Vertical distribution of water content within the polythermal Storglaciären, Sweden

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Introduction

It is known that small percentages of water within glacier ice increase considerably the strain rate (up to three times for a 1% increases in water - Duval, 1977). Accurate understanding of water distribution is required to improve predicting ice-flow modelling of ice masses; however, little is known about water-content variations with depth in glaciers. Observations of water-content at Storglaciären are limited to the cold temperate transition surface (mean value of 0.8%, Pettersson et al., 2004) and the distribution with depth is still unknown. Additional investigations throughout the rest of the ice column can bring new insights and validate recent developments in polythermal glaciers modelling (Aschwanden and Blatter, 2009). Since electromagnetic wave propagation velocity is sensitively dependent on water content, measurement of this parameter allows calculation of water content. In this study we investigated the water-content distribution in the upper ablation area of Storglaciären, northern Sweden (Figure 1) using detailed profiles of electromagnetic velocity variations with depth obtained from zero offset radar profiles (ZOP) collected in boreholes approximately 80 meters deep. Supporting datasets such as common offset (CO) radar profiles and temperature profiles were also analysed.

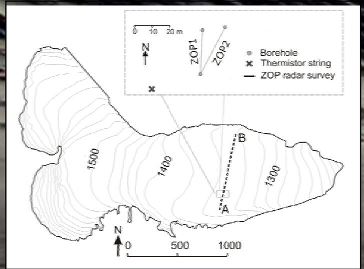

Figure 1. Map of Storglaciären with location of the boreholes, thermistor string and radar surveys using in this study. Dashed line indicates the 25 MHz CO line (figure 3).

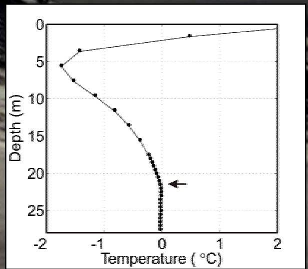

Figure 2. Temperature profile from thermistor string. The cold ice is 21m thick. Below this depth the ice is at the pressure melting point.

Methodology

Boreholes were drilled using a hot water drill and located using a Trimble differential GPS system. Inclinometry measurements were also collected to compute at each depth the distance between boreholes. ZOP surveys were collected using a Måla Geoscience GPR system. In a ZOP survey an EM pulse is radiated from a transmitting antenna located in one borehole, and recorded from the receiving antenna, located in an adjacent borehole. The antennas are then progressively lowered down the two boreholes with the transmitter and receiver at the same depth. We used a 1 meter depth-step and, for each antenna depth, the time required to an EM radiation to travel through the inter boreholes region was hence measured. Detailed EM velocity profiles with depth were therefore computed and corrected for the presence of air within the glacier-ice matrix (Bradford et al., 2009). Water content values at each depth were calculated using the Looyenga; 1965 mixture formula.

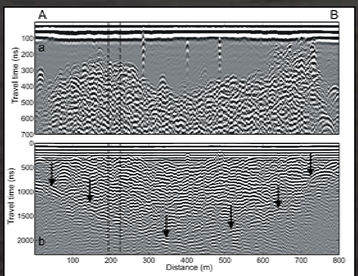

Figure 3. 25 MHz CO line AB used to estimate ice thickness and general thermal state. The boreholes area is in between the dashed lines. a) dewowed radar gram, the cold ice (transparent region) is ~ 21 m thick (250 ns using 0.168 m/ns). b) low-pass filtered radargram showing bed reflections (arrows) at 130 m in the study area.

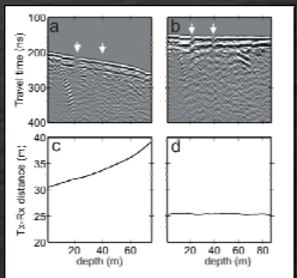

Figure 4. Example of 100 MHz ZOPs (a; b) and variation of distance between boreholes with depth for the two surveys (c; d). a, c: ZOP1; b, d: ZOP2 (location in Figure 1). White arrows indicates regions of low amplitude arrivals

Results

Temperature data (Figure 2) and the CO line (Figure 3) show that in the drilling area the glacier is polythermal with a 21 m thick cold surface layer (Pettersson et al., 2003). The ice thickness at this location is ~130 m (Figure 3b). The ZOPs surveys show that the first arrivals from within the ice column are clearly identifiable in the radargrams (Figures 4a, 4b): the signal to noise ratio appears to be consistently high, even at the largest Tx-Rx distances (e.g. 40 m in figure 4a). Boreholes distance in ZOP1 changes considerably with depth (figure 4c) whereas remain appreciably constant in ZOP2 (figure 4d); this effect is observable in the radargrams (figure 4a and 4b). The main qualitative features in these radargrams are anomalously low-amplitude first arrivals in some parts of the survey (arrows in figure 4). The resulting EM velocity profiles together with uncertainty boundaries for each survey are shown in figure 5. Figure 5 also shows the recorded amplitude at each depth. As expected, EM velocity is higher in the cold layer and decreases noticeably within the temperate ice. Absolute values correlate for the two surveys: EM velocity is higher at the surface and decreases gradually with depth until it reaches a sharp boundary, represented as a negative spike. Excluding minor perturbations (e.g. at 20 and 40 m in both surveys , Figure 5) EM velocity then tends then to stabilise on almost constant values within the temperate ice and although it appears to decrease with depth at depths greater than 50 m. Amplitude profiles with depth show clear low amplitude spikes (e.g. at 20 and 40 meters) of about one order-of-magnitude smaller than the average values throughout the whole investigated ice-column. Those minima in amplitude are identifiable in the radargrams (Figures 4a and 4b), and clearly correlate with minima in EM velocity (Figure 5).

