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Snowpack Stratigraphy Evolution at Forested and Open Sites

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ABSTRACT

Field observations of seasonal snowpack stratigraphy evolution over the course of a winter are described at open and deciduous forest sites. The predominant stratigraphic features of the two sites were similar, although the snow sometimes had dramatically different behavior in response to tree- and slope-induced local meteorologic differences. Differences in solar radiation between the two sites produced differences in the early snowcover, which then controlled the formation and nature of the basal ice layer that remained throughout the season. At this location, the greater longwave radiation induced by the trees at the forested, south-facing hillslope offset the greater solar radiation at the open site, so that net allwave radiation at the two sites was approximately equal. More snowpack mass was lost during snowmelt at the forested hillslope than at the open site because the melt generated in the upper half of the pack flowed laterally through the pack in the downslope direction. At the open site, snowmelt at the surface flowed vertically through the pack, sometimes adding mass to lower layers. In addition, field observations illustrate that capillary effects produce observable changes in snowpack layering, and need to be included in modelling of metamorphic snowmelt processes.

INTRODUCTION

Although the notion of a snowcover as a uniformly soft white blanket over the earth is appealing, in reality snowcovers are composed of complex systems of layers with stratigraphic features including ice layers and vertical columns, cup crystals and depth hoar, new precipitation, and many other crystal types. These stratigraphic features and crystal types affect physical processes that occur in snow, such as wind-induced ventilation of the snow, vapor transport, radiation penetration, and meltwater movement through the snowcover. In turn, these physical processes affect snow metamorphism and stratigraphy; complex feedback loops occur, and seasonal snowpacks are in a constant state of change.

Descriptions of snowpack stratigraphic evolution over time and on varying terrain are important both for understanding basic metamorphic and layering processes, and for model verification for remote sensing and hydrological forecasting. The purpose of this paper is to examine some of the preliminary findings of this year's field investigation of snowpack evolution at an open, flat site and at a nearby wooded, sloped site, and to describe our observations of several interesting events.

While there are no published reports comparing snowpack stratigraphy evolution at open and wooded sites over the course of a winter, there are publications that are relevant. Price (1988) examined snowmelt rates in a deciduous forest and concluded that the net allwave radiative energy flux is a good predictor of snowmelt rates; a model was suggested that used incoming solar radiative flux and air temperature to drive snowmelt. He did not consider periods other than the snowmelt period, and the snowmelt model assumed the snowpack was homogeneous and of uniform temperature.

Ohta et al. (in press) conducted energy budget snowmelt analyses at an open site and in a deciduous forest. They also found that net radiation was the major energy flux influencing snowmelt at both sites.

As in the paper by Price, they treat the snow as a uniform mass. LaChapelle and Armstrong (1977) measured snow temperatures in alpine areas and related snow temperature gradients to crystal metamorphism, but did not address layering.

Albert et al. (1992) concluded from field tests with snowmelt lysimeters that layering has a large effect on snowmelt outflow through much of the melt season in northern Vermont. Colbeck (1991) reviewed the current state of knowledge on the layered nature of snow. He concluded that many of the outstanding problems in snow studies can be solved only by dealing with snow as a layered medium, and that field, laboratory, and theoretical studies of layered snow systems are all in early stages; there is much yet to be learned.

FIELD MEASUREMENTS

Detailed field observations were made on seasonal snowpacks at two sites in the Sleepers River Research Watershed in northern Vermont, during the winter of 1992–93. Townline, the open site at an elevation of 550 m, is flat, has an open area of approximately 1.6 ha, and is surrounded by conifers. The wooded site is on a hillslope in the W9 basin at an elevation of 540 m, and is located on a predominantly south-facing slope of inclination approximately 15%. The trees on the hillslope are mainly deciduous, maple and beech, with a few scattered conifers. The two sites are approximately 2 km apart.

Field data on stratigraphy were observed from snowpit excavations conducted at least weekly at the two sites throughout the winter. Snowpack characterization included measurements of snow depth, stratigraphy, crystal type (Colbeck et al. 1990), grain size, density, liquid water content, and crystal photography. Continuous, automatic measurements were made of snow temperature profiles and meteorological data. Meteorological data (measured by Campbell automatic weather stations with Eppley radiometers) were recorded at fifteen-minute intervals through the winter at the open site, and at hourly intervals at the forested site. The snow depth sensor at the open site was in an area (about 40 m away from the snowpit area) that received slightly more snow than did the snowpit area; however, the snow depths at the two areas track well over time.

