56TH EASTERN SNOW CONFERENCE
Fredericton, New Brunswick, Canada, 1999

Preferential Melt Pathways in a Natural Snow Pack

M. ALBERT,[1] G. KOH,[1] AND F. PERRON[1]

ABSTRACT

Melt pathways in a natural seasonal snowpack were investigated using high frequency FMCW radar to determine whether radar is a useful tool for investigating water flow through snow, and to develop preliminary estimates of the number of fingers that form in snow and the amount of melt water that is transported via this mechanism. Field investigations are presented that show that the radar can be used to sense melt features at distances to about a meter within the snowpack. Old refrozen fingers and new wet fingers both generate visible radar returns. Excavation of fingers within the snowpack verified that the radar signals were from flow fingering. By counting the number of fingers observed in the radar images and using snow lysimeter measurements of outflow from the snowpack, we estimate that in the early stages of the main snow melt season, this snowpack contained approximately 2 fingers/m^2, and that the flow through each finger was approximately 0.8 mm water/finger/hour.

Key words: Snow melt, fingering, FMCW radar, lysimeter.

INTRODUCTION

Although poetic descriptions of snowcovers often depict snow as a uniform white blanket, natural snowpacks are more typically composed of non-uniform layers whose crystal structures reflect the nature of differing depositional events and post-deposition physical processes. Similarly, the physical processes that occur in snow are often not uniform. The formation of preferential flow pathways in porous media has long been recognized (e.g. Dullien, 1979), and its importance to melt water progression through snow has been acknowledged (e.g. Marsh, 1991). Models of snowmelt that attempt to include these effects have been developed (e.g. Marsh and Woo, 1985; Colbeck, 1979), but unfortunately leave as 'user input' the unknown number and size of flow channels through snow. This fundamental omission has severely limited application of the models. It has been shown (Albert and Hardy, 1993) that homogeneous, or "ripe" snow may exists only for the last several days of the snow melt season; thus for snow melt modeling it is important to ascertain whether preferential flow pathways are likely to be important to snow melt predictions through most of the season.

One difficulty in investigating preferential flow pathways in natural snow lies in the means of detection of the pathways. Many dye tracing experiments have been performed (e.g. Hughes and Seligman, 1939; Gerdel, 1954; Woo et al, 1982). Typically the dyes are sprayed on the snow surface and then the snow is excavated to observe the pathways. There are several drawbacks to this approach: changing the color and composition of the snow surface changes its albedo, which

---

[1] U.S. Army Cold Regions Research and Engineering Laboratory, 72 Lyme Road, Hanover, New Hampshire 03755-1290, U.S.A.

is a key factor in melt generation, and spraying water on the snow surface disturbs natural snow melt conditions. An approach that is non-intrusive, does not change the surface albedo of the snow, and does not necessitate adding material to the snow is needed so that the flow channels detected will be the naturally-occurring melt caused by ambient meteorological conditions only.

The objective of this research is to investigate the use of radar for non-intrusive detection of the preferential flow pathways (e.g. flow fingers) in natural, undisturbed snow, and to assess the utility of radar for determining the number and distribution of flow pathways in a natural snow pack. The large difference in the complex dielectric constants of ice ($\varepsilon* = 3.17$) and water ($\varepsilon* = 71 - j33.6$ at 4.5 GHz) at microwave frequencies strongly favors radar for detecting even small regions of wet snow within a snow pack. In this study, we used frequency modulated continuous wave (FMCW) radar operating at 2-6 GHz bandwidth. The radar bandwidth was considered to be an ideal compromise between radar resolution and penetration for these tests (as the frequency increases, the resolution improves at the expense of penetration). FMCW radars have been previously used to detect surface and near-surface melting of snow (e.g. Koh, 1992; Koh and Jordan, 1995); however, there are no reports in the literature on the use of radar to investigate flow channels in a snow pack.

