High-Resolution Near-Surface Snow Stratigraphy Inferred from Ground-Based 8-18 Ghz FMCW Radar Measurements: Devon Ice Cap, Nunavut, Canada 2005-06, Cryosat Validation Experiment

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ABSTRACT

Broadband microwave Frequency Modulated Continuous Wave (FMCW) radar measurements were made during the spring of 2005 and 2006, at the CryoSat validation site on Devon Ice Cap, Nunavut, Canada. Metal reflector experiments were performed by inserting a large metal plate into a snowpit, parallel to visually identified layer transitions. This allowed unambiguous identification of specific radar reflections, which were relatively continuous in the region surrounding the study site (weak percolation facies). By mapping the snow depth to a given reflector, accumulation rate patterns over large areas can be estimated at high spatial resolution. We found that the depth to a given layer was shown to decrease in variability with depth, and that two spatial scales become evident in the structure, exhibiting lags of approximately 5 and 20 meters. Coincident measurements of surface hardness using a Snow-Micro-Penetrometer show more variability than layer depth, and also indicate an important process scale at ~ 5 m. We speculate that these spatial scales are related to the development of sastrugi, its burial and antecedent control of percolating meltwater, and suggest other complimentary data sources to further this line of inquiry.

INTRODUCTION

Reconnaissance methods employing lidar or radar altimeters aboard satellite and aircraft platforms are increasingly being used to study the variation of global and regional land ice mass budgets (e.g., Abdalati *et al*., 2004; Hopkinson and Demuth, 2006; Thomas *et al*., 2001; Zwalley *et al*., 2005). Because of surface motion and glacier dynamics, the principle challenge from a sea level change or water resources perspective is to retrieve mass change data from repeat measurements of surface height change. It is therefore necessary to understand more fully, processes that control internal layer development, densification and variability of the near-surface strata.

This paper describes the use of several precision and portable instruments towards a larger effort to understand this variability and the processes responsible for it across regions representative of Benson's glaciological facies assemblage (Benson, 1996), particularly for firn subject to percolation.

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MEASUREMENTS

FMCW radar has been used since the late 1970s (e.g. Ellerbruch and Boyne, 1980; Gubler and Hiller, 1984) for measuring snow depth, snow water equivalent (SWE), and snow stratigraphy (see Marshall and Koh, 2007 for review). Here we use a portable 8-18 GHz FMCW radar to measure snow stratigraphy on Devon Ice Cap, located in the Canadian Arctic (Fig. 1; see also Koerner, 2002). This site is one of the 3 Arctic land ice calibration/validation sites contributing to the European Space Agency CryoSat mission (http://www.esa.int/esaLP/LPcryosat.html).

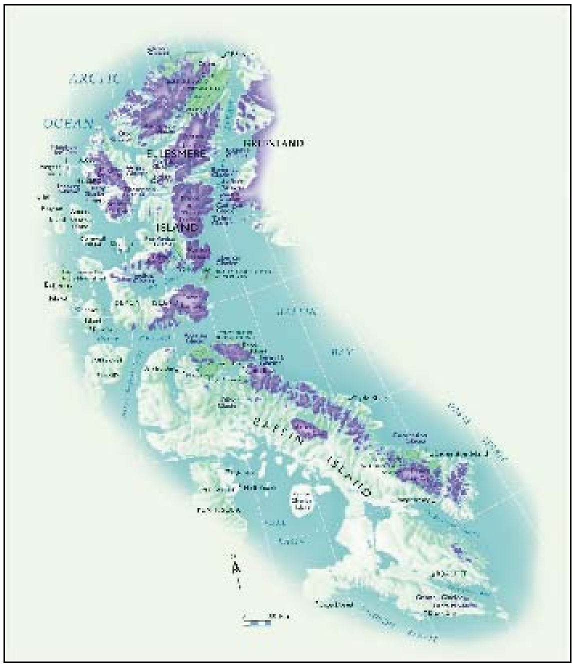

Figure 1. Canadian Arctic Archipelago. Devon Ice Cap is located on the eastern margin of Devon Island just north of Baffin Island (map courtesy of Canadian Geographic).

The data described were recovered in late April 2005 at an elevation of 1800 m a.s.l. over broad flat terrain where the primary agents of stratigraphic/SWE variability are post depositional through snow drifting/sastrugi formation and mass redistribution within the snowpack from meltwater percolation and refreezing.

