Reconstruction of the Snow Accumulation Patterns in the vicinity of Stake 18 on Storglaciären in Winter 2002/03

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Abstract

Measurements of air respectively snow temperature at different levels, of snow density and stratigraphy were carried through on Storglaciären (Tarfala Basin, Norrbotten, Sweden) in Winter 2002/03. The obtained values and trends were considered as indicators for the patterns of snow accumulation on the glacier during the winter. Continous temperature measurements showed smoothing of the graphs at different times at different levels, which has been correlated with the presence of snow. According to the data, the first snowfall took place at the end of October. The snow cover remained rather thin for a couple of months, and significant coverage of the 45 cm - level did not take place before mid of January. The 179 cm - level above ice surface did not show any signs of snow coverage until the end of March.
The snow depth indicated by these continous measurements is not in line with the observed depth in the last days of March. A comparison of recorded temperatures and measured temperatures in a snow pit indicated an offset of the real level of the thermistors of about 50 cm above the "official" level, maybe due to extensive ice melt in summer.

Introduction

Scope, goal and structure of the paper

Aim of this paper is to give an overview of the patterns of snow accumulation on Storglaciären (Tarfala Basin, Norrbotten, Sweden).
After a short introduction to the methods used for the research, the results will be presented and discussed in the main chapters of the paper. Also practical applications of the results of the research will be taken into account.

Methods

The data presented in this paper was obtained by own measurements and the analysation of automatic data recording. Different measurements were carried through during a field course from 28. 03. to 02. 04. 2003. Research site was the vicinity of stake 18 in the ablation area of Storglaciären, near the equilibrium line.

- **Snow pit measurements:** Two snow pits were dug in vicinity of each other to measure density and temperature of the snow and to get an overview of the stratigraphy. Temperature was measured in 10 cm - intervals, the density was obtained by using 25 x 8 cm cylinders and weighing the content. Snow hardness was determined by using the scale fist (1), 4 fingers (2), 1 finger (3), pencil (4) and knife (5), with increasing hardness, depending on what is needed to penetrate into the sow.
- **Continous temperature measurements:** During the whole winter until the end of March, temperatures were automatically recorded near the ice surface and in heights of 45, 82, 132 and 179 cm above the ice surface. Interval of the measurements was two minutes, the values were averaged over an hour and stored on a datalogger.

Results

Snow temperatures

Temperature measurements at the snow pits showed relatively constant temperatures (-5,5 to -6,3 °C) between the ice surface and 50 - 70 cm below the snow-atmosphere-interface. In the uppermost snow layers, the temperature was closer to the air temperature. Also in the lower snow layers temperature underwent short-term changes, how the difference of about 0,2 °C within 35 minutes at Pit 1 indicated (fig.1).

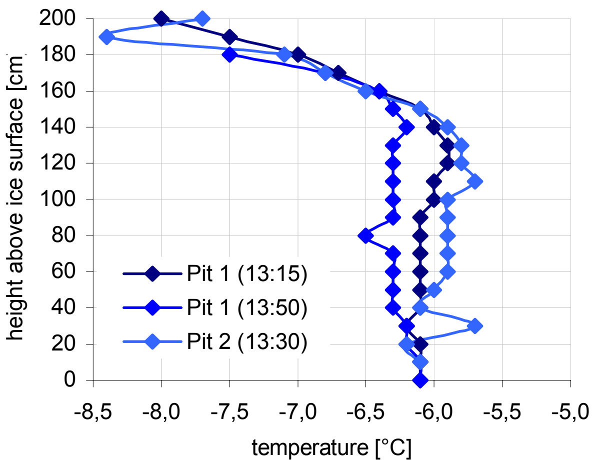


Fig. 1: Temperature profiles at two snow pits near stake 18 (29.03.2003)

The continous measurements showed clear differences in the temporal variability of the temperature (fig. 2a-e). At the thermometer 179 cm above the ice surface, pronounced temperature fluctuations occured during the whole period, while at some point of time the curves become relatively smooth at the lower levels.
Considering each graph in more detail, it is possible to figure out the time period when the temperature fluctuations became weaker and the curve smoother (fig. 3a-d).