METHOD

The field measurements were made on a natural seasonal snow cover at the Sleepers River Research Watershed in northern Vermont. At this site, a meteorological station provides measurements of air temperature, wind speed, relative humidity, solar and long wave radiation, and precipitation. Two snowmelt lysimeters continuously record snowpack outflow. In northern Vermont the snow on the ground is typically ephemeral during the month of December, but the ground is characteristically snow covered between January and early to mid April, with snow depths typically a meter or less. Measurements of snow properties were done on a weekly basis through the season, and the radar measurements were done on four days in March with differing snow and meteorological conditions.

The radar investigations were done on a flat area of undisturbed snow approximately 20 m from the meteorological tower. For each day of testing, a fresh snow trench was excavated and then portable tracks installed. The radar was mounted on a platform and pulled along the track at constant rate by a motorized pulley system (Figure 1). The antennas were directed so that the

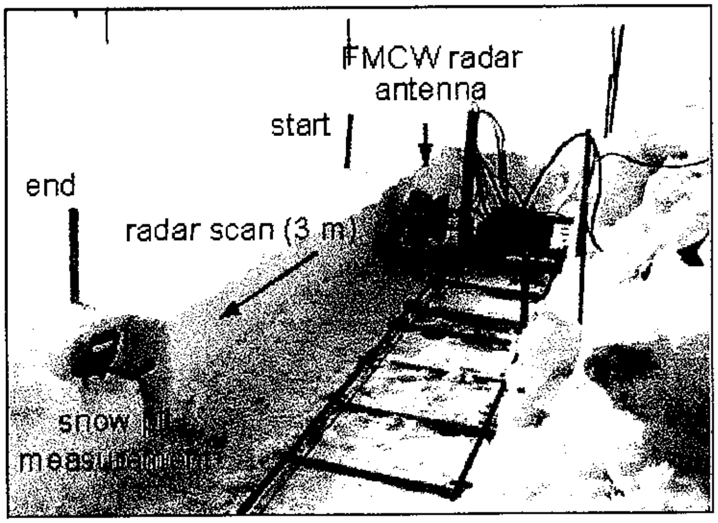

Figure 1. The track, pulley, and radar system for scanning along the face of a snow trench.

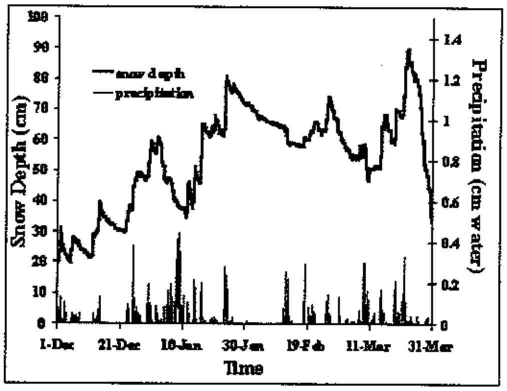

Figure 2. Snow depth and precipitation data for the season.

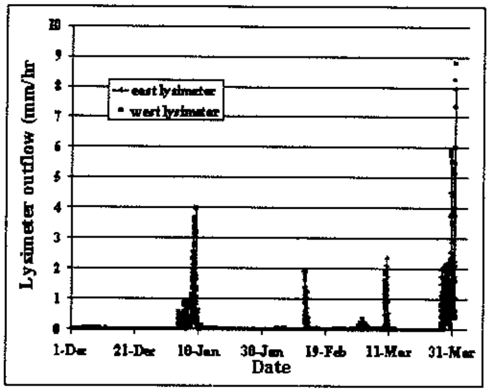

Figure 3. Snow melt lysimeter data for the season

radar would profile the trench wall. The antennas were oriented to maximize sensitivity to the vertical features in the snow. The antenna was offset 20-30 cm from the wall face, which placed the snow in the near field radiation zone. Two angle irons were inserted vertically into the snow pack, one near the start of the track and one near the end (approximately 3 m separation). These served as reference markers for start and end of radar scan, for horizontal distance into the snow pack from the trench wall, and also served as a measure of radar penetration in the snowpack. Stratigraphy parameters of density, crystal type, and moisture content were measured at one end of the snow trench, along with snow permeability measurements.

