Mass-balance measurement on Storglaciären, Swedish Lapland

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Abstract

The net mass-balance of Storglaciären was computed for the hydrological year 1999-2000, using a separate winter and summer balance. The data to the first one was collected in early May by a dense snow survey, and two snow pits; ablation stakes measurements throughout the summer, in addition to a combined snow pit and drilling snow pack analysis, provided data to the second one. A GIS approach using the Matlab software was developed. The method is exposed, as well as its advantages, disadvantages and accuracy discussed in confrontation to the results.

Storglaciären is a small valley glacier in the Kebnekaise Massif, Swedish Lapland (67°54'N, 18°35'E), where a long-term study of the climatic impact was initiated in 1946 by V. Schytt. Thus the annual mass-balance record is the world longest continuous record using direct glaciological methods [Holmund et al., 1996]. From the beginning on, the annual mass-balance was divided into winter- and summer balance, which enables to have a better evaluation of the response to climatic changes.

1 Winter accumulation: snow-depth survey

1.1 Method

Winter accumulation is measured in May, to determine the amount of new fallen snow available for melting. Snow-depth is monitored by ca. 300 manual soundings regularly spaced on the glacier surface, as shown in fig. (1). The depth is measured with a snow-probe that is inserted into the snow mantle down to the hard (summer) layer from the previous year. As

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an indication, 12 to 16m long stakes are drilled in the accumulation area in late summer, from which the thickness of the annual layer can be approximated; it is then possible to distinguish between a simple ice-lense and the summer-layer. Resuming former efforts [Jansson, 1999], a new GIS (Geographic Information System) approach was developed using the Matlab software: using the same 10x10m grid, the punctual measurements were interpolated with a biharmonic spline method, specifically developed for GIS data [Sandwell, 1987]. The 'griddata' function in Matlab does not perform any extrapolation. Thus, in order to cover the whole surface of the glacier, a set of points on the border of the glacier were added, for which the average value at that altitude was assigned.

The snow-depth can be converted into water-equivalent by multiplying it with the appropriate density. New fallen snow has a density of about 0.2; later processes, such as compaction by the wind or late deposited snow layers as well as snow metamorphosis increase usually this density. Every year, five to six snow pits are digged up to 5 m depth to measure the density profile. Long term observations show that the density profile is rather uniform horizontally, leaving aside data scattering due to local effects such as ice lenses or topography-dependent wind compression. The density-depth points obtained in the different snow-pits are fitted by an algebraic expression in a least-square sense. According to a simple model of snow compression under the weight of the layers above (with an analogy to hydrostatic pressure), the logarithmic regression was adopted. Other regression method yield sometimes a better correlation coefficient; thus the mass-balance obtained by different density models were compared (cf. fig. 2).

1.2 Results and discussion

Although the principles for mass-balance remain the same as presented by Jansson, using Matlab to compute it represents a significant improvement in that all tasks can be integrated. Previously, the punctual measurements were entered in Golden Surfer to be plotted, corrected and interpolated; the output files were read by a Fortran program, which computed the actual mass-balance; the results were then plotted by yet another software Grapher. On the contrary, reading in the data, interpolating it, computing the mass-balance and representing the results can be done instantaneously by a sequence of M-files (i.e. small Matlab programs). Due to the high number of measurements, the imposed boundary conditions do not influence significantly the final result.

As shown in previous studies, the accuracy of the mass-balance is about 0.1 mEq. This is well confirmed by fig. (2), in that the different models yield very close results for altitudes lower than 1500m, and then diverge of less than 0.5 mEq. Adopting a constant density tends to under-evaluate the

