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ICE COLUMNS AND FROZEN RILLS IN A WARM SNOWPACK, GREEN LAKES VALLEY, COLORADO, USA

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Abstract

Here we provide information on ice columns and frozen rills found in late-season snowpacks in and near the Green Lakes Valley of the Colorado Front Range, USA. The presence of ice columns and frozen rills in late season snowpacks may provide insights with which to understand the spatial distribution of preferential flowpaths in melting snowpacks. In July and August of 1996 and 1997 we found ice columns in every one of the more than 50 snow fields we investigated. The ice columns showed a consistent morphology; each column was approximately 75 cm in vertical extent, with about 5 cm projecting above the snow surface and 70 cm extending into the snowpack. An analysis of variance test shows that the 81 ice columns on the south-facing slopes were significantly greater than the 57 ice columns on the north-facing slope ($p = 0.01$). There were about 3 ice columns per square meter on the south facing slopes and 2 ice columns per square meter on the north-facing slopes. There was an interesting hysteresis in snow and ice temperatures that became stronger with increasing depth in adjacent thermocouple arrays. This hysteresis in the temperature profiles is consistent with the release of latent heat from the freezing of greater amounts of liquid water in and near the ice columns compared to the surrounding snowpack. At the Martinelli catchment, spacing between the frozen rills averaged 2.6 m ($n = 73$). We interpret these "ribs" of solid ice to be the remnants of surface rills. Vertical ice columns were connected to these frozen rills. The ice columns and frozen rills may provide a snapshot or "schematic" diagram of the major flowpaths in a ripe and draining snowpack.

Introduction

Much remains to be learned about meltwater flow through snow. Movement of liquid water through snowpacks is generally recognized to occur in distinct flow paths rather than as uniform flow through a homogeneous porous medium. Seligman (1936) found that snowpack permeability was enhanced when flow channels were present in the snowpack. Oda and Kudo (1941) described flow fingers and flow along layer interfaces. Dye was used to trace flow paths during the Cooperative Snow Investigations (Gerdel 1948 and 1954; US Army 1956). Preferential flowpaths, ice layers, and ice columns have been observed in many other studies, in a wide range of different geographical settings (*e.g.* Wankiewicz 1979; Higuchi and Tanaka 1982; Marsh and Woo 1984a,b; Kattelmann 1985, 1989; McGurk and Marsh 1995).

However, attempts to characterize the spatial distribution of preferential flowpaths have had only limited success (*e.g.* Marsh and Woo 1985, Kattelmann 1989). Attempts to understand meltwater flow through snow from first principles have also had only limited success (*e.g.* Colbeck 1979, 1991). An understanding of the spatial distribution of preferential flowpaths in melting snowpacks has suffered from the ephemeral nature of the flowpaths and the problems caused by destructive sampling of the snowpack (*e.g.* Schneebli 1995). The ability to characterize the spatial distribution of these meltwater flowpaths would be useful in developing snowmelt runoff models which could better characterize snowmelt hydrographs.

The presence of ice columns in late season snowpacks may provide a useful tool with which to understand the spatial distribution of preferential flowpaths in melting snowpacks. Ice columns, described previously by Ahlmann and Tveten (1923), Ahlmann (1935), Seligman (1936), and Gerdel (1948), were recognized to be the residual flow network in cold snow by Sharp (1951). Woo et al. (1982) provided additional information on ice columns in Arctic snowpacks and Pfeffer and Humphrey (1998) report the presence of ice columns near the equilibrium line on the Greenland Ice Cap. An improved understanding of the morphology of individual ice columns, heat flux to and from the surrounding snow, and their distribution over space may provide insights into how meltwater flows through snow.

Dendritic rill patterns on snow cover appear to be a surface expression of preferential flow paths on sloping terrain (Marsh 1991). In one of the few studies of dendritic rills, Higuchi and Tanaka (1982) reported increased flow volumes and grain sizes beneath rill patterns. McGurk and Kattelmann (1988) suggest that the surface depression of rills results from the removal of small grains by liquid water and resulting collapse of the overlying snow. Frozen rills may provide information on preferential flowpaths as terrain increases in slope.

Here we provide information on ice columns and frozen rills found in late-season snowpacks in and near the Green Lakes Valley of the Colorado Front Range, USA. Specific objectives include: (1) characterizing spatial frequency; (2) aspect controls on spatial distribution; (3) description of the morphology of individual ice columns; (4) energy balance and liquid water regime of the ice columns; and (5) comments on the evolution of the ice columns and frozen rills.

