MEASUREMENTS OF SNOW TEMPERATURE DURING RAIN

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ABSTRACT

Measurements from a spatial array of thermistors set in a natural snowpack are used to track the progress of the 0°C isotherm during two rain on snow events. Zones that are at 0°C are assumed to contain liquid water and the profiles show details of the patterns of water infiltration into snow. The patterns were different during each event. In one case the development of vertical drainage structures was slow. Water was diverted laterally at stratigraphic horizons and the maximum depth of penetration was less than 15 cm during the first hour of rainfall. In the other case the snowpack was more homogeneous and grains had coarsened. Vertical channels evolved through a part of the snowpack and less water was diverted laterally. Water penetrated 50 cm during the first hour and drainage through the full depth of the snowpack was established rapidly.

INTRODUCTION

Rain on snow is a common cause of avalanche release in maritime climates. The usual assumption is that stability decreases after liquid water has penetrated and weakened a basal layer (Perla and Martinelli, 1976). However recent observations of the timing of avalanches suggest that slab avalanche activity is common immediately after rain starts and before water and the associated thermal wave has penetrated to the depth of the basal sliding layer (Heywood, 1988; Conway and others, 1988). Further, it has been suggested that stability might increase after drainage has been established through the full depth of the snowpack (Conway and Raymond, 1992).

For these reasons it is of interest to investigate the rate and patterns of water infiltration into snow. The physical process involves the release of latent heat when liquid water freezes on contact with cold snow. Water may exist in the liquid phase after the snow has warmed to the melting temperature but further infiltration occurs only after the water content has increased sufficiently to form a continuous liquid film through the pore spaces (Colbeck, 1972, 1975).

In this paper we use measurements of snow temperature from a two-dimensional array of thermistors buried in a natural snowpack to define the position of the 0°C isotherm. We assume that snow at 0°C contains liquid water and in this way we track the progress of water through the snowpack and calculate the rate of wetting and the rate of infiltration.

FIELD AREA AND INSTRUMENTATION

Snow temperature profiles were measured in a horizontal snowpack at an elevation of 915 m in the Cascade mountains near Snoqualmie Pass, Washington during the winter of 1991-92. Measurements were made at 15 minute intervals using 110 thermistors (Thermometrics P100DA202M) multiplexed to a data logger and storage module (Campbell Scientific Inc., units AM416, CR10, and SM716). The thermistors had been potted in white heat-shrink tubing and white epoxy (to make them waterproof and also to minimize heating from penetrating solar radiation) and each thermistor had been calibrated at the ice point using an ice bath made from distilled water. The error at the ice point was less than ± 0.01°C.

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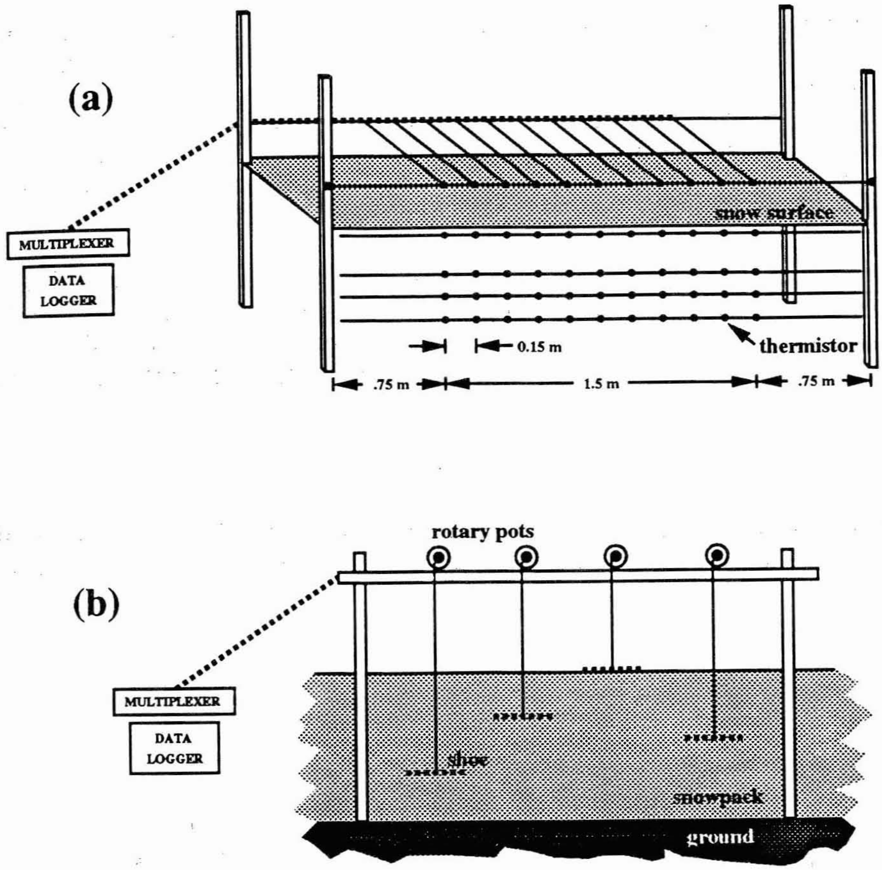