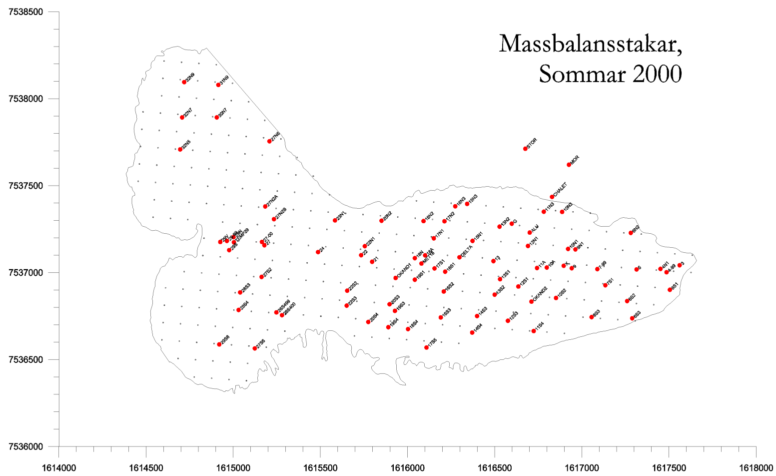


Figure 1: Map of the summer stake net (up to 83 stakes during summer 2000). The points MOR and STOR mark the locations from which photos were taken.

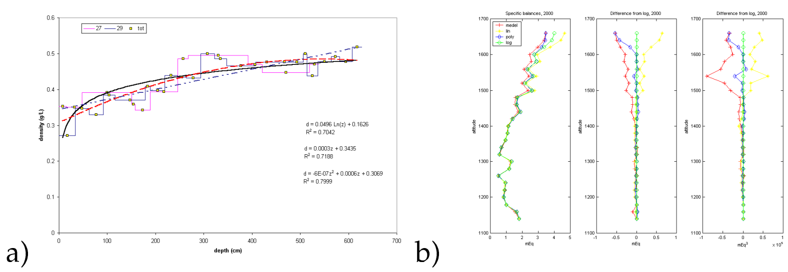


Figure 2: Comparison of winter mass-balance computation using different density models. The figure a) represents the density measurements for different depths, obtained on May 6th-9th, 2000 by M. Nyman *et al*. Several regression methods were used to calculate the snow density with depth: polynomial regression of degree 0 (called *medel*), degree 1 (called *linear*) and degree 2 (called *poly*), and at last a logarithmic (called *log*).
The figure b) represent the difference in the computed mass-balance when using the different density models.

water equivalent for high snow thicknesses as in the accumulation area, whereas the linear model exaggerates it in the same regions. The final model retained was the logarithmic profile, since it ensues from a physical explanation for snow accumulation.

2 Summer ablation: stake net survey

Ablation is measured throughout all summer, in our case study from the June the 29th to September the 3rd, 2000. The glacier is equipped with approximatively 80 ablation stakes, distributed over the whole surface but more concentrated in the ablation area, as shown in fig. (1). Every week, the length of the stake sticking out is measured with a folding rule, giving the ablation during this laps of time. Maintaining the stake net is also part of the monitoring work: as soon as stake is likely to smelt out, a new one is drilled, providing thus a continuous ablation record.

2.1 Snow stratigraphy in the accumulation domain

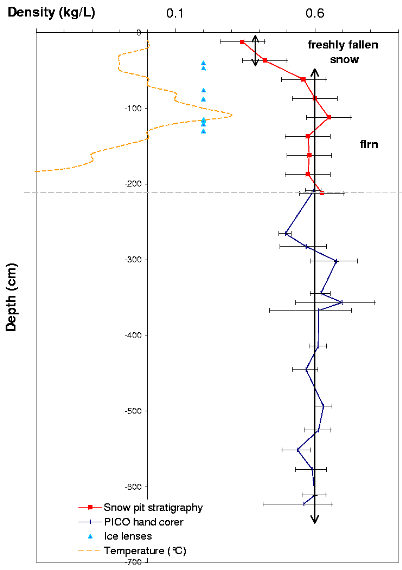
Investigations were carried out in the accumulation area, at a location called Norra Nichen, to determine the density profile of the snowpack, and thus convert snow-depth into water equivalent. One the first two meters, a snow pit was digged, to examine the detailed stratigraphy of the snow, the density and temperature profile. A PICO, hand driven corer extended the stratigraphy and density observations down to six meters, where it reached the glacier ice.