Site Description

Research was conducted in 1996 and 1997 in the Green Lakes Valley (40 03' N, 105 35' W) of the Colorado Front Range (Fig. 1). The Green Lakes Valley is an east-facing headwater catchment that abuts the Continental Divide and is located entirely within the Arapahoe-Roosevelt National Forest. The basin is 700 ha in area and ranges in elevation from 3,250 m to ≈ 4,000 m (Fig. 1). The catchment appears typical of the high-elevation environment of the Colorado Front Range, and includes Niwot Ridge, where research has been conducted since the early 1950's (Caine and Thurman 1990). About 80% of the annual precipitation in the Green Lakes Valley occurs as snow. Streamflows are markedly seasonal, varying from less than 0.1 m^3 s^{-1} during the winter months to greater than 1.5 m^3 s^{-1} at maximum discharge during snowmelt just below Lake Albion at the lower end of the valley (Caine 1996).

Niwot Ridge forms the northern boundary of Green Lakes Valley (Fig 1.) and is an UNESCO Biosphere Reserve and a Long-Term Ecological Research (LTER) network site. Much of the research that we report here was conducted in the 8-ha Martinelli catchment, located above treeline on the south slope of Niwot Ridge at an elevation of 3,415 m (Caine and Swanson 1989). Slope angles ranged from about 5 to 30°, generally increasing from the bottom of the catchment towards the top. The Martinelli catchment accumulates a snow cover which often exceeds 10 m in depth at maximum accumulation and persists through late summer in most years (Caine 1989). Measurements of the spatial distribution of ice columns were also made in late-season snowpacks located on the floor of Green Lakes Valley between lakes 4 and 5. Additionally, we noted the presence or absence of ice columns on about fifty late season snow patches on a serendipitous basis in Green Lakes Valley and on Niwot Ridge.

Methods

Ice columns were identified on the snow surface using these criteria: (1) Unusual hardness relative to the surrounding snow; (2) enlarged grain size; (3) notable relief relative to the surrounding snow, either raised or depressed; and (4) presence of a debris cap at the top of the ice column. Density of snow and ice were measured in the field using a 250-mL density cutter and a digital weighing scale (± 2 g); ice was cut to fit the shape of the density sampler. Grain size was measured with a 10x hand lens and crystal card with 1- and 2-mm grids. Samples of debris that form a cap on the ice columns were analyzed for mineral and organic content using standard laboratory methods, including air drying at 35°C and then determining size separates using the sieve-sedigraph method.

The morphology of individual ice columns was investigated through excavation and measurements. Lower density snow was removed from the denser and harder ice columns using snow shovels, ice tools, and finally paintbrushes. Dimensions of features such as height and width were made with a metric tape measure. The height of ice columns relative to the surrounding snowpack was measured by placing a 1-m ruler on the snow surface and then measuring the height of the ice column with the horizontal ruler at the 0-cm height. Depressions were negative heights away from the horizontal ruler and protruding ice columns were positive heights increasing with distance above the horizontal ruler.

The spatial distribution of individual ice columns was mapped with an accuracy of ±5 cm. We found that late in the melt season the ice columns became connected by "ribs" of protruding ice oriented along the fall line of the snow patches. We measured the distance separating these ribs using a tape measure and selecting measurement points using a random walk method.

The spatial frequency and aspect controls on the distribution of ice columns was investigated on a seasonal snowpatch near Green Lakes 4 (Fig. 1) using a nested plot design. Eight plots were established, each 2 m x 2 m in area, with four on the south-facing aspect and four on the north-facing aspect. Plots were randomly selected by tossing rocks onto the snowpatch and using the rock location as the center of the plot. The number of ice columns was recorded in each plot. Additionally, we counted the number of ice columns along a transect oriented from south to north aspects of the snow field. The transect was 34 m in length. Ice columns were counted in 34 sections, each 1 m in length by 0.30 m in width.

Changes in height of three ice columns were monitored over an eleven-day period. Two columns started as depressions in the snow surface and one column started as a projection above the snow surface.

The temperature regime of the ice columns and surrounding snow were measured using a paired array of thermocouples, with one array positioned in the ice column and the second array positioned 20 cm away in the snowpack. Thermocouples were installed at three depths below the surface of the ice column or snowpack: 5, 10 and 20 cm. Thermocouples were installed by digging a snowpit, creating a small-diameter hole at the appropriate depth by heating a brass wire and inserting the wire horizontally about 30 cm into the ice or snow to minimize edge effects, inserting the thermocouple into the hole, and then backfilling the snowpit to its original depth. Thermocouples were made from copper-constantine wire with a soldered junction and connected to a Campbell CR21x data logger. Temperatures were measured every 5 s and means recorded every 5 minutes. A one-point calibration of all six thermocouples was conducted before and after each experiment using an ice-bath that was constantly agitated over the 20-minute calibration period. Precision of the temperature measurements was ± 0.2°C.