RESULTS

Three rain on snow events occurred before the middle of March, and the period of active snow melt began near the end of March. Figure 2 shows the snow depth and precipitation over the course of the season, and Figure 3 shows the snow melt lysimeter data for the season. The first radar measurements were made on March 12. The passage of a cold front several days earlier included a rain event, and was immediately followed by a sharp drop in air temperature of over 20^0 C. Figure 4 depicts the snow stratigraphy on this day, as well as on the days of subsequent testing. The top half of the snow pack consisted of refrozen snow, with developing facets on the

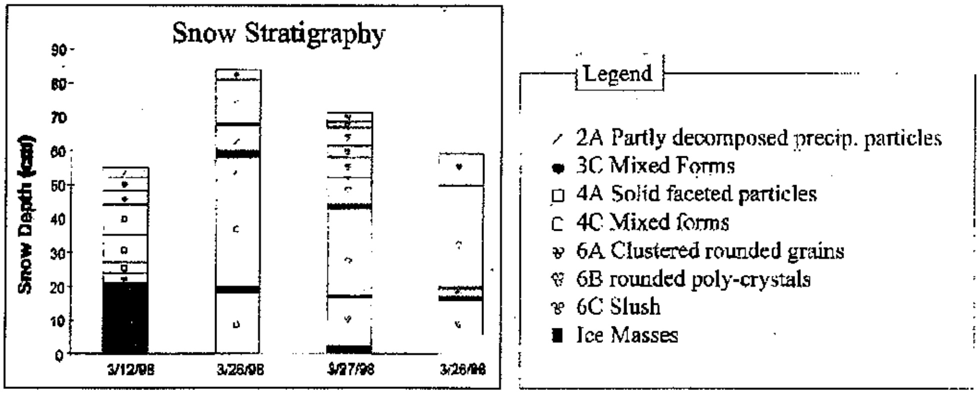

Figure 4. Snow pack stratigraphy on the days of radar profiling.

crystals, while the bottom 20 centimeters consisted of old melt freeze crystals with a small residual water content.

The purpose of the first test was to determine the background signal of old refrozen snow, and also to measure the radar signatures as water was introduced into the snow. The background signal of the refrozen snow is shown in Figure 5a. The radar image is characterized by a continuous reflection from the wall of the snow pit (shown laterally across the top of the radar scan). The variability in reflection from this air/snow interface is due to the uneven surface at the face of the snow pit. The large reflections at the bottom left and right corners of the figures are metal reference markers located at the start and end points of the scan, respectively. For these tests the reference markers were located 40 cm from the snow pit wall and were approximately 3.5 m apart. Radar reflections from ice channels, which are presumed to have formed from previous rain on snow events, are also visible. Photographs of these ice channels, which were approximately 15-20 cm long and whose diameter ranged from 2-5 cm, are shown in Figure 6.

In order to determine the nature of radar returns from regions of wet snow in a snow pack, cold water was poured on the snow surface. A large area was first wetted with a sprinkling can approximately 1 m from the start reference marker. A second, smaller area was wetted approximately 1.7 m from the reference marker using a steady stream of water. Before wetting the second area, a vertically oriented hole in the snow was made with metal rod in order to confine the water flow to a smaller zone. The radar was then scanned again along the face of the snow pit, with the profile of returns shown in Figure 5b. The locations of both wet zones are