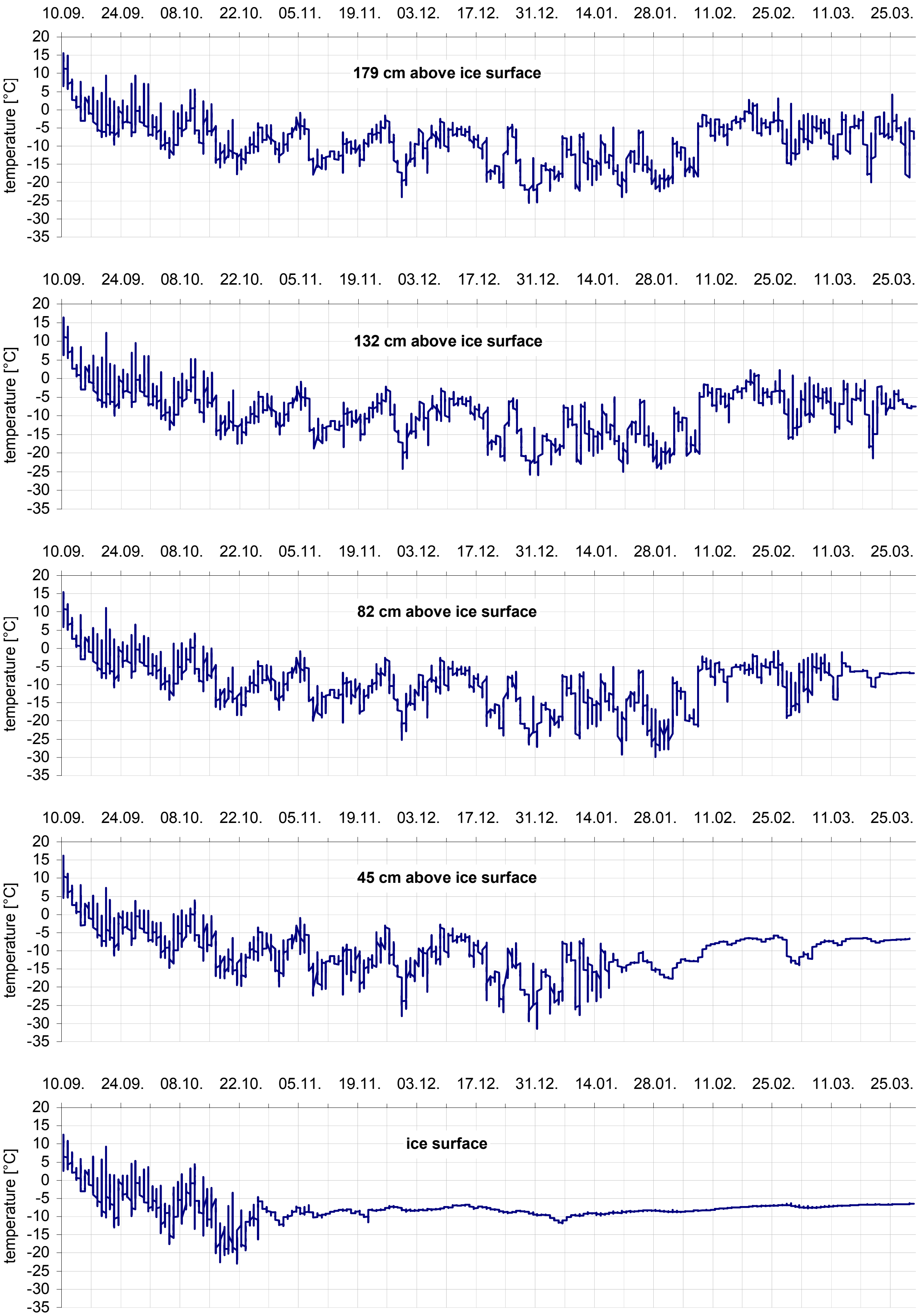


Fig. 2a-e: Temperatures from September 2002 to March 2003 at different layers at Stake 18