Results

Surface expressions of the ice columns were easily recognized by the presence of large, melt-freeze, polycrystalline snow grains. The effective size of the snow grains was 3-5 mm in diameter. Generally, the snow grains were frozen together in a permeable, honeycomb structure if air temperature were below 0°C, similar to the report by Marsh and Woo [1984a] for ice columns in an Arctic snowpack. If air temperature was greater than 0°C, the large snow grains on the surface of the ice column disaggregated into a loose pile over the harder ice column below.

In July and August of 1996 and 1997 we found ice columns in every one of the more than 50 snow fields we investigated. Azimuth angles of the snow fields ranged from 0 to 360°, slope angles ranged from 0 to 35°, and elevation ranged from 3100 to 3800 m. Ice columns were ubiquitous in late-season snowpacks throughout our study area.

Ice columns appeared to start as depressions on the snow surface and then become elevated as a result of differential melt, with the surrounding snow depth melting faster than the ice column. Measurement of ice column height relative to the surrounding snow for three columns that were followed for eleven days shows that the height of ice columns increased relative to the snow surface over time (Fig. 2). Over the 11-day period in July these three ice columns gained about 4 cm in height relative to the surrounding snowpack.

Five ice columns were excavated at the Martinelli catchment in August of 1996. Slope angles of the snow field varied from 10 to 18° and snow depths ranged from 2 to 4 m. The ice columns showed a consistent morphology (Fig. 3). Each column was approximately 75 cm in vertical extent, with about 5 cm projecting above the snow surface and 70 cm extending into the snowpack. The tops of the ice columns were composed of polycrystalline ice grains with an effective grain size of about 5 mm and topped with a cap of debris composed of both organic and inorganic material. The tops of the ice column that projected above the snowpack ranged in diameter from 10 to 25 cm. The diameter of the ice columns became progressively wider with depth in the snowpack, with each ice column reaching a maximum width of about 30 cm in diameter. At a snow depth of about 70 cm, all ice columns terminated in a large ice lens. This ice lens was approximately 6 cm in thickness, 30 cm wide, and continuous up and down the fall line but not laterally.

An interesting observation was the presence of reddish rings surrounding some of the ice columns. These rings in appearance were similar to tree rings. The rings were composed of alternating ice and snow arranged in concentric circles, with the ice layers raised by a cm or two relative to the lower snow layers (Fig. 4). Three to five rings generally surrounded an ice column, with the largest (outside) rings having a diameter of 0.5 to 1.0 m. A reddish snow algae (presumably the resting stage of *Chalymdomonas nivalis*) was located in the snow circles, providing a somewhat unique and unusual pattern to the surface of these late-lying snow fields. The presence of the alga in the snow layers may be the result of preferential trapping in the non-frozen portion of the rings. Alternatively, the alga may be preferentially located in the snow rings because nutrients such as nitrate become concentrated in the liquid water as surrounding areas freeze (*e.g.* Williams *et al*. 1996).

We looked at aspect as a possible control on the frequency of the ice columns in early July. Somewhat surprisingly, the plot experiments showed that south-facing aspects had more ice columns than the north-facing plots. An analysis of variance test shows that the 81 ice columns on the south-facing slopes were significantly greater than the 57 ice columns on the north-facing slope ($p = 0.01$). There were about 3 ice columns per square meter on the south facing slopes and 2 ice columns per square meter on the north-facing slopes. The transect data also show that there was significantly more ice columns on the south-facing slope than the north-facing slope ($p = 0.004$). However, most ice columns on the south-facing slope were protruding while many ice columns on the north-facing slope were located in depressions. We may have found more ice columns on south-facing slopes simply because they were better exposed on south-facing slopes relative to north-facing slopes. The greater amount of snowmelt on the south-facing slopes may have resulted in better exposure of the ice columns, with ice columns on north-facing slopes still buried below the snow surface. Alternatively, Pfeffer and Humphrey (1998) show that refreezing is enhanced by greater amounts of meltwater input. Consequently, more ice columns may actually be formed on slopes with a southern aspect as compared to a northern aspect because of the presence of more meltwater in the snowpack with a southern exposure.

Night-time temperature profiles of paired thermocouple arrays showed some interesting differences. (Day-time temperatures were not used because of radiative heating of the thermocouples). Here we illustrate the temperature profiles of adjacent ice and snow thermocouple arrays during a summer night in August when air temperatures decreased below 0°C after a warm day with considerable snow melt. Snow and ice temperatures at a depth of 5 cm were near 0°C at 1800 hrs (Fig. 5). Temperatures then decreased in both the snow and ice to a diurnal minimum of about -3.0°C near 0600 hrs. A simple linear regression shows that temperatures at a depth of 5 cm tracked each other well, with an r^2 of 0.94 and a slope of 0.89 (ice temperature = -0.35 + 0.89snow temperature; $n = 187$).

The cooling curves for 10 and 20 cm depths for both snow and ice columns show significant differences, possibly reflecting the refreezing of meltwater in the ice columns.

