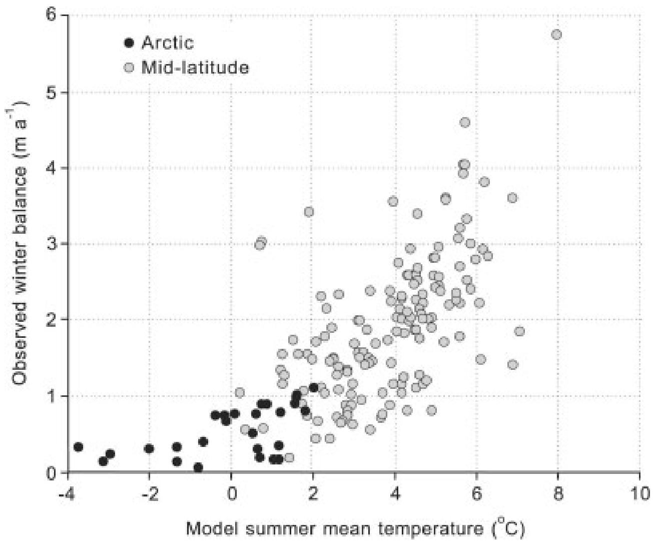

Fig. 4. Observed winter balance of 180 glaciers vs summer mean temperature (June–August) at the ELA. Temperature is extrapolated from the gridded climatology of New and others (1999) with three different values of VLR.

degree of glacier cover in the arctic islands. By contrast, ELAs of mid-latitude and tropical glaciers can be 1000–2000 m higher than the corresponding climate grid altitude. We give the regression line in Figure 2, which is forced through the origin, merely as a guide and we claim no physical meaning. We expect the correct choice of VLR to be critical where ELA is substantially higher than the climate grid-square altitude (e.g. for most tropical glaciers), while it will be less critical for arctic glaciers.

MODEL VERIFICATION

We verify the model by comparing calculated accumulation at the ELA with winter balance for those 180 glaciers where separate measurements of winter and summer balances are available (Fig. 1). The 'winter balance' here refers to the mean specific winter balance area-averaged over the whole glacier, but this is approximately equal to the winter balance at the ELA (Ahlmann, 1948; Hoinkes and Rudolph, 1962; Trabant and March, 1999). This verification is problematic because annual accumulation and winter balance are not the same concept (Anonymous, 1969). Annual accumulation is the total amount of snowfall in the year that has to be entirely melted away at the ELA, including possible refreezing as superimposed ice that has to be remelted, while winter balance represents the largest net accumulation in the year before substantial runoff from melting. Winter balance is well defined on glaciers with strong seasonality (arctic glaciers) and poorly defined on glaciers with weak seasonality (e.g. on tropical glaciers even though annual accumulation might be several metres of water equivalent). Although winter balance is well defined on arctic glaciers, there is often substantial precipitation in summer that contributes to annual accumulation which is therefore larger than winter balance.

In principle, we could modify the model to calculate winter balance with the degree-day model rather than accumulation, but that would be tedious and we will only attempt it if really necessary, invoking the glaciological equivalent of Occam's razor (Occam's ice axe?).

Even if we accept that annual accumulation is not precisely the same as winter balance, the correlation between observed winter balance and model annual temperature sum (Fig. 3) is encouraging. Each glacier appears as three points in the plot because we use three different values of VLR to calculate the temperature sum at the ELA: low VLR (5.5 K km^{-1}), medium VLR (6.5 K km^{-1}) and high VLR (7.5 K km^{-1}). Correlation coefficients are 0.76, 0.75 and 0.71 for the three values of VLR (all correlations significant at <1% level). These correlations are higher than the correlation between observed winter balance and annual precipitation from the gridded climatology (0.496, significant at <1% level). However, the latter is high enough to confirm the link between glacier accumulation and regional precipitation pointed out by Cecil and others (2004).

The three regression lines in Figure 3, which are forced through the origin, have slopes that we interpret as estimates of DDF for melting snow at the glacier ELA: low DDF (3.49 ± 0.05 mm d^{-1} K^{-1}), medium DDF (3.96 ± 0.06 mm d^{-1} K^{-1}) and high DDF (4.40 ± 0.08 mm d^{-1} K^{-1}). These estimates correspond well with the range of values reported in the literature (Braithwaite, 1995; Braithwaite and Zhang, 2000; Hock, 2003) for snowmelt on glaciers, and the high DDF is also very close to that reported for seasonal snow cover (de Quervain, 1979). As these DDFs are obtained from observed winter balance, they will somewhat underestimate the annual accumulation.