Measurements were made with the radar illuminating the snowpack at nadir from a boom fixed at 1m height to a man-hauled sledge. Continuous profiles were recovered over1 km transects, at 5 cm horizontal resolution. The broadband characteristics of the FMCW radar system allow a vertical resolution ~1.5 cm. The Two-way Travel Time (TWT) of electromagnetic waves through the snow can be measured, and is related to snow depth and to a lesser extent snow density. The magnitude information from radar measurements is much more difficult to interpret, as it is strongly influenced by instrumentation-specific characteristics. Careful and time-consuming calibration measurements are required, and interpretation is difficult, as the magnitude depends on many factors including grain size, complexities associated with thin layer (less than 1 cm) responses, and wetness. Here we focus on TWT, which can be used to estimate snow depth and SWE to within 10% (e.g. Gubler and Hiller, 1984).

Coincident with FMCW radar measurements, we also made measurements of snow hardness and microstructure with a Snow-Micro-Penetrometer (Schneebeli *et al.*, 1998), snow density measurements with a neutron probe (e.g., Morris and Cooper, 2003), and a 900 MHz pulsed radar. Traditional snowpit measurements were made, and digital photography was used to document pit walls.

ANALYSIS

We developed a semi-automated layer-picking routine to locate prominent layering in the FMCW radar architecture. Control points are chosen by hand using a Graphical User Interface designed in MATLAB. These points are adjusted to lie exactly at the nearest local maxima, fit with a cubic spline, and then adjusted to local maxima along each trace. In this way layers are controlled to fit visually identified layer transitions at a few control points, then found automatically in between. Figure 2 shows a 100 m FMCW profile near the summit of the ice cap, containing 3,125 FMCW radar traces (average spacing ~3 cm). Many continuous layers can be followed in this processed image, and we chose 5 of the most prominent layers using our application-specific software (we make no attempt at this stage to identify annual layers).

The resulting 5 layers that are used in the analysis are shown in Figure 3, in red over white. White over black shows the picked surface. The measured TWT to each of the 5 layers was subtracted from the TWT of the surface pick, resulting in the TWT within the snow to the depth of each major chosen reflector. Using the average density measured with the neutron probe, this TWT was used to calculate an estimated snow depth.

We performed spatial auto-correlation analysis using location measurements from an odometer wheel encoder attached to the radar sledge (horizontal control was confirmed with L1/L2 DGPS measurements). A generalized, relative semi-variogram (Isaaks and Srivastava, 1989), was calculated for each layer depth after:

$$\gamma(h)=1/N(h)\ \sum[(u-v)^2/m(h)^2]$$

where $\sum[]$ is the sum over the $N(h)$ pairs of data points (u, v) that are separated by a distance h. This is the same as the traditional semi-variogram, but it is divided by the square of the mean of the data $m(h)$ used in the sum. Finally, the function we will display is the square-root of 2 times the above equation: $(2\gamma(h))^{0.5}$. This statistic represents the average relative difference of two measurements separated by a distance h. For example, if the value of this function at h=5 meters is 0.5, on average, two measurements separated by 5 meters will differ by 50%.