Figure 1. Instrumentation.
(a) Thermistor Array. Physical arrangement of five of the ten strings of thermistors used during the 1991-92 winter. In this illustration string No. 5 is still suspended between the posts above the snow surface. String Nos. 1 to 4 had been released from the posts as they were buried by new snowfall. The vertical spacing between thermistor strings (dz) started at approximately 15 cm but this decreased as the snowpack compacted.
(b) Settlement Array. The settlement profile was obtained from the position of shoes that were buried at different depths within the snowpack. Each shoe was made from aluminium screening and its position was measured by running a cord from the shoe up to a rotary potentiometer suspended above the snow surface.

The thermistors were strung between two vertical posts by horizontal strings suspended above the existing snow surface. Each string supported 11 thermistors spaced 15 cm apart. A parallel horizontal string set at the same height 1 m away supported the leads from the thermistor beads to the multiplexer (fig. 1a). This technique minimized the possibility of introducing a vertical thermal or hydraulic connection between thermistors. The vertical spacing between thermistor strings started at about 15 cm. Each string was released from the supporting posts after it had became buried by accumulating snow and the spacing decreased as the snowpack compacted.

The depth of each string was tracked by measuring snow settlement. The settlement profile was measured at a site 2 m from the thermistor array by measuring movement of shoes buried at different depths within the snowpack. Each shoe was made from 30 cm square, light-weight aluminium screening that had been placed sequentially at the snow surface after 10 to 30 cm of new snow had accumulated. The shoes became buried by further snowfall and their position was measured by running cords vertically up from each shoe to a 10-turn, rotary potentiometer suspended above the snow surface (fig. 1b). The resolution of the depth measurements was $\pm$ 0.2 mm.

Our measurements of snow temperature are two dimensional in the vertical plane and we assume that the profile measured is representative of the entire snowpack. We assume that each thermistor defines the temperature of a surrounding area of snow. This area is rectangular and its boundaries bisect the line segments connecting each thermistor and its nearest vertical and horizontal neighbors. We also assume that all the thermistors on a particular string are at the same depth (calculated from the settlement profile) but in fact the string may not be horizontal because snow usually settles differentially during water infiltration (Wakahama, 1974).

To visually interpret the infiltration of water into the snowpack we have binned the temperature measurements into three ranges that are represented by a gray scale. Temperatures at 0±0.01°C (the accuracy of our measurements) are shaded black; we assume that liquid water exists in the snow at these temperatures. Temperatures between -0.01°C and -0.1°C are gray and temperatures less than -0.1°C are white.

CASE STUDIES

We measured temperature profiles in a horizontal snowpack during January 1992 when a period of warming and rain was followed by three days of sub-freezing air temperatures and then a second period of warming and rain.