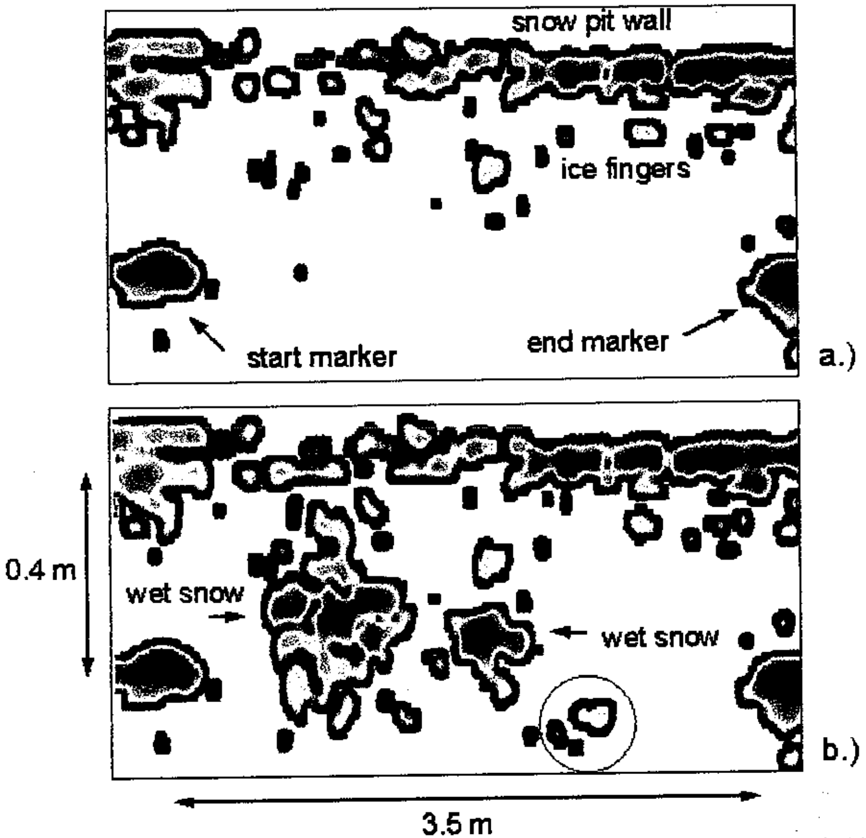

Figure 5. Radar images of a snow trench obtained on 12 March. a.) Image of old previously wetted (rain event), refrozen snow and b.) the same test area after water was poured on the snow surface to produce regions of wet snow. The circled area represents water flow approximately 0.4 m away from where a steady stream of water was introduced. The start and end markers are angle irons inserted approximately 0.4 m away from the snow pit wall. These markers are 3.5 m apart.

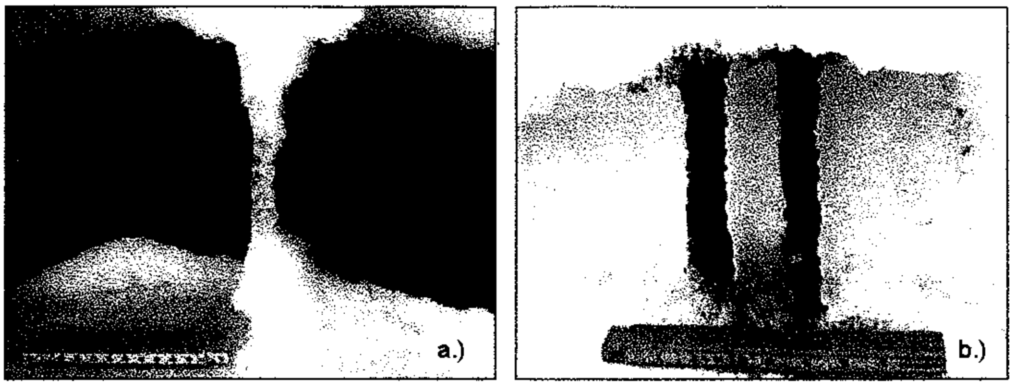

Figure 6. Excavated ice channels from rain on snow event. In order to increase contrast a.) a black background was placed behind an ice channel and b.) dye was sprayed on two channels.

clearly visible from the image, along with the pre-existing ice channels, which are in agreement with the background image (see Fig. 5a). Figure 5b also shows a wet zone (circled in the figure) approximately 0.3 m away from where the steady stream of water was introduced which suggests that flow pattern in snow can be complex. This test verifies that the radar is sensing the wet features within the pack, and shows the relative signal level expected from various features within a snow. It is pointed out that the snow conditions were ideal for these tests. The snow was dry which enhanced radar penetration, and the dielectric contrast between the liquid water and the dry snow background was strong as discussed earlier. As the snow becomes wetter, the increased absorption loss makes it difficult to detect features with low radar reflectivity.