The 10 and 20 cm records all showed initial periods of steady temperature while temperatures at 5 cm were falling. The records during the interval of steady temperature were within 0.2 - 0.25°C of 0°C, within the error of the temperature measurements. Thus, the periods of steady temperature near 0°C are assumed to be at 0°C. The duration of the interval of steady temperature was longer for the the records from the ice column than the corresponding depth in snow, indicating greater initial liquid water content in the ice column. Once the 10 and 20 cm depths commence cooling, the rate of cooling was comparable in all 4 curves. Since the records for 10 and 20 cm depth in the ice column were held at 0°C for longer, those locations cool to a warmer final temperature only because the duration of the interval of cooling (following refreezing) was shorter. While the thermal conductivity of the ice column was higher given the ice column's greater density of 870 kg m^{-3} vs 470 kg m^{-3} for snow, cooling in the ice column was delayed owing to a presumably greater initial liquid water content.

There was an interesting hysteresis in snow and ice temperatures that became stronger with increasing depth. A simple regression analysis shows that there was little difference between the cooling and warming limbs of the temperature profile at a depth of 5 cm ($p > 0.05$ for slopes) (Fig. 6). The ice column and snow pack cooled and heated at about the same rate. However, at a depth of 20 cm there was little change in temperature of the ice column until the corresponding snow cooled down to -1.8°C (slope = 0.016, n = 145) (Fig. 6). The ice then cooled at a faster rate than the surrounding snow until the ice reached a temperature of -0.4°C (slope = 1.55, n = 12). The ice column then remained at a temperature of about -0.4°C as the surrounding snowpack began to warm towards 0°C. The hysteresis in the temperature profiles at a depth of 10 cm was intermediate between that of the 5-cm and 20-cm depths. This hysteresis in the temperature profiles is consistent with the release of latent heat from the freezing of greater amounts of liquid water in and near the ice columns compared to the surrounding snowpack.

Potentially, a greater volumetric water content may be accomodated in the ice columns despite their greater density if the ice columns were at full saturation (void space fully occupied by water) because of higher capillary tension, while the snow will be nearly at irreducible saturation (water occupying ca. 5% of void space). Densities of 870 and 470 kg m^{-3} translate to bulk porosities of 0.05% for ice and 0.49% for snow. For full saturation in the ice and 0.05% saturation in the snow, the bulk volumetric water content in the ice column is ca. 0.05% of bulk volume, vs. 0.02% of bulk volume for the snow.

The relative difference - the column carrying approximately 2.5 times more water in bulk - is comparable to the relative difference in duration of the initial periods of steady temperature. If the refreezing in the ice column includes a volume of highly saturated snow surrounding the ice column, then this number can be higher.

Late in the snow melt season (August) "ribs" of solid ice were exposed at the snow surface on the Martinelli catchment (Fig. 7). In general, these ribs were continuous and oriented parallel to the fall line. At times two "ribs" of solid ice would coalesce into a single unit. We interpret these "ribs" of solid ice to be the remnants of surface rills. Vertical ice columns were connected to these frozen rills. The snowpack between the frozen rills rarely contained vertical ice columns.

At the Martinelli catchment, spacing between the frozen rills averaged 2.6 m (n = 73). Spacing of individual columns along the frozen rills ranged from 5 to 68 cm, with a mean of 29 cm (n = 87). The height of individual ice columns above the surface of the surrounding snow pack ranged from 1 to 21 cm, with a mean of 8 cm (n = 69).

Discussion

The size of the vertical ice columns are comparable to the ice column removed from a cold snow cover in the Canadian High Arctic and described in Woo et al. (1982). In contrast, flow fingers in snow are often an order of magnitude smaller and closer together than the ice columns we report. For example, Marsh and Woo (1984a) reported a mean finger width of 3.6 cm and a spacing of 13 cm for an Arctic snow pack. Similarly, McGurk and Marsh (1995) report flow fingers spaced 2 to 4 cm apart with mean diameters of 1.5 to 2.0 cm for a snowpack in the Sierra Nevada. In contrast, the size of our ice columns were about an order of magnitude greater, ranging from 10 to 25 cm in diameter.

The relationship between the larger ice columns and smaller fingers is not well understood. Marsh (1991) suggests that they may be related to the same processes which control the development of surface rill patterns and related internal flow channels described by Higuchi and Tanaka (1982). Higuchi and Tanaka (1982) studied the morphological regularity of surface rills on a melting snow cover in the Tateyama mountain range in Central Japan. They report that surface rills followed the fall line (maximum inclination) of the slope and corresponded to preferential flow channels of meltwater in the snow cover. Wankiewicz (1979) also noted the geometrical pattern of surface rills on a sloping snow surface (Fig. 29, p 241). He states that accumulating lateral flow of meltwater occurs between the depressions, with vertical flow at the depressions.