In order to facilitate the tracking of layers throughout the season, small wooden dowels were placed vertically in the snow near the area used for snowpits, and small markers made of clear polyethylene sheeting, with a hole for the dowel, and marked with the current date, were placed on the snow surface each week during the snow accumulation season. As the season progressed and the snowpit layering became complex, a dowel and markers were excavated at the time of the snowpit characterization in order to verify the stratigraphy tracking.

AN OVERVIEW OF STRATIGRAPHY EVOLUTION

The layers in the snowpack over time at the open (Townline) and forested (W9) sites are depicted in figures 1 and 2, respectively. The symbols in each layer denote the ICSI snow classification (Colbeck et al. 1990). It is evident from figures 1 and 2 that the layering patterns at the open and wooded site were similar in their overall appearance, although differences, including wind crust, surface hoar, basal ice characteristics, and snow depth existed.

From a general inspection of the pack from the surface to the ground, the predominant features of the pack included layers composed of precipitation particles, rounded grains, faceted crystals, ice layers and crusts, cup-shaped striated crystals, and basal ice. Vertical features such as drainage channels also occurred at both sites. Stratigraphic changes over relatively short time scales (e.g., observed daily or weekly) are most easily seen under three conditions: (1) early in the season when the snowpack is thin, and large temperature gradients induce kinetic crystal growth metamorphism, (2) late in the season when warm air temperatures and rain bring about the thinning and demise of the pack, and (3) throughout the season in the upper portion of the pack where precipitation is deposited and where meteorological changes affect local snow temperature gradients.

For most of the season, layers in the bottom half of the pack retained their predominant characteristics, due both to the insulating effect of the snow above, and also to the strength of the snow in the ice and crusty layers in the lower part of the pack. At both sites, a "crusty" layer (about 5 cm thick, located at heights between 15 and 25 cm,) and an ice layer (approximately 1 cm thick, at heights between 30 and 40 cm) persisted over a large part of the season. The crusty layer was actually composed of several thin ice layers sandwiching faceted crystals. Despite large changes in overall snow depth, these strong layers experienced almost no settlement over time, and protected the integrity of the weak, poorly bonded, faceted crystals beneath them, even after the melt season was well underway. The melt season started with rain on March 18 (JD 77); active snow melt, as observed

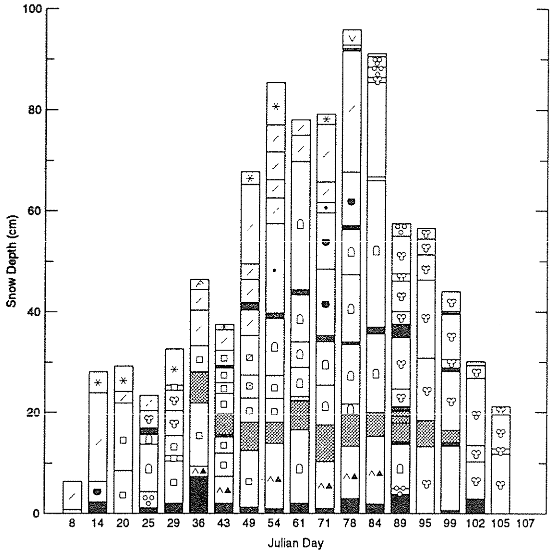

Figure 1. Stratigraphy at the open site.

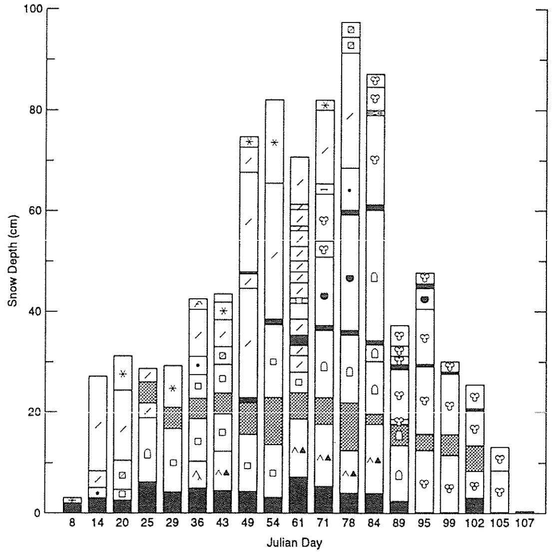

Figure 2. Stratigraphy at the forested hillslope site.