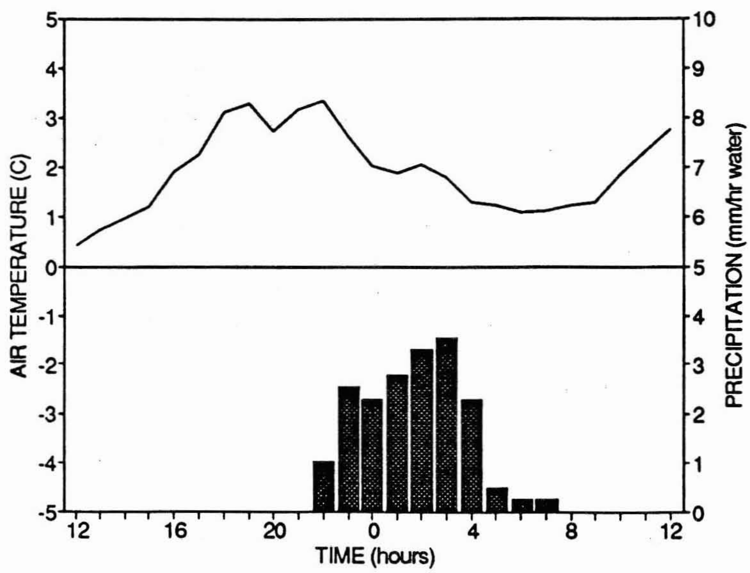
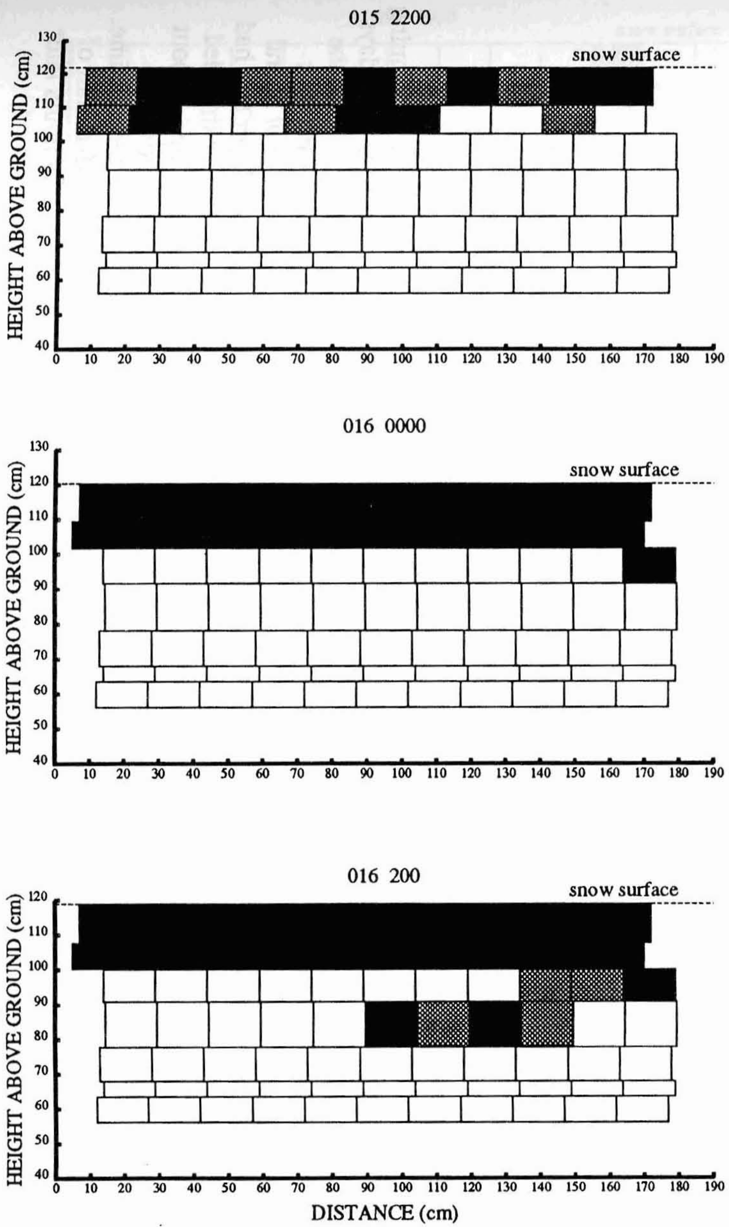


Figure 2. Hourly measurements of air temperature and precipitation made at the study plot (915 m elevation) starting at 1200 hours on the 15th of January, 1992. Rain started at 2100 hours on the same day.