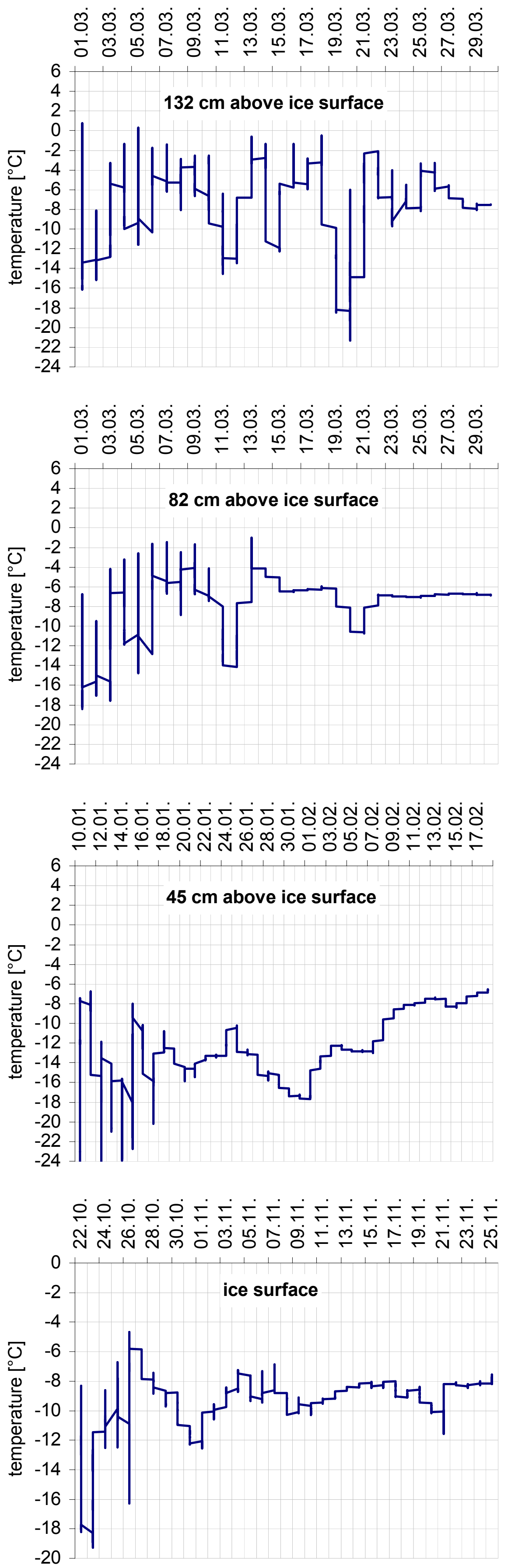


Fig. 3a-d: Temperatures at different levels in the transition period between fluctuating and smooth graph

132 cm above ice surface, it is not possible to observe a smoothing trend until the last third of March. Between 22nd and 29th of march the fluctuations decreased and finally the temperatures stabilized at about -7,5°C.

One level lower, at 82 cm above ice surface, beginning of smoothing can already be observed in the first third of March, around the 14th day of the month. There were some more or less pronounced fluctuations until temperatures stabilized at about -6,8 °C on 22nd of March.

The situation is more complicated at a level of 45 cm above ice surface. The graph was already smoothing around the 18th of January, but the temperatures were not really stable until the end of March, when there was a slight warming trend at about -7°C. Within that period, there were two pronounced fluctuations of the scale of about one week towards colder conditions, while the general trend was towards warming.

Also near the ice surface, the transition took place rather continous than at a certain point of time. This transision period can be observed between 27th of October and 22nd of November, when the temperature stabilized at about -8,1 °C. Later in winter, there were some longer term fluctuations with a minimum of -11,76 °C on 6th of January and a following continous warming trend ending up at about -6,5 °C in the end of March.

Snow density

Snow density was continously increasing from about 185 kg m^{-3} at the snow surface to 410 kg m^{-3} at a depth of about 1,5 m. Below, density was decreasing to about 300 kg m^{-3} at the snow base (fig. 4).

The arithmetic average of snow density was calculated with 335 kg m^{-3} for measurement 1 and 316 kg m^{-3} for measurement 2.

The snow pack is equivalent to a water column of 694 mm (measurement 1) respectively 665 mm (measurement 2).