Precipitation Particles:
- ✳ Stellars Dendrites
- ⌒ Irregular Crystals

Decomposing and Fragmented Precipitation Particles:
- ∕ Partly Decomposed Precipitation Particles
- ⸝∕ Highly Broken Particles

Rounded Grains (monocrystals):
- • Small Rounded Particles
- ● Mixed Forms

Cup-Shaped Crystals; Depth Hoar:
- ∧▲ Cup Crystal
- ∧ Columns of Depth Hoar

Feathery Crystals:
- V Surface Hoar Crystals

Ice Masses:
- ▬ Ice Layer

Surface Deposits and Crusts:
- ⊚⊚ Melt Freeze Crust

Faceted Crystals:
- ☐ Solid Faceted Particles
- ☒ Small Faceted Particles
- ∩ Mixed Forms

Wet Grains:
- ⊛ Clustered Rounded Grains
- ⊛ Rounded Poly-crystals
- ∘∘∘ Slush

Key to figures 1 and 2.

from snow lysimeter data, occurred continuously from March 24 (JD 83) until the end of the snow season, a result of the combination of warm weather and occasional rain.

Snowmelt hydrology models currently in use assume the snowpack is "ripe," i.e., the snow grains are round and the snowpack is homogeneous; they do not account for layering effects. The data presented here support earlier determinations (Kattleman 1989, Albert et al. 1992) that important layers can exist throughout a significant portion of the snowmelt season and affect the nature of lysimeter outflow. This year, our observations show the upper snowpack beginning to ripen on March 30 (JD 84), one week after initial outflow, yet the ice and crusty layers became weak and more permeable only on April 9 (JD 99) at the forested site, and on April 15 (JD 105) at the open site. Efforts to produce improved snowmelt models that account for these effects are underway.

We will now focus on two field observations that illustrate differences in the nature and behavior of the snowpack at the wooded and open sites. The first is a description of essential differences in the basal ice layer, and the second describes the snow response to early season melt at the two sites. Other stratigraphic differences between the sites exist, but for brevity must be discussed elsewhere.

BASAL ICE

Although not often discussed in the literature, the basal ice layer is an important layer for snowmelt hydrology, especially in temperate climates where there is only a small amount of ground frost penetration early in the winter and the ground may thaw during the course of winter due to the insulating effects of a thick snowcover. In the absence of frozen ground, snowmelt will infiltrate the soil. If present, a uniform, solid layer of basal ice would deter the meltwater from entering the ground, and ponding or "overland" flow above the ice layer will occur (until the melt reached a physical opening, such as a tree well). In contrast, an irregular or discontinuous layer of basal ice would result in a variable pattern of snowmelt infiltration into the soil during the winter (even in the absence of tree wells). The nature and timing of snowmelt infiltration to the soil in temperate climates is unlike that found in colder climates (Marsh and Woo 1984), where permafrost causes continual growth of the basal ice layer until the end of the snowmelt season.

As illustrated in figures 1 and 2, the basal ice layer at the wooded site appears thicker and more uniform over time than at the open site. The basal ice layer at the wooded site was also fairly uniform over space, despite the fact that the snow pit locations (all within twenty meters of one another) were on the undisturbed and irregular surface of the forest floor. In contrast, the basal ice at the open site had high spatial variability, even though the pits were excavated at a uniform, relatively flat, undisturbed area and within twenty meters of one another. These differences are largely attributable to the way in which the basal ice layers were formed.