This data yields confirms the qualitative field observations.

- The first 30 cm consist of new snow that was deposited during the week preceding the experiment. Its density is rather low and no ice lenses have yet developed.
- The snow fallen during the former winters, also called firn, has a mean density of 0.6. Large variations can be observed from this average value; they are independent from depth, but can be related to the frequency and thickness of ice lenses within the snow pack.
- The profile of temperature indicates that all layers are near the freezing temperature of water. The trends may not be significant, because all variations are of the same order as the presumed precision of the thermometer (indicated by the positive temperatures physically in contradiction with the presence of ice crystals).

Since the temperature is near 0° C, melting water is supposed to be leaking through the whole snow pack. Ice lenses are not taken into account to determine the mean density, since they do not form any identified horizon, but

Figure 3: Snow stratigraphy in the accumulation area. See the text for details.



are very restricted locally. This confirms the observations of previous years: snow metamorphosis occurs uniformly in the entirely saturated snow mantle, leading to round grain crystals (symbol •) of constant density around 0.6.

2.2 Calculation of the summer balance

The summer balance is computed in a similar way as the winter balance. A constant density of 0.9 was assumed for ice. Average values at a given altitude were assigned as boundary conditions to perform the extrapolation over the entire range of the glacier; in those regions were no data was available, the ablation gradient was used. Consequently, the mass-balance is computed over always the same grid and enables thereby sensitive comparisons from year to year .

The accuracy of folding rule measurements is estimated about 5 cm, due to uneven ice-surface and multiple executants, whereas the errors introduced by extrapolating the data set cannot be known precisely. The accuracy of the final mass-balance is estimated about 0.1 mEq, [Jansson, 1999]. The number of stakes required to calculate an accurate mass-balance is a controversial topic (cf. special issue of Geografiska Annaler). It is generally admitted that 5 stakes are sufficient for a 3-km2 wide glacier such as Storglaciären. Furthermore, weekly stake readings are not necessary to

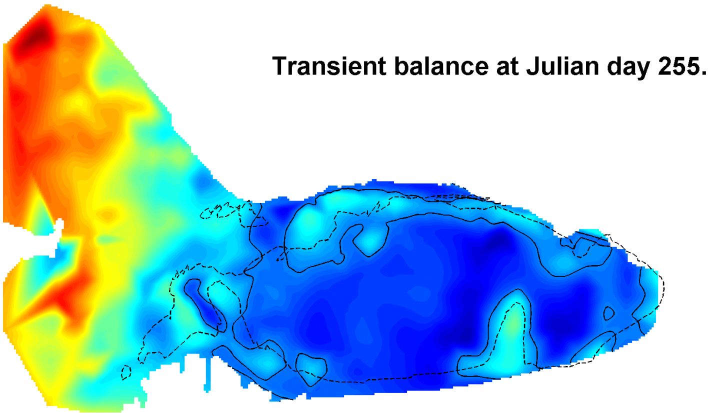


Figure 4: Computation of the net balance on the September the 11th, 2000. The dashed line represent the snow-line as mapped with a Garmin hand-hold GPS receiver, the full line represent the equilibrium line as derived from the net balance.

compute the summer mass-balance, for which only the last record in the season is required; such a regular survey enables firstly to maintain better the stake net by preventing stakes to melt out, secondly to assure the validity of the last measures by comparison with the previous ones. One should also consider that detailed mass-balance measurements are needed as input or calibration data for ice-flow models or energy-balance computations. In such respect, Storglaciären provides a unique and considerable amount of mass-balance data over a long period that was exploited for calibrating a new mass-balance method, as exposed in a publication to come.

3 Conclusion

By summing the two partial winter and summer mass balances, a detailed net mass balance is obtained, from which parameters such as the equilibrium line or the accumulation area ratio can be derived, as can be seen on fig (4).

Subdividing the balance analysis into two seasonal terms is of great interest for climatologic studies. Hence the general trend of positive mass balance in the Swedish Lapland could be related not to a colder climate, but to a more maritime climate with milder and more humid winters and little colder summers.

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