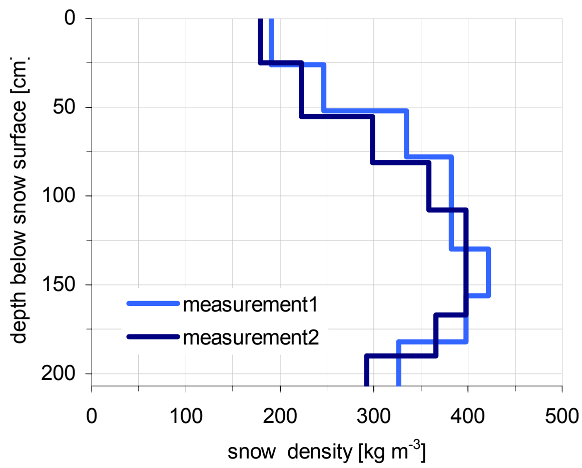


Fig. 4: Density profile at Pit 1 near stake 18 (30.03.2003)

Stratigraphy and snow hardness

The measurements of snow hardness in the two pits showed quite different results (fig. 4a and b).

In Pit 1 with a snow depth of 200 cm, a soft (fist/4 fingers) layer of decomposed snow with a grain size of 1 - 2 mm

was observed in the uppermost 20 cm. Below (let's call the transition "Interface A"), the snow consisted of rounded grains with grain sizes of approximately 0,5 mm. Hardness increased considerably to 1 finger/pencil and was further increasing moderately at a height of 120 cm above ice surface (Interface B). At a level of 40 cm above ice surface, an ice layer with a thickness of 1 cm was located (Interface C). The layer between the ice layer and the ice surface consisted of rather soft depth hoar (4 fingers) with a grain size of 3 - 4 mm.
In Pit 2, which was 215 cm deep, the uppermost snow layer consisted of new snow with a grain size of about 1 mm and a hardness of 4 fingers. Its thickness was 43 cm, thus more than double of the thickness of the comparable layer of Pit 1. Below Interface A, layers of hard (pencil) and soft layers (4 fingers), both with grain sizes of about half a millimeter were alternating until a depth of 190 cm, including a transition probably correspppFonding to Interface B of Pit 1 in a height of 114 cm above ice surface.
There was no ice layer observed like in Pit 1. The lowermost 25 cm, below Interface C consisted of very soft (fist) sugar snow with a grain size of 2 - 4 mm.

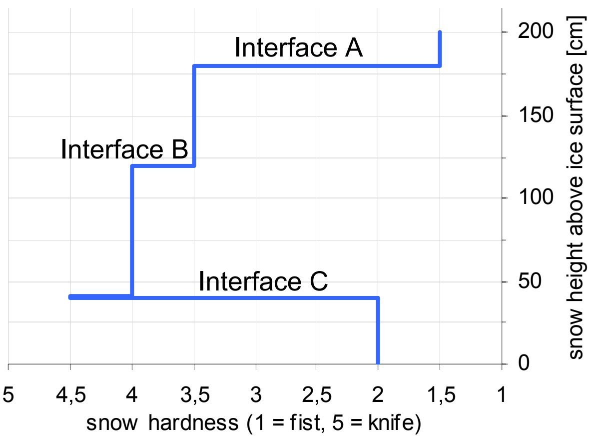


Fig. 5a: Snow hardness profile at Pit 1 near Stake 18 (29.03.2003)