The frozen pipes and rills of our snowpack are consistent with the results of Higuchi and Tanaka (1982) and Wankiewicz (1979). Late in the melt season almost all the ice columns were directly connected to the frozen rills on the Martinelli snow field, with few ice columns in the snowpack between the frozen rills. Most likely these areas of relatively large meltwater flux are used continuously throughout the melt season. The frozen pipes that we observed on late-lying snowpack were most likely the remnants of the largest vertical flowpaths in the seasonal snowpack. These vertical flowpaths and resulting ice lenses appear to be directly connected to areas of the snowpack transporting the most liquid water downslope. Surface depressions or rills were then caused by settling of the overlying snowpack.

The question remains on whether the smaller flow fingers of liquid water have some connection to the large ice columns that we report and that are also reported by Woo et al. (1982). At the initiation of snowmelt, small flow fingers as described above appear to be ubiquitous in most snowpacks [*e.g.* Marsh and Woo 1984a; Kattelmann 1985; McGurk and Marsh 1995). Ice columns are formed with similar dimensions and spacing as meltwater flows into a cold snowpack and the liquid water freezes. For example, Kattelmann (1995) reports ice columns 1.0 to 2. cm in diameter with a density of 30 to 100 m^{-2} for a cold snowpack in the Sierra Nevada. Our results suggest that there is a positive feedback system such that as snow melt advances in time certain areas receive more meltwater than others. As rill areas form on the snow surface the flow fingers and ice columns associated with these features carry more meltwater than the lateral contributing areas. These ice columns continue to grow in diameter as liquid water freezes on the outside of the existing ice columns, a growth mechanism analogous to the formation of icicles. In contrast, once the surface rills are formed much less liquid water flows in the fingers or ice columns in areas between rills. Consequently these small ice columns do not grow in size and melt out over time in a warm snowpack.

The temperature differences in the ice columns and surrounding snow support the idea that there is more liquid water associated with the vertical pipes than the surrounding snow. The hysteresis in the temperatures of the snow and ice columns at the same depths appear to be due to differences in the amount of liquid water. The ice columns remain warmer and have a higher heat flux than the surrounding snow because there is more liquid water to be frozen in and near the pipe compared to the snow. Consequently, the latent heat released during freezing of the liquid water in the ice columns results in the temperature of the ice columns remaining near 0°C while the surrounding snow cools at a faster rate. Once the liquid water in the ice column is frozen, the ice columns then begin to cool. Liquid water may remain in the ice columns because of the high capillary tension caused by the small pore size of the ice columns, in constrast to the large pore size of the surrounding snowpack where most liquid water drains by gravity.

A simple calculation shows that the large heat flux associated with the pipes is compatible with the refreezing of liquid water in and/or near the pipes. The heat flux between the 5 and 20 cm depths of the ice columns is about 50 W m^{-2} over an 11-hr period, equivalent to a total heat loss of 1.96×10^6 J m^{-2}. We can than calculate the mass of ice frozen using the latent heat of fusion (3.34×10^5 J kg^{-1}) as about 60 kg m^{-2}. For a frozen pipe with a diameter of 20 cm (includes the very wet snow surrounding the pipe), 1.82 kg (1.82×10^{-3} kg m^{-3}) of ice would be refrozen during the 11-hr period. If the part of the ice column involved in refreezing is 40 cm in depth, the volume of the pipe is 0.013 m^{-3}. The amount of liquid water refrozen is then about 14% of the volume of the ice column and surrounding wet snow.

The lateral spacing of our frozen rills of 2.6 m supports the observations of Wankiewicz (1979) and Higuchi and Tanaka (1982). Wankiewicz (1979) suggested that the lateral distance between crests on surface rills on a uniform slope was about 3 m. It is worth noting that the spacing of surface rills in Japan of 1.1 m reported by Higuchi and Tanaka (1982) was less than half that of the 2.6 m from our continental site in the Rockies. Meltwater flux in the maritime climate of Japan is most likely much greater than in the continental climate of Colorado, suggesting that the spacing of surface rills in a melting snowpack may be inversely proportional to the melt rate of the snow surface.

Peckham (1999) has found several analytic solutions to an "ideal landform" equation that is based on first principles, spatially uniform excess rainrate, and a parameterization of unit-width discharge as a function of slope. One of these solutions takes the form of regularly-spaced rills that descend an inclined plane of slope c. The solution shows that the spacing (λ) between rills is given by: $\lambda = q1/(c * R)$, where $q1$ is the unit-width discharge for unit slope, c is the slope of the plane, and R is the steady excess rainrate when the rills were formed. This solution is expected to model the kind of rills that would be seen on a road cut.