I. Warming and rain on 15-16 January 1992.

Figure 2 shows measurements of precipitation and air temperature at the study site during the first period of warming and rain on 15 January 1992. Figure 3 shows a time-series of five snow temperature profiles during the infiltration event. Liquid water apparently had already penetrated to a depth of 15 cm before rain first started at 2100 hours. The air temperature had warmed above freezing several hours before rain started (fig. 2) which would be conducive to meltwater production. It is also possible that some rain fell before the time shown because the gauge records only after 0.254 mm of precipitation has accumulated.



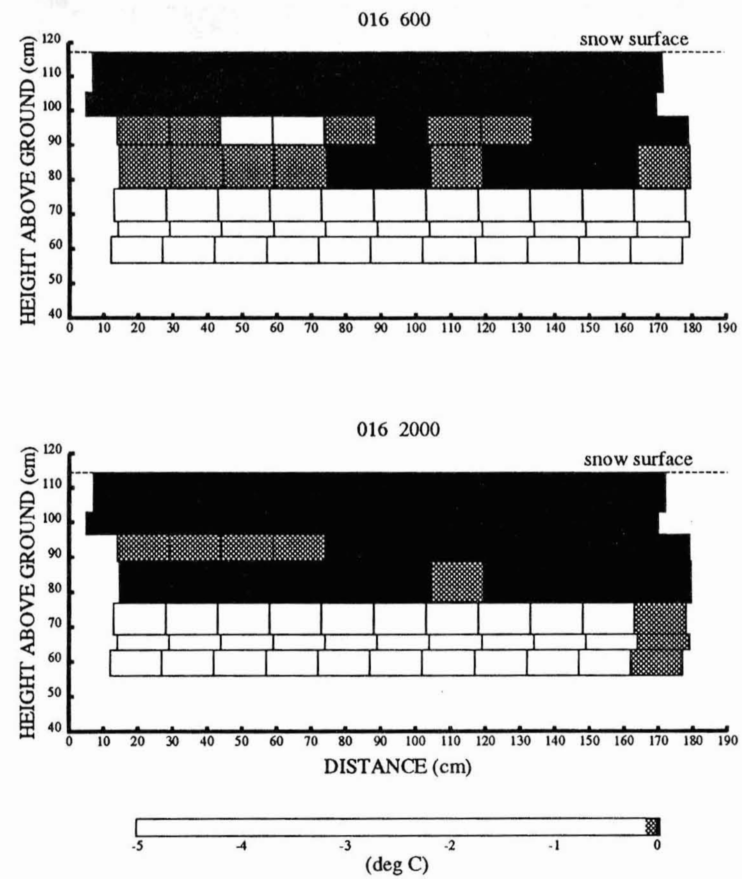


Figure 3. Snow temperature profiles for the 15th and 16th of January, 1992. We assume liquid water exists in the black areas that are at 0°C. Areas shaded gray are between 0 and -0.1°C, and white areas are less than -0.1°C. Rain started at 2100 hours on the 15th and stopped at 700 hours on the 16th. The maximum depth of penetration was 35 cm.

Figure 3 also shows that water first penetrated through small channels or "fingers". Infiltration progressed in step fashion into the snowpack. Downward flow of water was impeded for several hours 15 cm below the surface and when this occurred the water spread laterally. The snow stratigraphy showed an ice crust 0.5 cm thick at 15 cm. The water penetrated the crust only after most of the snow above had been wetted and then a vertical channel progressed another 20 cm to a second ice layer that was 1 cm thick and 35 cm below the surface. Again the wetting progressed laterally rather than vertically at that depth and water still had not penetrated beyond 35 cm when rain stopped several hours later. Apparently the ice crusts impeded vertical flow in both cases and although intuitively this is not surprising, it is different from our earlier observation that water usually penetrates ice layers in maritime snowpacks rapidly (Conway and Raymond, 1992).