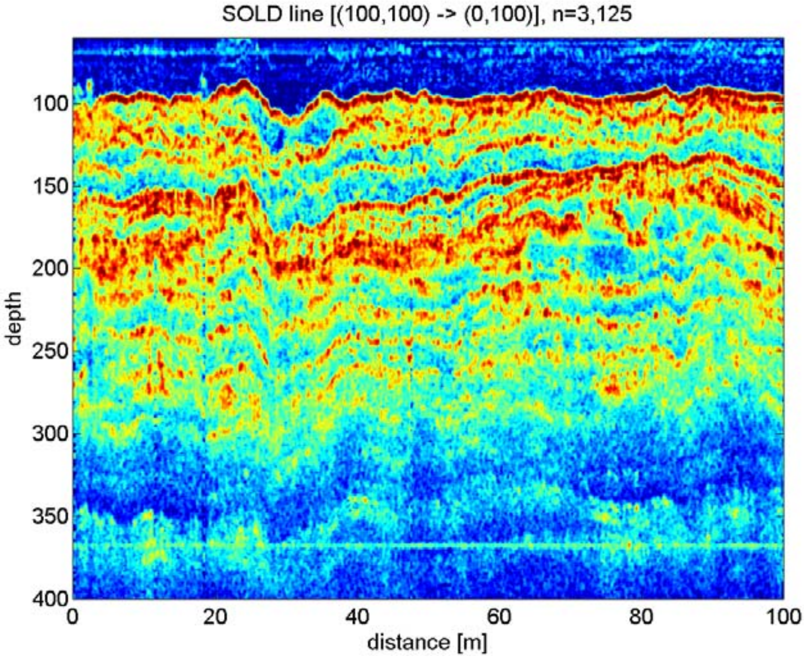

Figure 2. 8-18 GHz FMCW radar image over 100 m near summit of Devon Ice Cap. Continuous layering is visible down to a depth of 250 cm at high vertical and horizontal resolution .

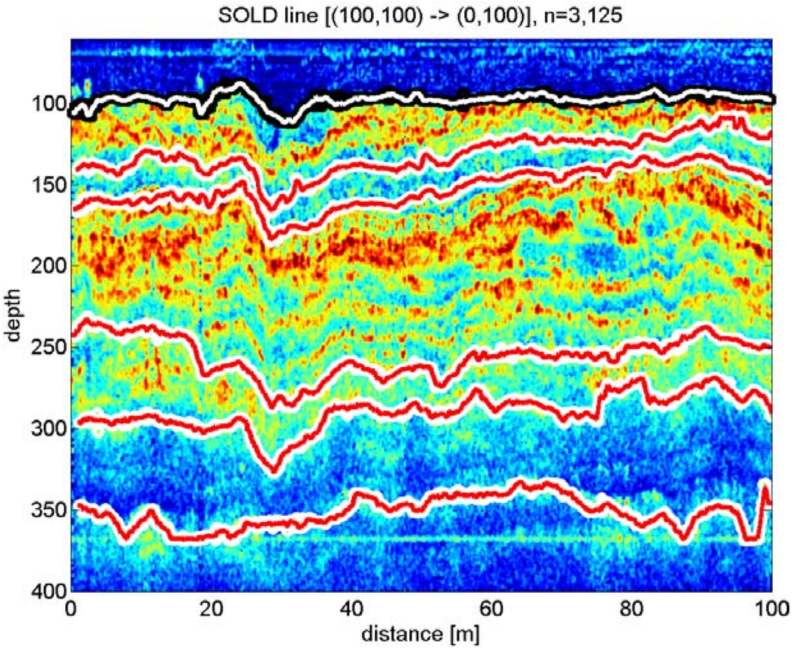

Figure 3. Layer depths calculated with MATLAB-based semi-automatic layer picking software. Layers are shown in red over white; surface location is shown in white over black.

RESULTS AND DISCUSSION

Figure 4 shows the semi-variogram for the 5 layers highlighted in Figure 3. Layers are numbered L1-L5, in order of increasing depth. Black dashed lines are shown at 5 and 20 m for reference. Note the large change and local range that is located in several of the layers at 5 m, and the range of 20 m in the deepest 3 layers. This indicates there are processes operating at both the 5 and 20 meter length scales. Variability decreases with depth, however L4 and L5 have a very similar spatial structure. It is therefore likely that in the upper 2 meters, some process is causing variations that average themselves out over ~ 4-5 year time scales. Spatial structure at the 5 and 20m length scale, however, persists. Measurements out to 20 meters are spatially correlated at this depth, but points separated by more than 20 meters are no more related than points more than 50 meters apart.

At the 5 meter scale there is some process that is controlling layer depth as well. Figure 5 shows the generalized relative semi-variogram of snow surface hardness from penetration measurements with the Snow-Micro-Penetrometer. Note the clear range defined beyond ~5 meters, indicating a spatial structure out to this distance, and much more variation in hardness than depth.

We suggest that the decorrelation lengths and associated variability revealed by our analysis may be related to the process of sastrugi development and the control these structures, once buried, exert on preferential horizontal pooling and vertical pathways of percolating meltwater (in this glacier-climate regime, significant accumulation occurs in Summer).

Further examination of the timing and magnitude of melt events coincident with the time span covered by our radar measurements will assist in interpreting these and related observations. For example, was the melting in any one year intense with percolation occurring into a substrate that was still well frozen, or was the melting more protracted and coincident with a generalized warming of the snowpack and isothermal conditions? In addition, the neutron probe snow density measurements will assist us in determining annual horizons, allowing us to comment further on variability of SWE in firn subject to percolation.