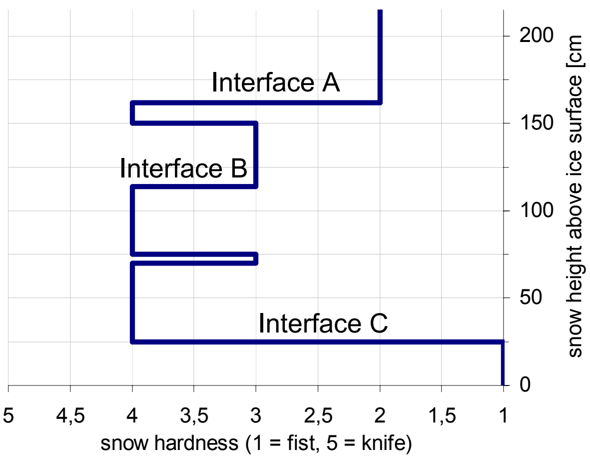


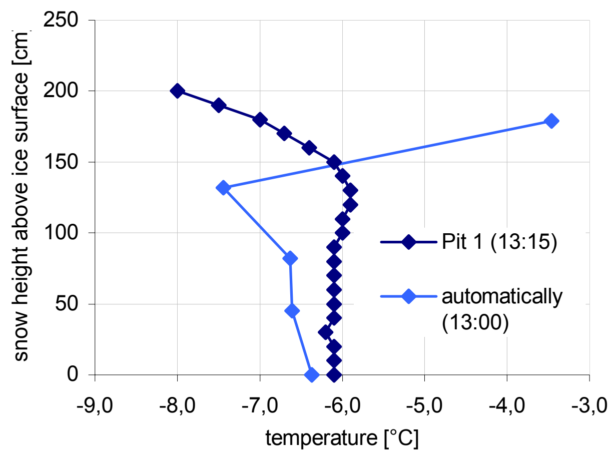
Fig. 5b: Snow hardness profile at Pit 2 near Stake 18 (29.03.2003)

Discussion

Temperature

The relationship between the recorded temperatures during the winter and the accumulation of snow is quite obvious. The transition from fluctuating graph to smooth graph corresponds with the covering of the thermometer with snow. Due to the isolating properties of snow, the temperature fluctuations of the atmosphere can not penetrate into the snow, a fact which is reflected in rather constant temperatures. The deeper the thermometers are buried, the more constant are the snow temperatures.
Considering the graphs of different levels in more detail, the history of snow accumulation in winter 2002/03 can be reconstructed.
There was hardly any evidence for snowcover until the end of October. There might have been only a thin layer which had no effect on the thermometers because also the lowermost one might not have been situated exactly at the ice surface but some centimeters above (see below). The first significant snowfall indicated by the temperature record, took place around the 27th of October. The cover was probably not very thick, because only the temperatures at the lowermost level were affected and also there, some fluctuations in temperature could be observed until the last third of Novemer. Temporarily, some snow might have been blown away, so that fluctuations could penetrate again. But the variations never reached the scale of before 27th of October. There is no indication for melting, because the temperatures remained steadily below zero. Around 22nd of November, there might have been some additional snowfall, because there were no more significant short-term temperature fluctuations at the lowermost level. Temperatures remained stable until mid of December, and the slow cooling until the first week of January probably reflects the decreasing of air temperatures which is indicated by the temperatures at the other levels. The pronounced minimum on 6th of January is likely to reflect a decreasing snow thickness due to wind deflation.
After this date, a period with significant snowfall is likely to have taken place. This is indicated by the stabilization of the temperature values at the lowermost level and the beginning of a smoothing trend at the 45 cm-level on 18th of January. The snow cover of this thermometer was probably rather thin during the next two months, because fluctuations of air temperatures could penetrate to some extent. The minima in the first days of February and March are reflected properly, but also the general warming trend during February. Snow temperatures remained clearly below zero, altough the air temperatures especially at the two uppermost levels partly rose above the melting point. However, these maxima were occuring during the noon periods and are probably errors caused by absorption of solar radiation by the thermometer, altough unusual high temperatures were recorded in Kiruna in February (pers. comm. R. Hock).
Temperatures at 45 cm stabilized at the same point of time when the smoothing at the 82 cm thermometer began. This coincidence indicates extensive snowfall, also covering the 82 cm-level. The short cold period around

20th of March was still clearly reflected at the 82 cm-level, and had also some influence on the temperatures at the 45 cm-level. Temperatures after this period were quite stable at both levels.
The onset of the smoothing trend at the 132 cm-level around 22nd of March indicates continued snowfall. Until the 29th of March, the snow cover seems to having become thick enough not to allow the penetration of short-term variations of air temperature. At the 179 cm-level, no indication of snow cover was present until 29th of March.
When the snow pit measurements took place on 29th and 30th of March, the snow cover was between 200 and 215 cm. Two explanations are possible for this mismatch: There could have taken place extensive snowfall on 28th and 29th of March, which is in line with personal observations of the author, or the ice surface has lowered in summer, so that the levels of the thermometers did not correspond to the real surface.
Fig. 6 indicates that rather the second explanation is likely to be the solution of the problem, because the recorded graph (the uppermost value clearly represents air temperature) would have to be lifted about 50 cm to correspond at least approximately with the measured graph.