It is not yet clear whether these results are also applicable to "snow rills". This approach suggests that for snow increasing rates of melt (R) for a given slope (c) will cause a decrease in the spacing (λ) of surface rills. The spacing of 2.6 m at our continental site with relatively low rates of snow melt and the rill spacing of 1.1 m in the maritime climate of Japan with relatively higher rates of snow melt appear to be in qualitative agreement with the mathematical formulation of Peckham (1999). Additionally, rills should become more closely spaced with downslope distance because of the increase in water supply from upslope areas.

Moreover, 5 meters may be the upper limit on the spacing of rills on a flat or near-flat snow surface. Pfeffer and Humphrey (1998) report surface rills separated by a wavelength of about 5 m on a 2° slope near the equilibrium line in Greenland. Similarly, Sommerfeld *et al*. (1994) and Williams *et al*. (1999) report vertical flowpaths with a wavelength of about 5 m late in the melt season for flat to nearly flat snow surfaces in the continental US. The approach of Peckham to understanding the spatial distribution of surface rills bears investigating on snow surfaces.

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Figure Captions

Figure 1. Topographic map of Green Lakes Valley and surrounding area. Ice columns and frozen rills were investigated on the Martinelli snowfield, located on the center of the map. Aspect controls on the spatial distribution of ice columns was conducted on late-lying snowpacks located between lakes 4 and 5.

Figure 2. Changes in height of three ice columns relative to surrounding snow over an 11-day period.

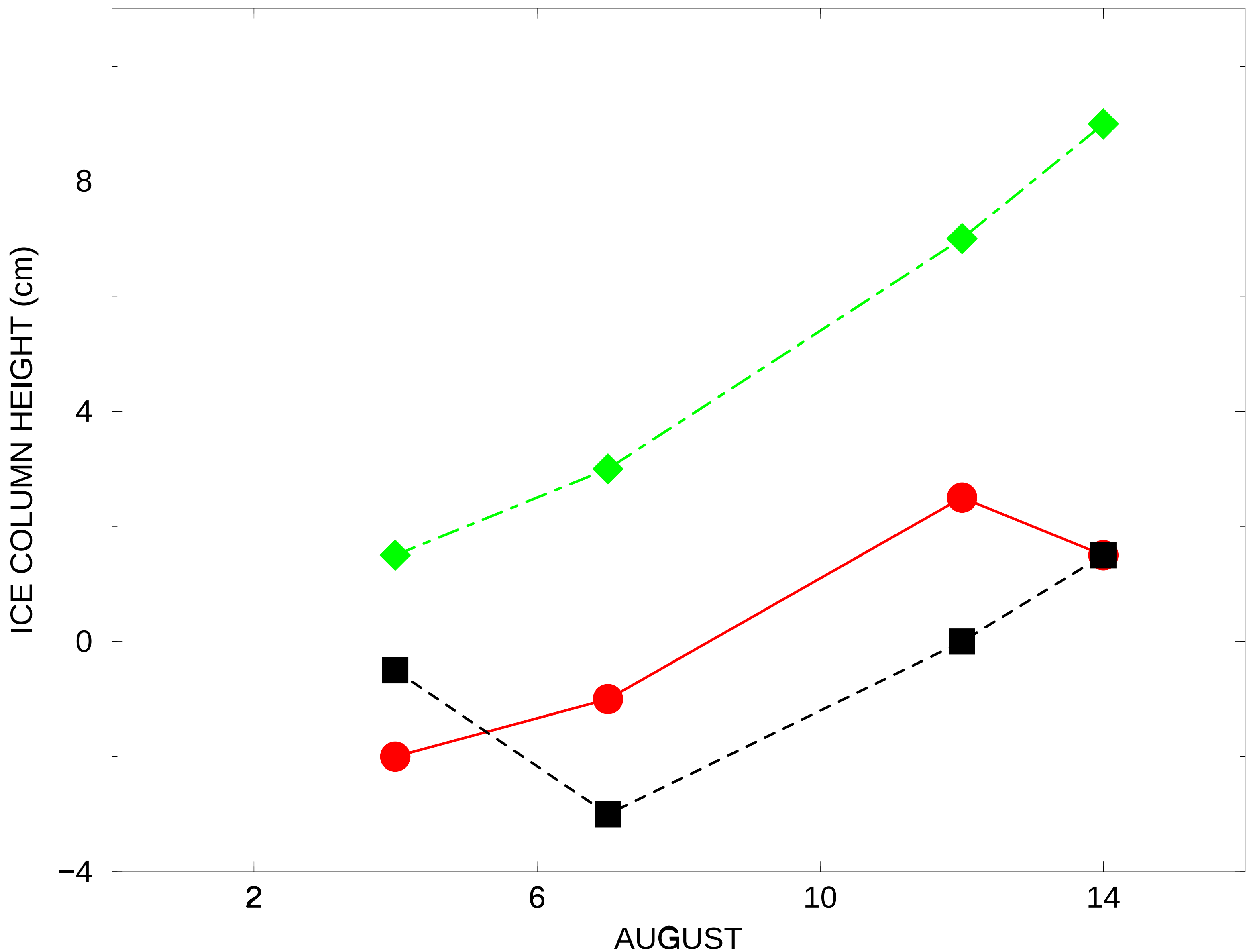
Figure 3. An *in situ* photograph of an ice column excavated in August of 1996, 75 cm in vertical length and a diameter of 15 cm at the top. The folding ruler on the left is 80 cm in length.