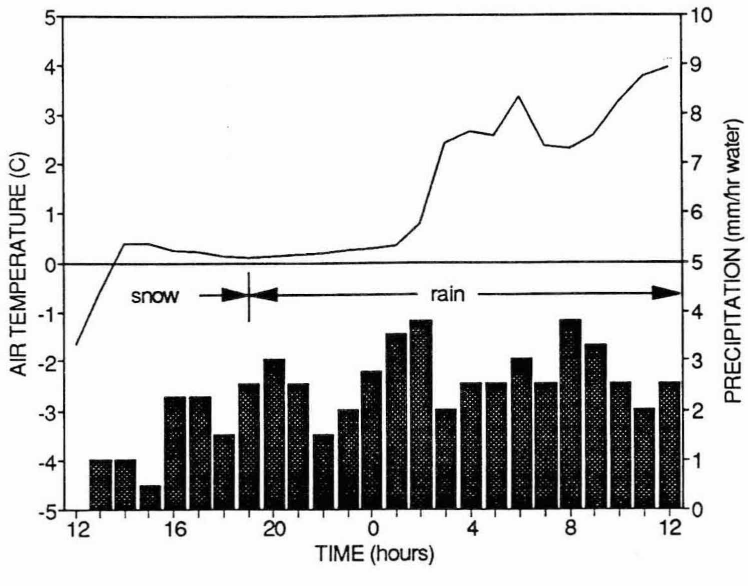
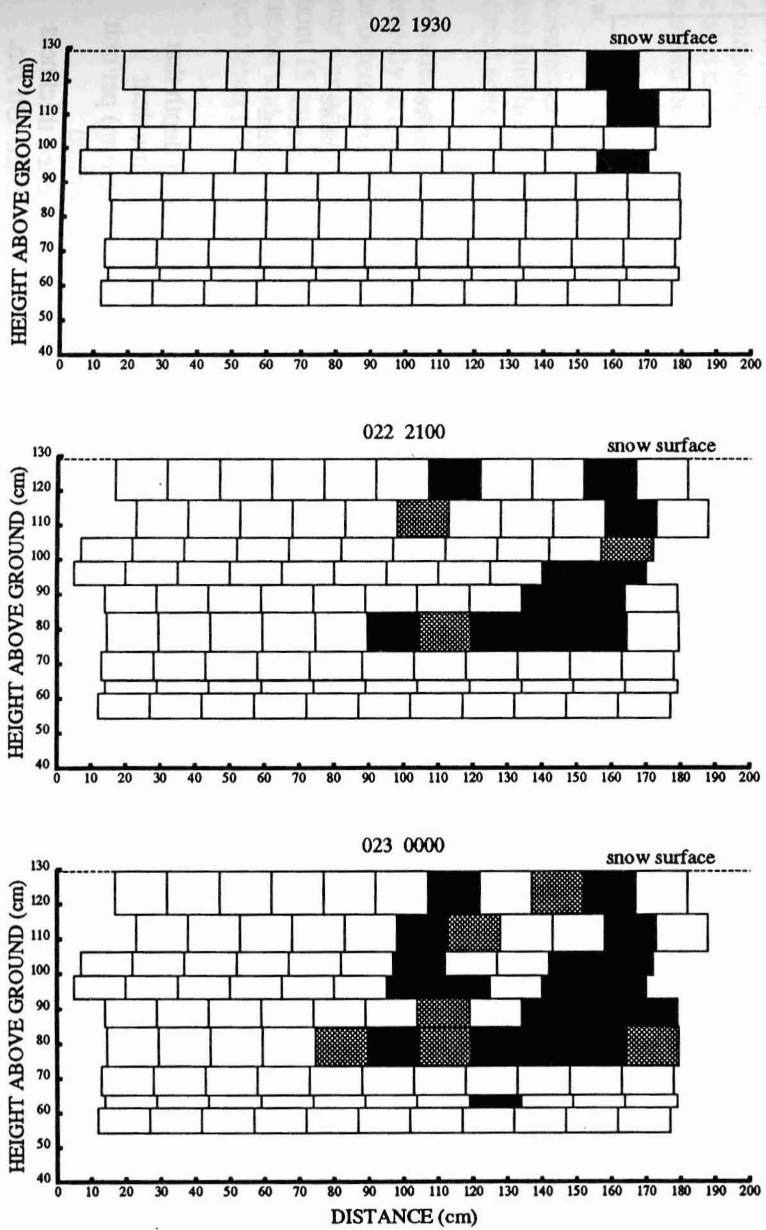