The basal ice layer formation processes were different at the open site than at the wooded site. December was a month of light snowfall, where thin deposits of snow melted away before the arrival of the next snowfall. On December 21, there were 8 cm of snow at the open site and 5 cm at the wooded site. In the following days, solar radiation caused the snow at the open site to melt completely, while the thin snowcover protected by the trees in the forest remained. A hard rain in the early days of January saturated the snow in the forest, and the immediate arrival of cold weather turned it into ice. On January 8 the ice on the forest floor was widespread, completely covering the sublayer of leafy litter and making it difficult to walk uphill. At that time, the ice layer at the open site was sufficiently thin that the (mowed) grass poked through the ice. These layers of ice at both sites were covered by snowfalls that did not melt away. Rain on January 22, 23, and 25 percolated through the snow and contributed to the basal ice and the crusty layers at both wooded and open sites.

The differences in the nature of the basal ice at the two sites occurred because most of the basal ice in the forested site was formed when rain in early January wetted a thin but continuous snow cover and then froze, while most of the basal ice at the open site formed from rainwater at the end of January percolating through snow, perhaps traveling laterally on icy layers, and then freezing at the bottom of the pack in a spatially variable pattern. Ground temperature profiles at the two sites were similar at that time, so that it is not likely that the variability in basal ice between the two sites is caused by differences in heat fluxes from the ground. Differences in solar radiation at the two sites produced differences in the early snowcover, which then controlled the formation and nature of the basal ice layer that remained throughout the season.

EARLY SNOWMELT AT THE OPEN AND FORESTED SITES

A striking difference in snowmelt patterns at the two sites occurred over a five-day period in the early snowmelt season. The snow depth at each site is plotted in figure 3a (where it is evident that both sites are responding to the same overall weather patterns), and the difference in snow depth between the two sites is illustrated in figure 3b. There is a curious jump in the depth difference that occurred between March 25 (JD 84) and 30 (JD 89), where in those five days the snow depth at the forested site decreased by 48 cm, while the snow depth at the open site decreased by only 32 cm. This melt event also had dramatic mechanical effects on several instrumentation support systems in the forest, where the demise of the snowpack at the forested site broke cantilevered dowels (0.625 cm diameter) at three locations within the forested site; similar support systems in the open site were not affected. Figure 4a shows that the forested site had an ice layer at a height of 59 cm on March 25 (JD 84) that was not present at the open site. The broken instrumentation supports at the forested site were likely due to shearing action of this ice layer

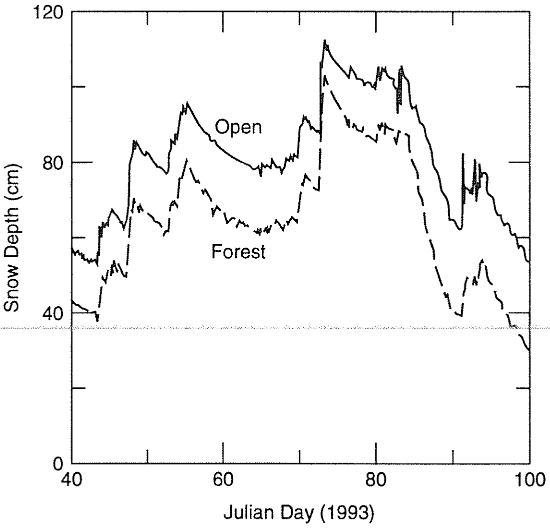

Figure 3a. Snow depth over time at the open and wooded sites.

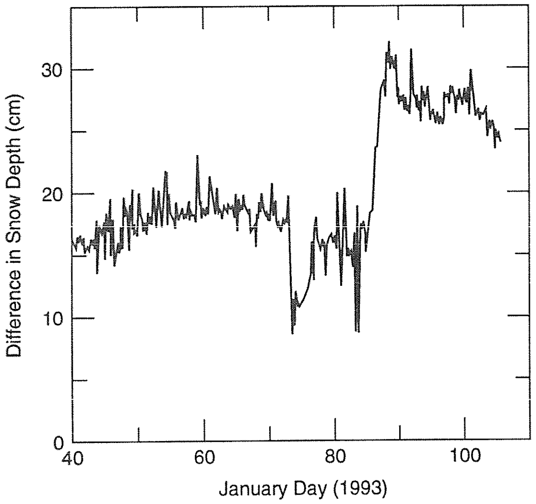

Figure 3b. Difference in snow depth between the open and wooded sites.

bearing down on the cantilevered supports. At the open site, the weakly-bonded snow did not have the strength to affect similar instrumentation supports. In addition to affecting heat and mass transfer in snow, even relatively thin ice layers can have remarkable mechanical effects due to their relative strength.