The following two weeks consisted of cold weather with snow the only precipitation. Figure 7 depicts the air temperature and snow melt lysimeter outflow through the period of subsequent radar measurements. A winter storm on 22 and 23 March increased the snow depth by 20 cm. A snow pit observation on 25 March revealed that the snow has no liquid water on that day. Warm air temperatures after 25 March caused the snow pack to begin to ripen, as depicted in the snow pit profile of 25 March (see Fig. 4). About an hour before the radar image in Figure 8 was taken on 26 March, a light and intermittent rain began to fall. As evidenced by no-outflow conditions on the lysimeter plot (see Fig. 3) and the snow moisture profile in snow pit plot (see Fig. 4), there was insufficient liquid water present in the snow pack to percolate to the bottom of the pack. Snow moisture meter profiles showed that there was some liquid water at all levels within the

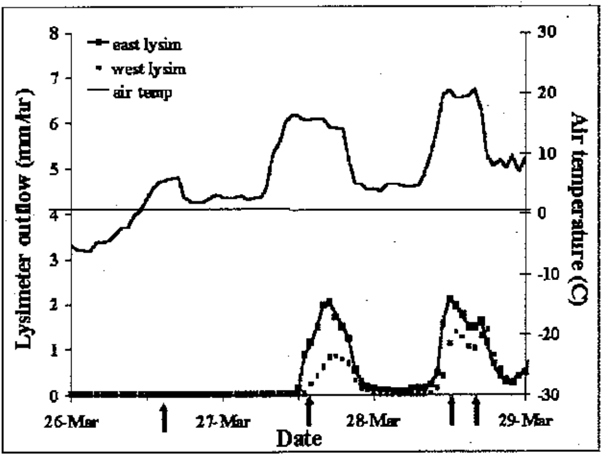

Figure 7. Air temperature and lysimeter outflow measurements during the radar testing at the start of the main melt period.

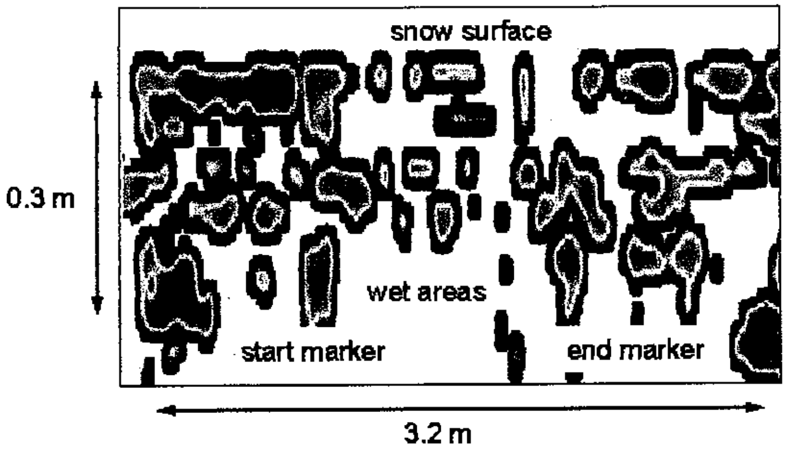

Figure 8. Radar image of snow trench obtained on 26 March.

pack, ranging from 0.4% to 0.7% wetness, near the level of the irreducible water saturation. The radar image clearly shows the presence of many wetted areas in the snow, probably due both to the new drizzle and also due to the initiation of grain-scale melting of the snow crystals (initiation of the ripening process) that began the day before. The magnitude of the radar signal from the reference markers were comparable to those observed in Figure 5, which indicates that the radar signals penetrated this snow. This suggests that the wet areas shown in this figure are likely due to small quantities of water distributed throughout the snow. The following warm days with night time temperatures above freezing started the main snow melt season.