ACCUMULATION VS SUMMER TEMPERATURE

A number of authors claim a non-linear relation between winter balance, accumulation or even annual precipitation at the ELA and the summer mean temperature (Ahlmann, 1924, 1948; Krenke and Khodakhov, 1966; Loewe, 1971; Leonard, 1989; Ohmura and others, 1992; Nesje and Dahl, 2000). The observed winter balances of our 180 glaciers show an obvious relation to summer mean temperature (average of June–August) with some degree of scatter (Fig. 4). We show the results with medium VLR, but higher or lower values of VLR will not much alter the overall pattern. Arctic

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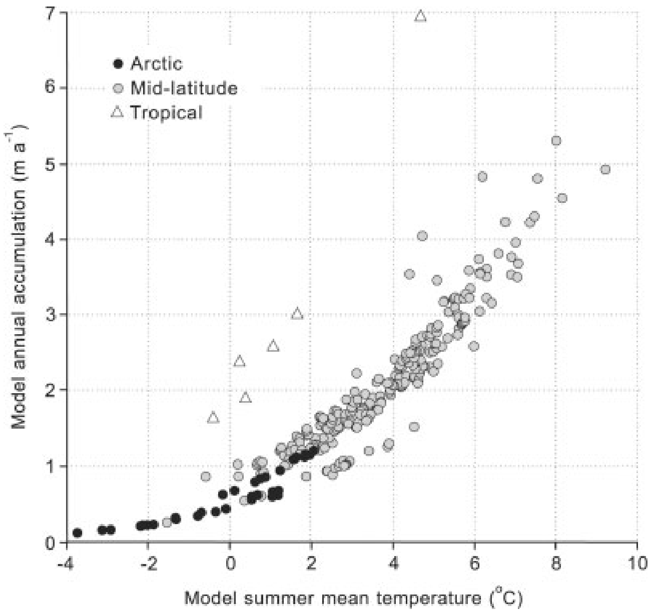

Fig. 5. Model annual accumulation at the ELA of 276 glaciers vs summer mean temperature (June–August) at the ELA. Model accumulation is calculated with medium values of DDF and VLR.

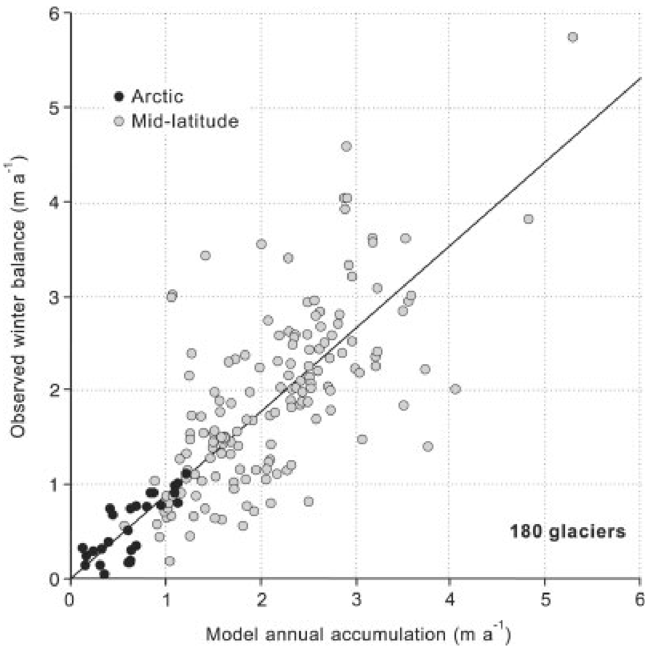

Fig. 6. Observed winter balance vs model annual accumulation for 180 glaciers. Model accumulation is calculated with medium values of DDF and VLR.

glaciers generally lie on the cold-dry side of the distribution, while winter balance data are not available for tropical glaciers.

We calculate accumulation using the degree-day model with low, medium and high values of VLR and DDF, so our calculated accumulation is somewhat underestimated. By comparison with Figure 4, model accumulation is strongly related to summer mean temperature (Fig. 5), but the points do not lie on any exact curve. Values for tropical glaciers lie on the high side of the distribution, while arctic glaciers lie, once again, on the low side of the distribution. This pattern can be explained in terms of the annual temperature range as first pointed out by Reeh (1991). As a basic property of the degree-day model, for a particular value of summer temperature, you get a relatively high degree-day sum with low annual temperature ranges (on tropical glaciers or for very maritime glaciers in mid-latitudes). Conversely, high annual temperature ranges give relatively low degree-day sums (arctic glaciers or very continental glaciers in mid-latitudes). Within the arctic glacier class, we can discern two curves that represent differing annual temperature ranges for the more continental arctic islands of Canada and Russia compared with the more maritime arctic of Svalbard.

The general similarity between Figures 4 and 5 is further verification of the model, but the very high model accumulation shown in Figure 5 for one of the tropical glaciers is unverified and appears improbable. It is probably an artefact of the model, but we emphasize that more data are needed from tropical glaciers, including climate data from near the ELA. This ought to be possible with modern lightweight data recorders.