Figure 4. Concentric rings with algal deposits surrounding ice columns. The scale of the photograph is approximately 2 m by 1 m.

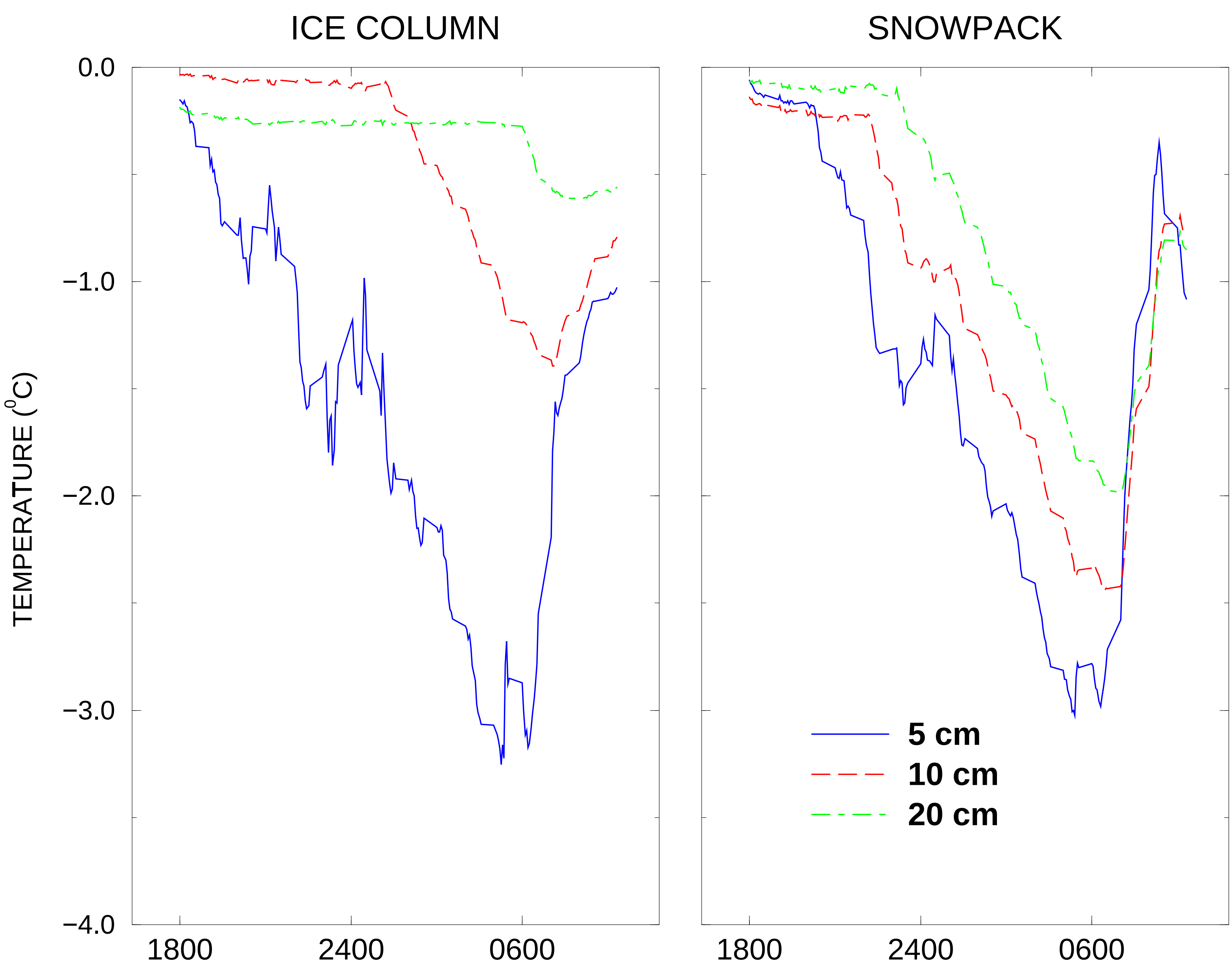
Figure 5. Adjacent temperature profiles of snow and an ice column separated horizontally by a distance of 20 cm, at depths of 5, 10, and 20 cm below the surface.

Figure 6. Hysteresis in temperature profiles at depths of 10 and 20 cm below the surface of an ice column and the snowpack in adjacent thermocouple arrays.