More water was lost from the snowpack at the forested site than at the open site. The depth changes and stratigraphy can be seen in figures 1 and 2, and in more detail in figures 4a and 4b. First, it is evident that the snow depth change is due to melt and consolidation in the upper part of the pack, but the strength of the ice and crusty layers allowed only minor changes in stratigraphy in the bottom half of the pack. In terms of snow-water equivalent (SWE) at the open site, most of the snowmelt in the upper pack served to increase the mass lower in the pack: of 6.9 cm of water lost by layers above the ice layer, 4.1 cm served to increase the mass or SWE of lower layers, while only 2.8 cm of water went to runoff.

In contrast, the forested site lost 11.2 cm of meltwater to runoff during this period. There were 11.2 cm of meltwater lost from the pack above the ice layer at 35 cm height, 1 cm of meltwater lost above the crust but below that ice layer, and 1 cm of SWE increase between the basal ice and crusty layers. Not only was much more melt generated in the upper layers of the pack at the forested site than at the open site, but—unlike the open site—this melt did not increase the SWE lower in the pack. Our previous dye studies done at the forested site (Hardy et al. 1992) showed that surface meltwater can travel "laterally" downslope through the pack for many meters before percolating vertically to the pack's base, even in the absence of ice layers. The mass loss and stratigraphy measurements indicate that the meltwater generated in the upper half of the pack at the forested hillslope flowed laterally through the pack in the downslope

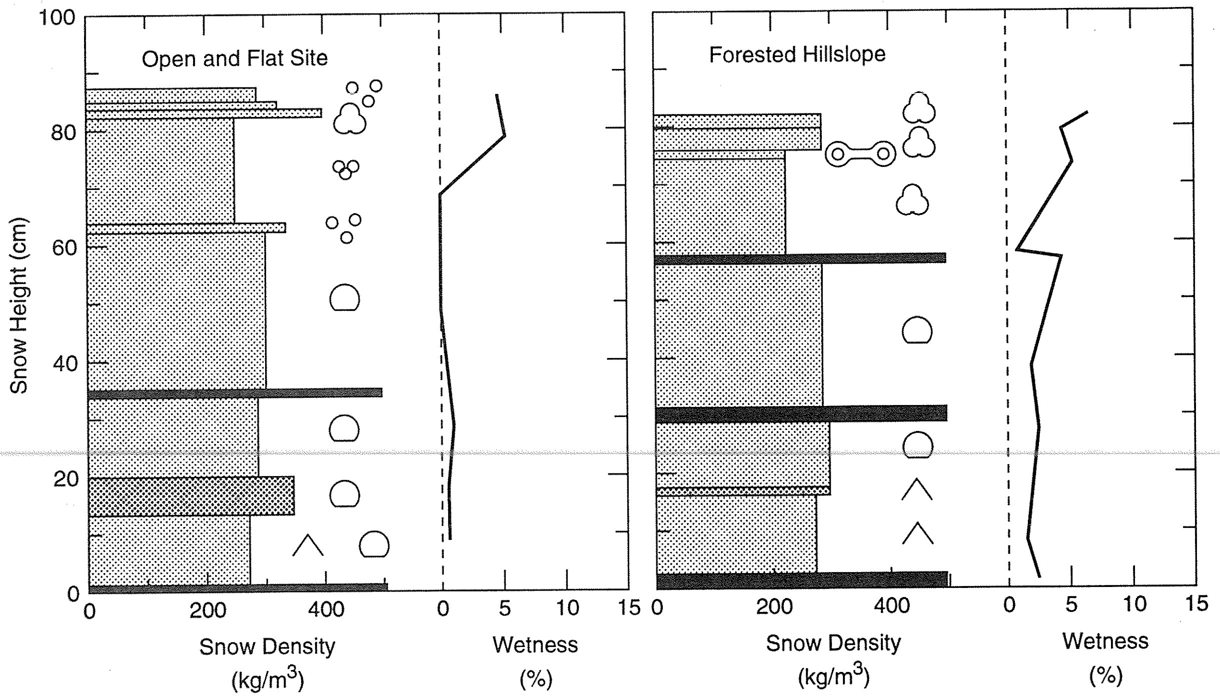

Figure 4a. Snowpit profiles on March 25 (Julian day 84).