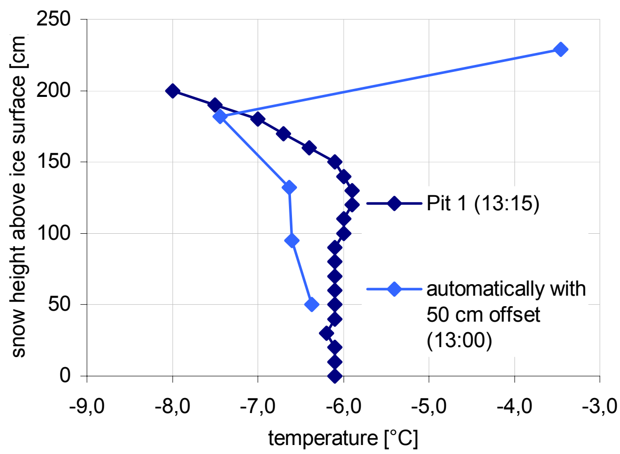


Fig. 6a and b: Comparison between measured and recorded temperature profile without and with 50 cm offset (29.03.2003)

Density and hardness

Density and hardness of the snow are tightly related to another and will thus be discussed together. The difference between the two profiles might be explained by real small-scale-variations (e.g. due to wind transport of snow) or by lacking experience of the researchers.
The uppermost layer of soft snow has a thickness of about 20 - 40 cm, the difference can probably be explained by small-scale differences in accumulation and wind effects. It is difficult to correlate the snow features with periods of snowfall because of the discussed uncertainties in the real height of the thermometers above the ice surface. However, if we assume an offset of 50 cm on the official height of the thermometers, the 132 cm level would be at 182 cm. Thus, the upper soft snow layer might be roughly corresponding to the snow precipitated in the period since 22nd of March.
Between the Interfaces A and C, the features differ considerably between the two pits. However, one common feature is the increasing hardness below about 120 cm above ice surface. Interface B would correspond to a 70 cm level of the temperature records. It might thus represent the snow surface between 14th and 22nd of March, when the 82 cm-level was already snow-covered, but there were still some temperature fluctuations.
The layer of low hardness and density in the lowermost part of the snow column (below Interface C) is connected with an ice layer in Pit 1, but not in Pit 2. With the assumed 50 cm - offset, the processes there are not reflected by the recorded temperatures and considerations are thus rather speculative. The 1st third of October was rather cold, while in the 2nd third the temperatures were above freezing. Thus, there could have been some decimeters of smow not reflected by the temperature record, which later underwent melting, what could explain the depth hoar with associated ice layer.
Fig. 7 summarizes the issues discussed above. However, all those reflections have to be considered with reservations because of the uncertainties concerning the 50 cm offset of the recorded temperature values. There have also been located some sites in the vicinity of stake 18 with a snow height of only about 140 cm, which would correspond to the recorded data (but the comparison in fig. 6 indicates that the height of the snow column at the thermistors corresponds rather to that at the snow pits). Without offset, there would be a good correlation of Interface A with the snow surface between 14th and 22nd of March and of Interface B with the snow surface from 18th of January to mid of March. However, more research would be necessary to enlight this issue.

Applications

What is the reason to carry through measurements of temperature, density and hardness of snow and to interprete the results? Is it just scientific interest? It might be partially, but there is also a couple of practical reasons to do such research, which will be discussed now.

- **Water budget and fluxes:** Snow can be considered as a big reservoir of water, which becomes mobile in spring when melting takes place. The amount of snow in a given area, but also the spatial distribution (especially the hypsographic curve) are essential for predicting the runoff in the corresponding basin. This can on one hand be important for water supply (in arid regions), on the other hand for the prediction of floodings.