By the time of the third radar measurement on 27 March, the warm weather had caused wet and rounded grains within the pack, melting at the surface had begun and there was flow out of the lysimeters. No surface pocks were yet visible. The radar penetration decreased significantly due to the increased moisture so that a range gain algorithm (amplification proportional to range) was needed to bring out the features in the snow. The radar image (Figure 9) shows fewer, but stronger radar returns, which we interpret to indicate flow pathways. By 28 March the warm weather had caused onset of the active melt period. Water was flowing out of the lysimeters constantly, surface pocks in the snow indicated probable surface finger sites. The snow pack was considerable strength. In Figure 10a the radar scan from early afternoon is shown. Figure 10b

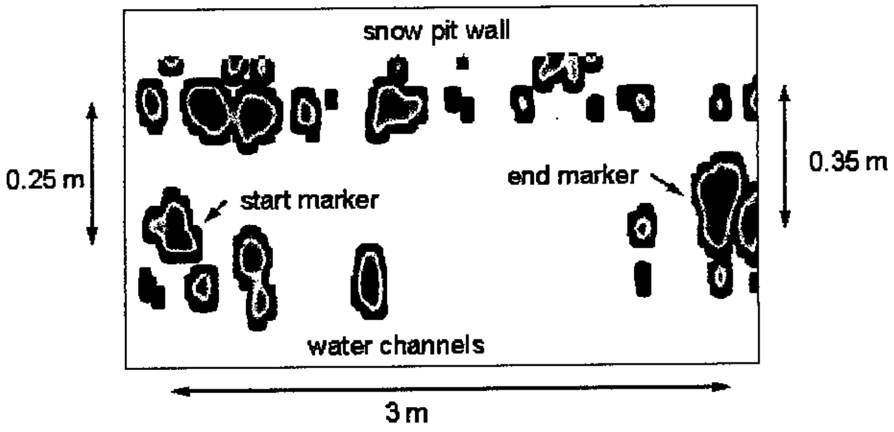

Figure 9. Radar image of snow trench obtained on 27 March. Due to increased snow moisture the radar penetration decreased. Range gain algorithm was required to bring out the features in the snow pack.