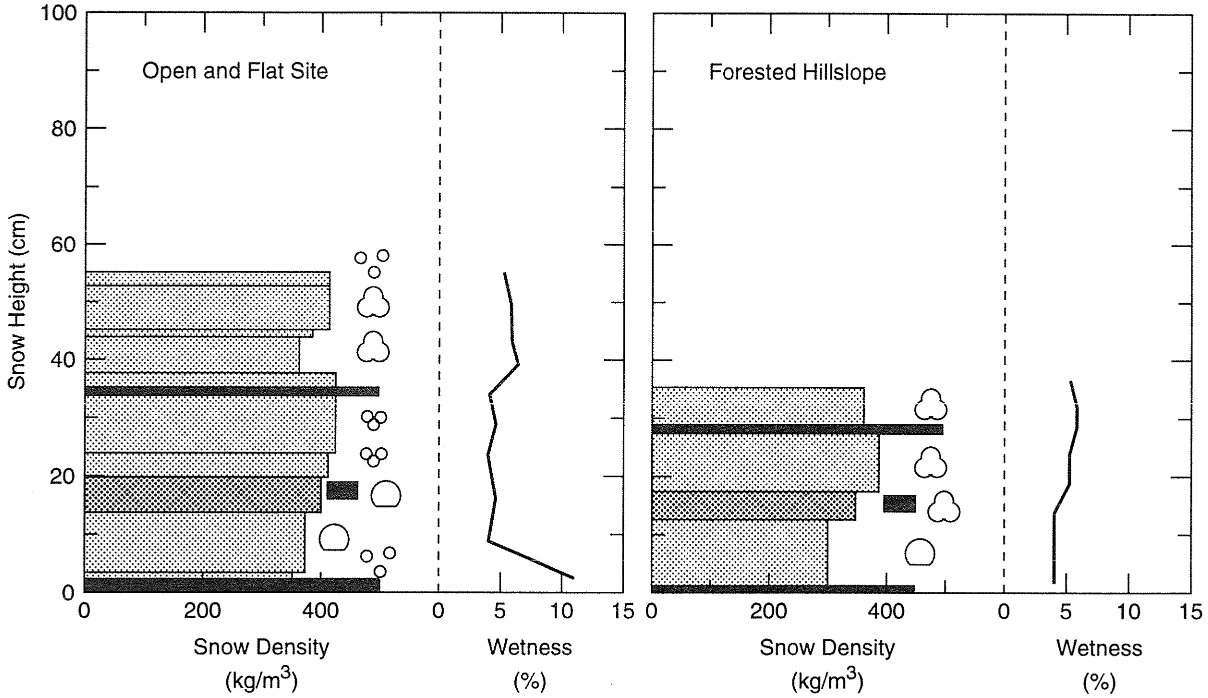

Figure 4b. Snowpit profiles on March 30 (Julian day 89).

direction, and hence could not add as much mass to lower layers as did the snowmelt at the open site.

Although both the open sites and forested hillslope experienced the same prevailing weather patterns, during these five days in March the snowpack in the forest experienced significantly more melt than the open site, and the meltwater was generated in the upper portions of the pack at both sites. This indicates that the local meteorology at the forested hillslope generated greater melting than at the open site.

Although a full energy budget is beyond the scope of the present paper, we note that during these five clear days the air temperature stayed above freezing, the wind speed was less than 1 m/s, and there was no precipitation. The previous work by other authors cited above indicates that net allwave radiation is the most important factor in the snowpack energy budget during snowmelt. Figure 5 depicts the cumulative average daily radiation (incoming solar, reflected solar, incoming longwave, emitted longwave, and total radiation) during these five days. The open site had more net solar radiation, as expected, but the forested site had more net longwave radiation. In fact, at the open site the net longwave radiation (–33.5 MJ/d/m^2) was negative (emitted from the pack), where at the forested site the net longwave radiation (16.7 MJ/d/m^2) was positive. The opposite sign at the two sites for net longwave radiation is true both for measured longwave radiation and for that calculated from the Stefan-Boltzmann law. The net longwave radiation into the pack at the forested site is an indication that the trees are emitting additional longwave radiation to the snow, i.e., the trees are warming the snow.