Figure 4. Hourly measurements of air temperature and precipitation made at the study plot (915 m elevation) starting at 1200 hours on the 22nd of January, 1992. Precipitation changed from snow to rain at 1900 hours on the same day.

II. Warming and rain on 22-23 January 1992.

Figure 4 shows measurements of precipitation and air temperatures made at the study site during warming and rain on 22 January 1992. About 15 cm of new snow had accumulated during the previous three days and precipitation changed to rain when the air temperature warmed above freezing at 1900 hours on the 22nd. The pattern of water infiltration during this event was different than the pattern during the first event. The series of profiles shown in figure 5 indicates that water infiltrated vertically with few lateral diversions until it reached a depth of 50 cm. This depth corresponds to the depth of the ice layer that had impeded vertical flow during the previous event (then at 35 cm). In this case vertical flow was impeded for four hours but water penetrated the ice layer before all of the snow above had become wetted. About 11 hours after the onset of rain a channel extended beyond the deepest thermistors (70 cm below the surface) and we suspect the channel extended through the full depth of the snowpack soon after that time. When water first reached the lower boundary of the cross-section (day 23 at 600 hours) less than half of the snow in the section had been wetted and it did not become completely isothermal until 29 hours later at 11 am on the 24th.



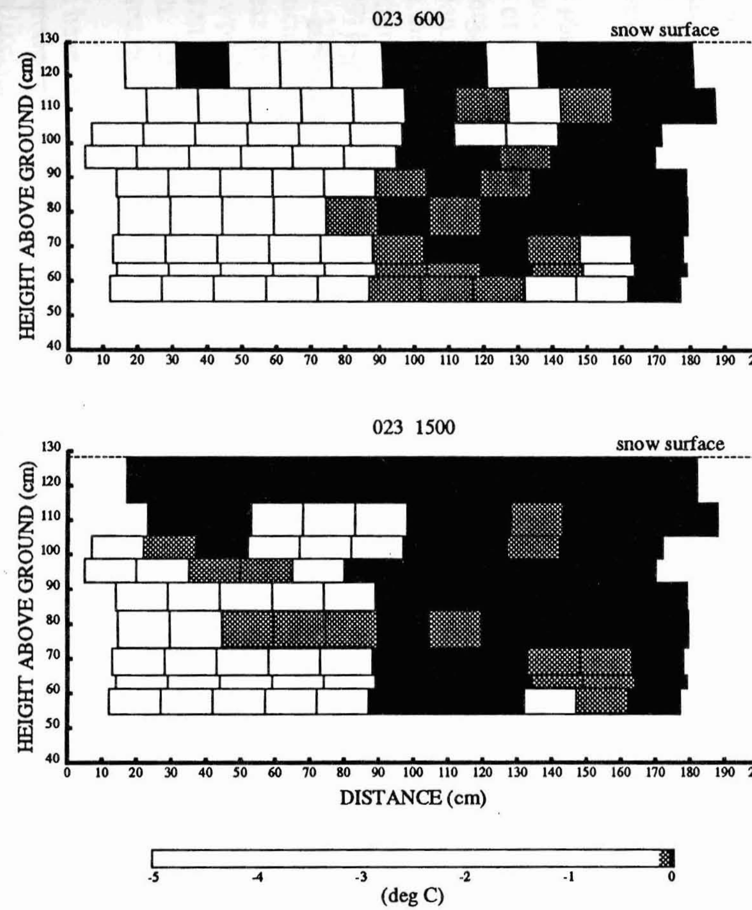


Figure 5. Snow temperature profiles for the 22nd and 23rd of January, 1992. We assume liquid water exists in the black areas that are at 0°C. Areas shaded gray are between 0 and -0.1°C, and white areas are less than -0.1°C. Rain started at 1900 hours on the 22nd and stopped at 700 hours on the 24th. Water first reached the lower boundary of the section on day 23 at 600 hours.