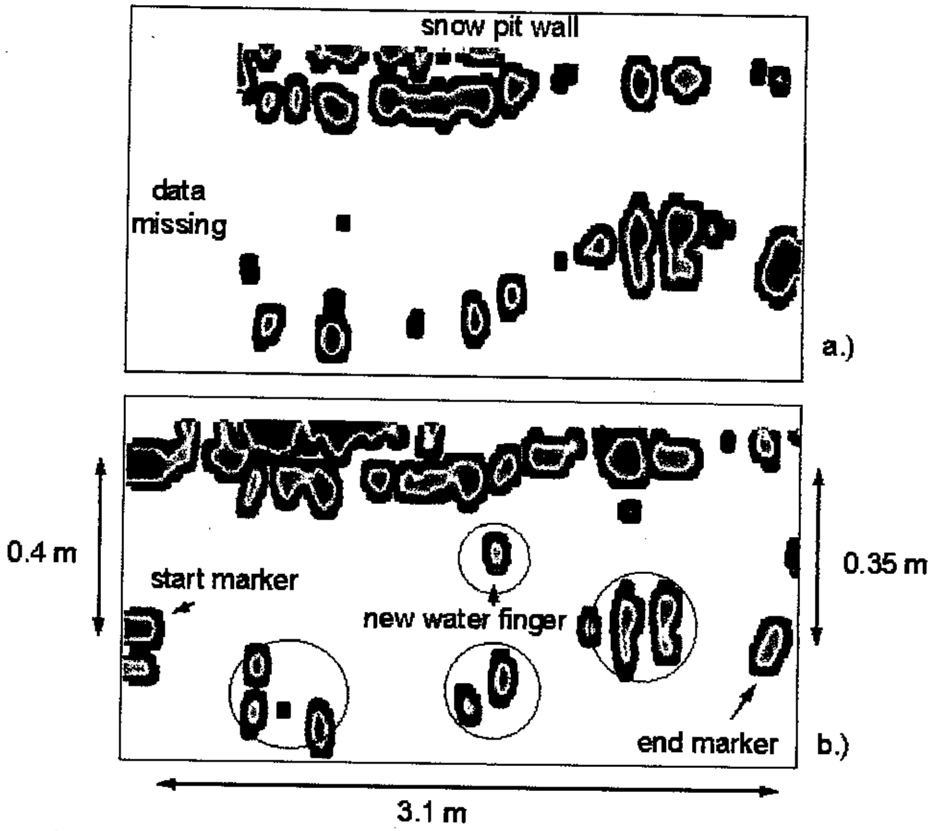

Figure 10. Radar image of snow trench on 28 March at a.) 1300 hrs and b.) 1600 hrs. A new water finger formed during this 3 hr period. Excavation of snow did not reveal well-defined streams of water. Large volume of saturated snow whose consistency differed from the surrounding snow was observed. The region of saturated snow (circled) is assumed to be a single flow channel.

depicts a scan of the same undisturbed snow approximately three hours later. Comparing the images, the same flow channels from the early afternoon image can be seen in the late afternoon image, with the afternoon image showing the formation of several new flow fingers. From inspection of Figure 10b, we see 4 fingers (each cluster was assumed to be a single flow channel) in a sample area of approximately 2 m^2.

From the lysimeter data, at 1600 hrs on 28 March, the flow out of the lysimeter was 1.5 mm water per hour. Since the wetting front had not yet passed through the pack, the mode of transport for this water was through the melt fingers. The average flow through each finger is calculated to be approximately 0.8 mm water/finger/hour. Clearly, the amount of water that each flow finger transports is governed both by microstructure dynamics and by the amount of melt water available for transport, so that this value may change in time. This represents the first estimate of the amount of water that a snow melt finger can transport in nature and should help snow melt models that rely on the specification of flow finger density and amount of water transported by each. Future work will investigate model predictions of snow melt through the season with further determination of the net effects of flow fingering to snow pack melt outflow.

CONCLUSIONS

The high frequency FMCW radar appears to sense melt features at distances up to about a meter within the snow pack. Old refrozen fingers and new wet fingers both generate visible radar returns. Excavation of fingers within the pack identified by radar signals verified that the radar signals were from flow fingering. By counting the number of radar images and using snow lysimeter measurements of outflow from the pack, we estimate that in the early stages of the main snow melt season, this snow pack contained approximately 2 fingers/m^2, and that the average flow through each finger was approximately 0.8 mm water/finger/hour.

REFERENCES

Albert, M. and J.P. Hardy, 1993, Snowpack stratigraphy evolution in open and forested sites, Proceedings of the 1993 Eastern Snow Conference, p. 205-212.

Colbeck, S.C., 1979. Water flow through heterogeneous snow, Cold Regions Science and Technology, vol. 1, p.37-45.

Dullien, F.A.L., 1992. Porous media: fluid transport and pore structure, Academic Press.

Gerdel, R.W., 1954. The transmission of water through snow. Transactions, American Geophysical Union, 35(3), p. 475-85.

Hughes, T.P., and Seligman, G., 1939. The temperature, melt water movement and density increase in the neve of an alpine glacier. Monthly Notices of the Royal Astronomical Society. Geophyiscal Supplement, 4(8), p. 616-647.

Koh, G., 1992. Effect of wind on FMCW radar backscatter from a wet snowcover, IEEE Transactions on Geoscience and Remote Sensing, 30, p. 619-621.

Koh, G and R. Jordan, 1995. Sub-surface melting in a seasonal snow cover, Journal of Glaciology, 41, p. 474-482.

Marsh, P., 1991. Water flux in melting snow covers. Chapter 9 in Advances in Porous Media I, Elsevier, p. 61-122.

Marsh, P., and M.K. Woo, 1984. Wetting front advance and freezing of meltwater within a snow cover 2: A simulation model, Water Resource Research, 10(12), p. 1865-1874.

Woo, M.K., R. Heron, P. Marsh, 1982. Basal ice in high Arctic snowpacks. Arctic and Alpine Research, 14, p. 251-260.