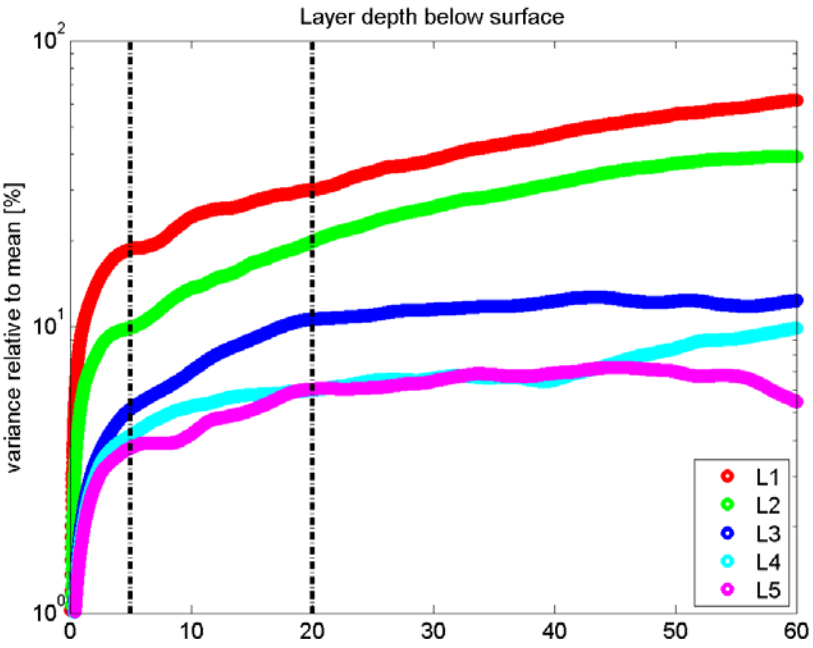

Figure 4. Generalized relative semi-variogram of layer depth for five prominent reflectors shown in Fig. 3.

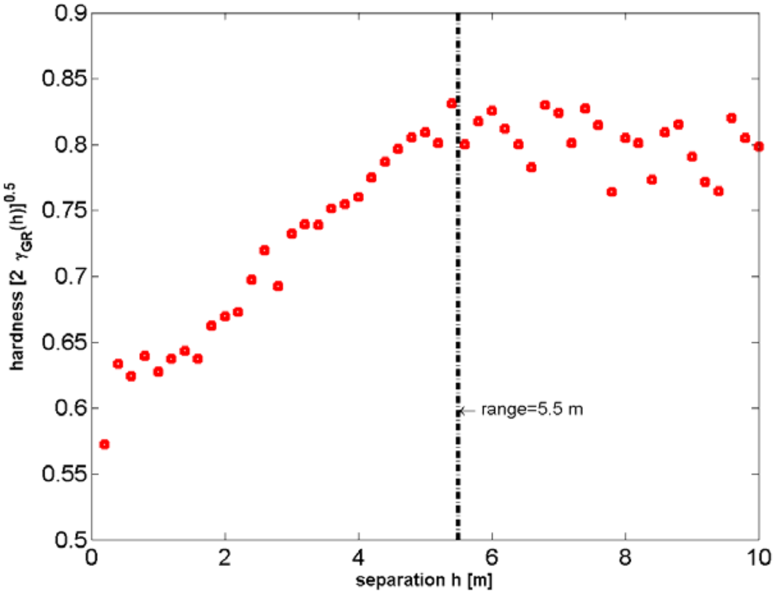

Figure 5. Generalized relative semi-variogram of snow surface hardness measurements made with the Snow-Micro-Penetrometer (after Marshall *et al*., 2006).

CONCLUSIONS

Continuous stratigraphy in the upper 2.5 meters was measured in the percolation zone of Devon Ice Cap using a portable 8-18 GHz FMCW radar. Five different obvious layers were chosen using custom-made semi-automatic layer picking software. The depth to a given layer was shown to decrease in variability with depth (i.e. averaging over time). Two spatial scales become evident in the structure, and a lag of approximately 5 and 20 meters. Measurements of surface hardness using a Snow-Micro-Penetrometer show more variability than layer depth, and also indicate an important process scale at ~5 m. Future work will examine radar architecture derived from a 900 MHz pulsed radar and complimentary neutron probe snow density measurements, meteorological and climate reanalysis data, and aircraft lidar data describing the surface topography in detail.

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