DISCUSSION OF WETTING

When liquid water first contacts cold snow some of the water will freeze and release latent heat. Calculations show that for these two events the amount of liquid needed to freeze and warm the snow to 0°C was small compared with the liquid water available from the precipitation (Conway and Benedict, 1992). In both cases more than 95% of the rainfall would have wetted the snow and less than 5% would have changed phase.

Figures 3 and 5 show the pattern of wetting was different for each of the events studied. In the first case the wetting penetrated in steps vertically into the snowpack. Typically a flow finger penetrated 5 to 15 cm into the snowpack and then water was diverted laterally for several hours. The next vertical step occurred only after most of the snow above the previous step had been wetted (fig. 3). Wetting progressed in steps during the second event also but the general pattern shows the steps were larger and less water was diverted laterally (fig. 5). The overall pattern of wetting during the second event was less uniform and water drained through the full depth of snow before all of the snowpack had become isothermal.

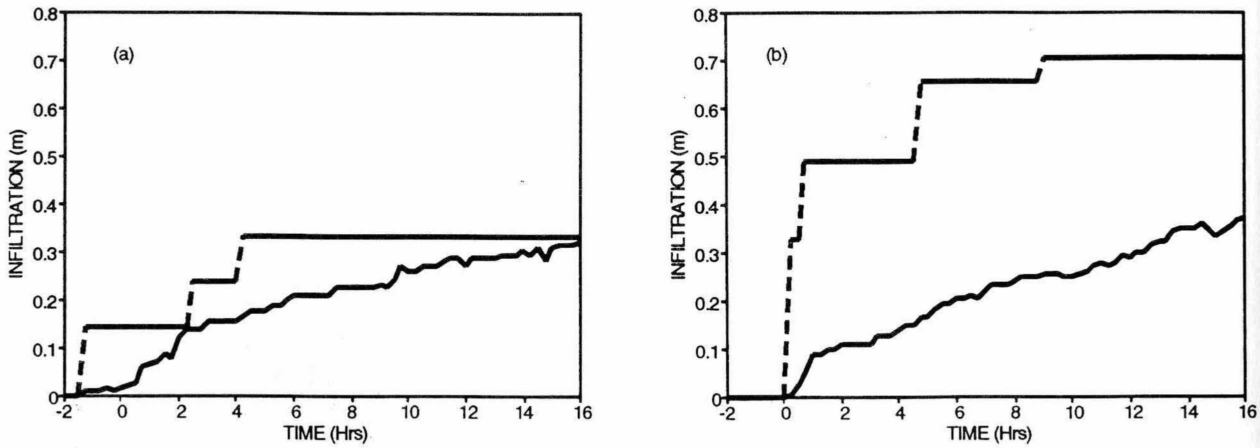


Figure 6. Rates of infiltration.
(a) Maximum depth of liquid penetration (dashed curves) and equivalent wetted thickness of the entire snowpack (solid curves) for the rain event starting on January 15th. Rain started at 0 hours but meltwater had already infiltrated 15 cm into the snowpack by that time.
(b) Maximum depth of liquid penetration (dashed curves) and equivalent wetted thickness of the entire snowpack (solid curves) for the rain event starting on January 22nd. Precipitation changed to rain at 0 hours and water penetrated 50 cm during the first 45 minutes. The overall rate of wetting was similar for each event but the maximum penetration rate was much faster during the second event.