- **Avalanches:** The danger of avalanches depends strongly on the thickness and the internal structure of the snow layer. Due to this, it is important to know these features for being able to predict the avalanche risk and taking appropriate measures.
  The avalanche risk is low if the hardness and density of the snow are increasing with depth and the snow structure is thus stable. The risk is especially high, if the reverse is the case. Of course, not only the properties of the now, but also other factors like steepness of the slope and mechanical stress (for instance by skiing) ar important for influencing the risk of avalanches.
- **Climate fluctuations and changes:** Amount and properties of snow on a given site are important indicators for climate factors like temperature and precipitation. Long-term records can tell a lot about fluctuations and changes in these factors and help to predict future trends.
- **Snow accumulation:** Temperatures can tell a lot about snow accumulation patterns, like showed in the previous chapter. This can for instance be important to predict the snow conditions for touristic activities.

Conclusions

Continous temperature recording during the winter combined with measurements of snow density and stratigraphy in spring can give valuable information on the patterns of snow accumulation. Because of the low heat conductivity of snow, temperature fluctuations at a given height above soil or ice surface are an excellent indicator for an approximation of snow thickness. However, in our case there were some problems connected with the applied methods:

Uncertainties remain in respect to the real height of the thermistors above ice surface. It was assumed an offset of 50 cm above the official height, but this is rather speculative and only based on weak correlation with a temperature profile. It would be necessary to dig out the stake (what would disturb further measurements) or to wait until snowmelt has terminated, to provide a solution for this problem.

To get more detailed information, it would be necessary to analyze the indicators for more than one point on the glacier. There were differences between directly adjacent pits, and it can be assumed that there would be much more pronounced differences over the whole glacier.

Finally, the data is incomplete, because the research was terminated in the end of March, altough also in April some additional snowfall has to be expected.

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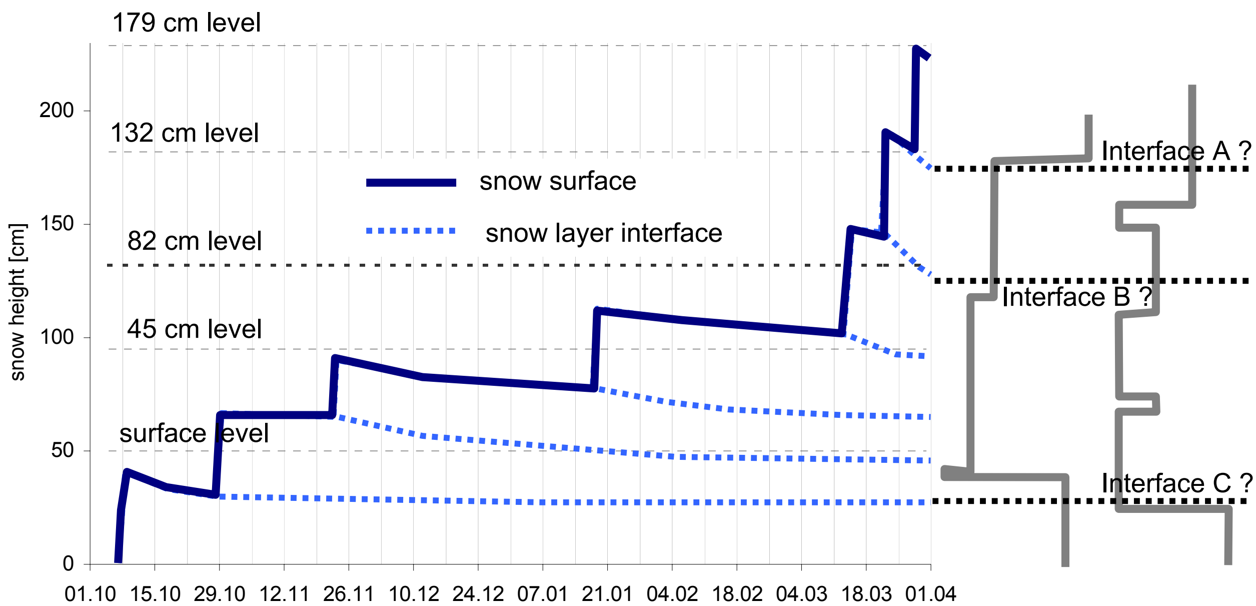

Fig. 7: Reconstruction of the temporal patterns of snow accumulation in the vicinity of stake 18, Storglaciären, with 50 cm offset of the thermistor levels. The compression of the snow was estimated with the measured densities. The profiles on the right side are the hardness profiles of the snow pits (compare fig. 5a and b)