MODELLING ACCUMULATION AND PRECIPITATION AT THE ELA

The model accumulation for 180 glaciers is compared with observed winter balance in Figure 6. The model is run for medium values of DDF and VLR, but the general pattern is not greatly different for high or low values of DDF and VLR. Overall there is reasonable agreement between observations and model with a correlation coefficient of 0.77 (significant at <1% level). The regression line (Fig. 6), which is forced through the origin, indicates winter balance somewhat less than annual accumulation, which is reasonable, although, as already pointed out, the annual accumulation is underestimated.

There is considerable scatter for individual glaciers, with some large differences between observations and models. For example, there are two glaciers with relatively high observed winter balance ($\sim$3 m a^{-1}) and relatively low model accumulation ($\sim$1 m a^{-1}). As these glaciers lie in Kamchatka, the low value of accumulation seems very unlikely (Shiraiwa and others, 1997), suggesting that the error lies in the temperature climatology. These errors and others will be investigated for individual glaciers in a future study. Aside from identifying error sources, future work will examine possible variations in DDF and VLR between different regions, as there is no real reason to believe that 'one size fits all' when it comes to modelling accumulation on glaciers.

One cause of error in Figure 6 is that ELAs for some glaciers are based on only a single year of measurement, or a few years, while the climate data (New and others, 1999) are based on a 30 year Normal period (1961–90). An ELA measured in an extreme year would not represent this Normal. If we only include glaciers with ELAs measured over at least 10, 20 or 30 years, the scatter of points does become much sharper than shown in Figure 6, but this seems like 'cheating'.

Some of the errors for individual glaciers must compensate when calculating averages over many glaciers (Fig. 7). Here we have discarded a few scattered results (five glaciers in South America, Greenland and New Zealand) and we calculate averages and confidence intervals for the five main

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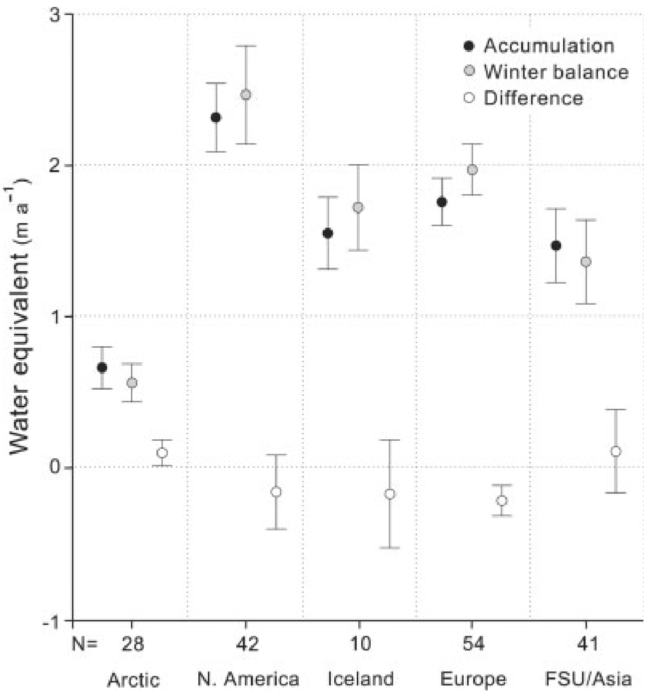

Fig. 7. Mean and 95% confidence interval for observed winter balance, model annual accumulation and their differences for 175 glaciers in five regions. Model accumulation is calculated with medium values of DDF and VLR.

geographical regions in which the remaining 175 glaciers occur. For such regional averages, model accumulation and observed winter balances agree quite well. For example, the model correctly identifies the Arctic as the region with lowest accumulation and winter balance, with relatively high values in North America (including some very maritime glaciers on the western coast of North America) and intermediate values in Iceland, Europe and the former Soviet Union(FSU)/Asia. The difference between average accumulation and winter balance is not significantly different from zero for all regions except Europe (Scandinavia and the Alps). The latter dataset is dominated by Norwegian/Swedish glaciers, where winter balance is routinely measured. There are also substantial variations within each region, which will be examined in a future study.

CONCLUSION AND RECOMMENDATION

Uncertainties in VLR and DDF need not have a large effect on calculations of annual accumulation on glaciers using a degree-day model if low, medium and high VLRs are paired with low, medium and high DDFs.

Although accumulation and winter balance are not identical concepts, there is generally good agreement between modelled values of the former and observed values of the latter, where data are available (180 glaciers). Agreement between model accumulation and observed winter balance improves when both are averaged for the five large regions (Arctic, North America, Iceland, Europe and FSU/Asia) for which most mass-balance data are available. As some unverifiable products of the degree-day model are highly correlated with annual accumulation, this raises confidence in them as well.

Mass-balance models have great potential, but every effort should be made to obtain climatological data from high mountains to verify present models and to develop more sophisticated models in the future. In particular, more data are required from tropical glaciers. More effort should also be put into measuring separate winter and summer balances on those arctic and mid-latitude glaciers where measurements are not presently available.

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