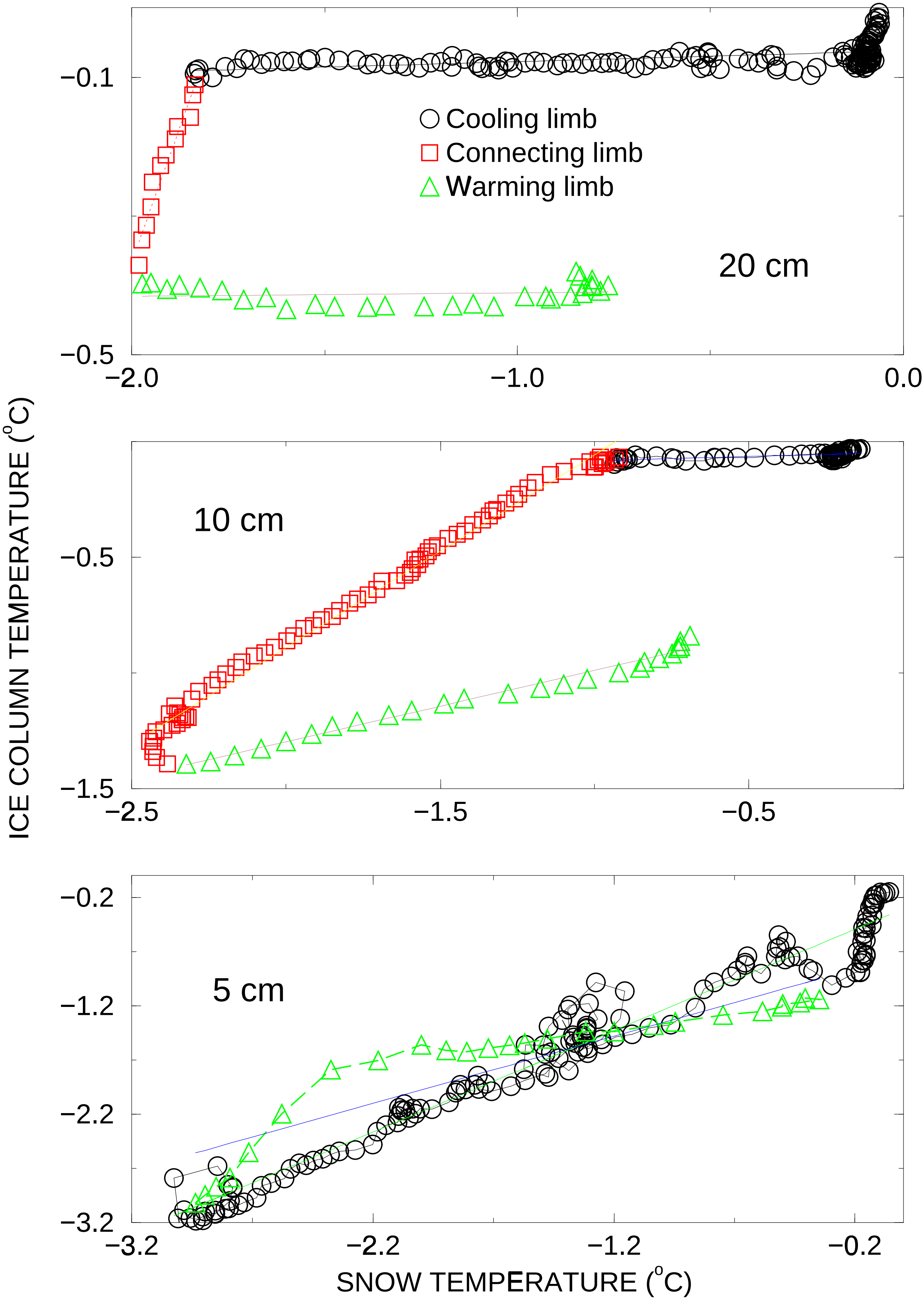
Figure 7. Looking upslope at frozen rills composed largely of vertical ice columns on the Martinelli snow field in August of 1996. Note that each of the ice columns has a dark cap composed primarily of organic debris. The distance separating the two frozen rills in the background is 2.6 m.


ICE COLUMN HEIGHT (cm)
8
4
0
−4
2
6
10
14
AUGUST


'96 8 8



ICE COLUMN
SNOWPACK
TEMPERATURE (^{0}C)
0.0
−1.0
−2.0
−3.0
−4.0
1800
2400
0600
5 cm
10 cm
20 cm



Cooling limb
Connecting limb
Warming limb
20 cm
10 cm
5 cm
−0.1
−0.5
−2.0
−1.0
0.0
−1.5
−2.5
−0.5
−1.5
−0.2
−1.2
−2.2
−3.2
−3.2
−2.2
−1.2
−0.2
ICE COLUMN TEMPERATURE (^{o}C)
SNOW TEMPERATURE (^{o}C)