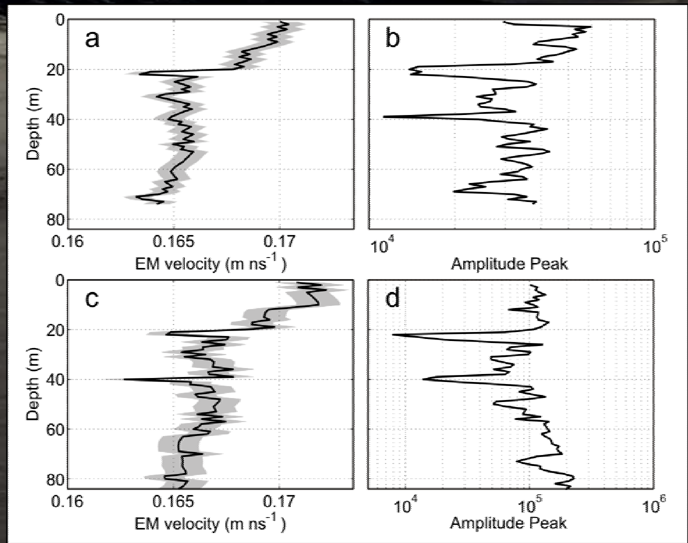

Figure 5. EM velocity and amplitude profiles with depth at Storglaciären, see figure 1 for location of the surveys. (a): velocity profiles for ZOP1; (b): amplitude profiles for ZOP1; (c): velocity profiles for ZOP2; (d) amplitude profiles for ZOP2. Gray areas indicate the measurement error.

Figure 6 shows water-content profiles with depth for the two surveys. Satisfactory agreement in terms of both absolute values and general water distribution is observed. The mean water content in the temperate ice are 0.72±0.18% and 0.56±0.25% for ZOP1 and ZOP2 respectively (quoted uncertainties are the mean error throughout the whole profile). These mean values are comparable to those derived by thermistor measurements at the CTS of Storglaciären in Pettersson et al. [2004] (0.8%, 0.75% and 0.58%). Estimates in the cold-surface layer (the upper 20 meters) are close to zero. The variability of water content with depth is almost negligible in the upper 30 meters of the temperate ice where water content values seem to stabilise on values 0.5%. From 55 meters depth a slight increases in water content with depth is observed with values up to 1% in the deepest part of the surveys

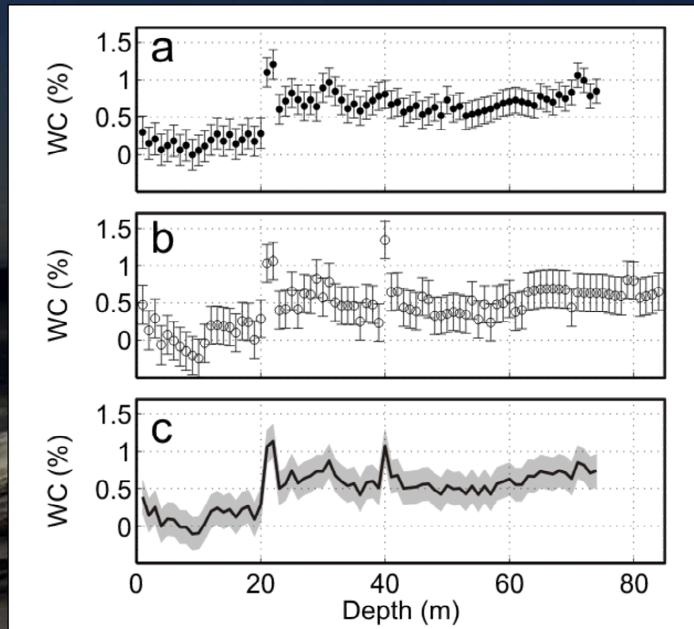

Figure 6. Water content (WC) vs. depth model obtained from EM velocity analysis for two ZOP surveys in the ablation area of Storglaciären. (a) ZOP1; (b) ZOP2; (c) mean values for the two surveys (black line), the gray area indicates the mean error calculated from the errors in each surveys. Water content estimates are computed using the Looyenga [1965] mixture formula.

Conclusions

Detailed borehole radar surveys were used to investigate the vertical hydraulic structure within the warm ice of the polythermal Storglaciären. We found no evidences of a complex layered model and a simple two-layer structure can be proposed with one upper layer of cold-ice with no free water and a lower layer with a minima water content of 0.6 ± 0.2%. Water content slightly increases (up to 1 %) at depth greater than 55 meters where the melt-water component due to the strain-heating starts becoming significant. This means that in the study area at Storglaciären, the temperate ice is at least 4 times softer than the cold ice [Duval, 1977] throughout the whole investigated ice column. Our findings suggest that future moisture-content and ice-flow models of Storglaciären should take into account a minimum water content of 0.7% (the average estimate at the CTS in Pettersson et al. [2004], which fall in the range of our estimates) throughout the whole temperate ice layer, this value slightly increases with depth. The observed increases of water content with depth validates recent models of Storglaciären's polythermal structure [Aschwanden and Blatter, 2009], but also shows that a more realistic ice-flow scenario is obtained if ours and Pettersson et al., [2004] average estimates are added to the water-content values predicted in Aschwanden et al., 2009.

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