The different patterns of infiltration are also illustrated in figure 6 which shows the maximum depth that water had penetrated into the snowpack and the equivalent wetted thickness of snow. The equivalent wetted thickness is the total wetted snow volume (including the lateral as well as vertical wetting) per unit area. The difference between the maximum depth of water infiltration and the equivalent wetted thickness is a measure of the spatial inhomogeneity of the wetting. When the equivalent wetted thickness is equal to the maximum depth of penetration the entire upper snowpack is wetted to that depth. On Jan.

22nd the equivalent wetted thickness always lagged the maximum depth of penetration by 50% or more (fig. 6b) indicating that less than 50% of the snowpack above the wetting front had been wetted. In contrast, on Jan. 15th the equivalent wetted thickness approached the maximum depth of penetration on two occasions. This occurred when vertical infiltration was impeded at a layer and water spread laterally to wet all of the snow above that depth (fig. 6a).

The pattern of infiltration depends on the rate of infiltration (Glass and others, 1989) and is also strongly influenced by the stratigraphy and texture of the snowpack. The rate of rainfall (about 2.5 mm hr^{-1}) and rate of overall wetting (about 28 mm hr^{-1}) were about the same for both events (fig. 6). We think that the different infiltration patterns were caused primarily by differences in snow stratigraphy. Prior to the rain on Jan. 15th the upper 50 cm of the snowpack contained two ice crusts separated by layers of fine-grained (< 1 mm dia.) partially metamorphosed snow. Flow is often impeded and diverted laterally at stratigraphic horizons or by slight heterogeneities in the snowpack (Glass and others, 1989; Wankiewicz, 1979) because both permeability and capillarity depend on grain size and texture (Colbeck, 1979). By Jan. 22nd, the snow stratigraphy had become relatively homogeneous and grains had coarsened - particularly in the upper portion of the snowpack which had been wetted during the previous event. Flow is less likely to be impeded and the rate of vertical infiltration through a homogeneous, coarse-grained snowpack is likely to be faster than through a layered and heterogeneous snowpack. Figure 6 shows that on Jan. 22nd the maximum depth of penetration of liquid water was about two times faster than on Jan. 15th. This type of behavior has also been reported by McGurk and Kattelmann (1986) who observed increased rates of drainage after a snowpack had became more homogeneous.

We have found that snowpacks that become unstable immediately after the onset of rain are usually layered and contain intricately shaped snow grains while snowpacks that contain more rounded grains are less likely to respond as quickly (Conway and others, 1988). Infiltration of liquid water affects snow strength but a local perturbation may not affect the stability of the entire snowpack until it has spread laterally over a sufficiently large basal zone. We are not certain how large these areas need to be, but our measurements suggest that liquid water is less likely to penetrate to depth rapidly when the snowpack is layered and contains intricately shaped grains. This supports the idea that the avalanches that release within minutes of the start of rain are not triggered by liquid water penetrating to depth and weakening a basal layer (Conway and Raymond, 1992). However we do not totally exclude this possibility because our measurements show that in one event liquid water had penetrated 50 cm during the first hour of rain. We also note that avalanches did not release immediately after rain started on either of the occasions discussed here.

CONCLUSIONS

Measurements of the thermal distribution of a snowpack offer a means of studying the infiltration of water into layered snowpacks during rain. Infiltration is complex and the thermal conditions cannot be defined adequately with a single vertical line of thermistors.

The pattern of infiltration was different for the two events studied and we attribute the differences primarily to textural and stratigraphic differences between the snowpacks. In one case the stratigraphy was heterogeneous, consisting of ice crusts and layers of fine-grained snow. In this event the flow of water was often diverted laterally at stratigraphic boundaries; the rate of vertical infiltration was slow (about 15 cm in the first hour). In the other case the snowpack was more homogeneous and grains had rounded and coarsened. Less water was diverted laterally and the water infiltrated into the snowpack much faster (50 cm in the first hour).

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