Finally, the net allwave radiation is very nearly the same at both sites, so that the greater longwave radiation induced by the trees at the forested hillslope is able to offset the greater solar radiation at the open site. Although net allwave radiation is important to the energy balance, all of the factors in the energy balance must be considered before quantitative snowmelt differences between the sites can be explained.

A NOTE ON THE MID-PACK SLUSH LAYERS

The open site had several layers of slush within the top 30 cm of snow on March 25, as depicted in figure 4a. These layers are the result of melting and meltwater infiltration as far as snow and meteorological conditions permitted at the time, probably both due to warm air temperatures and solar radiation penetration of the snow. Although it may seem curious to have a slush layer above rounding faceted particles, this observation provides field evidence of the capillary effects on melt flow. There is less capillary pressure required to retain water in the fine-grained snow than is required to draw water through the coarse-grained faceted snow beneath it. Water will

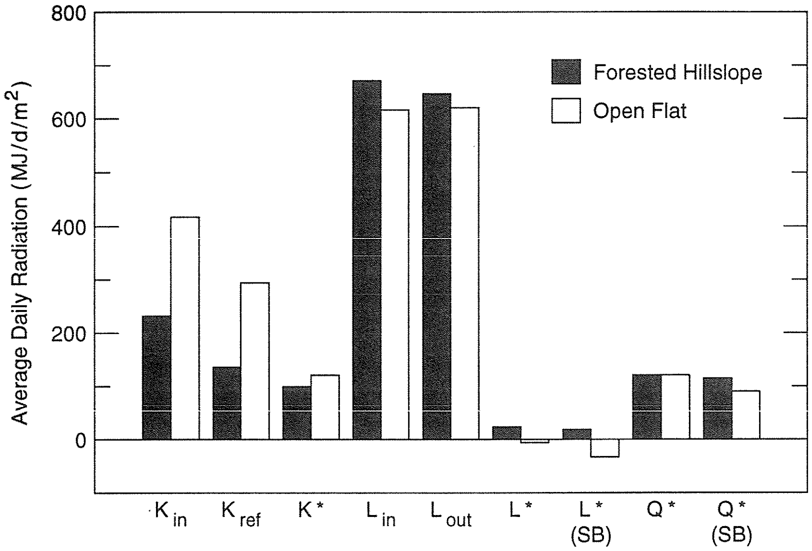

Figure 5. Comparison of the average daily radiation at the two sites. K *is solar,* L *is longwave,* Q *is allwave radiation. Subscript* in *indicates incoming,* ref *indicates reflected,* out *indicates emitted. Asterisks indicate net radiation, and* SB *represents values calculated from the Stefan-Boltzman law.*

continue to be retained locally until enough pressure head builds to overcome the pressure difference. Most snowmelt models do not incorporate the effects of capillary pressure or layering. Our field data illustrate that capillary effects are observable in the field. Capillary and layering effects need to be included when modelling metamorphic snowmelt processes.

CONCLUSIONS

Field observations of snowpack stratigraphy evolution at forested hillslope and flat open sites have been described for the winter of 1992–93 in northern Vermont. The predominant stratigraphic features of the two sites are similar, although the snow can have dramatically different behavior in response to tree- and slope-induced local differences. Stratigraphic changes occur over relatively short time scales early and late in the season, and in the upper portion of the pack in the mid-season. In addition to affecting heat and mass transfer in snow, even thin ice layers can have significant mechanical effects due to their strength relative to other snow layers in the pack.

Differences in solar radiation between the two sites produced differences in the early snowcover, which then controlled the formation and nature of the basal ice layer that remained throughout the season. This year the basal ice layer in the forest was mainly established from the freezing of a water-saturated thin early-season snowpack, which led to a thicker, more spatially uniform basal ice layer. However, most of the basal ice at the open site was caused by meltwater percolation through snow, which caused the basal ice to have more spatial variability. For the south-facing forest instrumented here, the greater longwave radiation induced by the trees at the forested hillslope is able to offset the greater solar radiation at the open site, so that net allwave radiation at the two sites was approximately equal. Our field data illustrate that capillary effects produce observable changes in snowpack stratigraphy (in addition to being important in fingering phenomenon), and need to be included when modelling metamorphic snowmelt processes.

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