Effect of Cover Type on Snow Isotopic Composition

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ABSTRACT

Use of stable isotopic tracers to estimate snowmelt contributions to spring runoff has become a common hydrograph separation technique. Estimation of the isotopic composition of the snowmelt end member may be affected by spatial and temporal variability of snowmelt under different vegetative cover types within catchments. At the Heiberg Experimental Forest in Tully, New York, snowpack and meltwater under three different cover types (open field, deciduous stand, and conifer stand) were analyzed for ^{18}O from February to April, 1994. Results showed that bulk snow samples collected under the three vegetative cover types differed isotopically although no consistent trends among the cover types were evident. Initial isotopic compositions of meltwater from the open field and from coniferous cover were lighter than the snowpack by 1.1‰ and 4.3‰, respectively, in contrast to that observed under deciduous cover which was 1.8‰ heavier than the snowpack. Isotopic analysis of individual snow layers revealed isotopic homogenization of the snowpack during the melt period. The $\delta^{18}O$ values of these layers as well as snowpit stratigraphic profiles provided evidence that metamorphic processes controlling isotopic evolution in the snowpacks of the three cover types differed. These results suggest that differences in vegetative cover type should be considered when estimating snowmelt contributions to runoff using isotopic hydrograph separation techniques.

Key words: snow isotopic composition, isotopic variability in snow, snowpack evolution.

INTRODUCTION

The use of naturally occurring stable isotopes for hydrograph separation of spring snowmelt has become prevalent in hydrology. Application of this technique requires isotopically distinctive, constant, and spatially homogeneous end members for effective separation of old and new water sources (Sklash and Farvolden, 1979). It is typically assumed that the isotopic composition of the meltwater was the same as that of the bulk snowpack (Dincer et al., 1970; Rodhe, 1981; Bottomley et al., 1986; Obradovic and Sklash, 1986; Lawrence, 1987; Ingraham et al., 1989; Cooper, 1991). However, recent studies have found meltwater isotopic compositions are significantly lighter than the snowpack during the initial melt period (Moore, 1989; Maule and Stein, 1990; Cooper, 1993). Isotopic signatures may also vary considerably over time, thus reducing the precision of the hydrograph separation (Hooper and Shoemaker, 1986).

Research in snow isotopic fractionation has indicated that significant changes in isotopic composition may occur during snow ablation and melting (Herrmann and Stichler, 1981; Cooper, in press). At 0°C, the equilibrium fractionation factors between ice and water are 1.0035 and 1.0208 for $\delta^{18}O$ and δD, respectively (Majoube, 1971). Therefore, during melt, the lighter isotopes are preferentially removed in the meltwater while the residual snowpack becomes increasingly enriched in heavy isotopes. A later cycle of partial freezing of meltwater results in new ice that is isotopically enriched relative to the residual meltwater. Herrmann and Stichler (1981) showed that the first meltwater from a homogeneous experimental snowpack exposed to a continuous thermal gradient was 15‰ lighter in δD than the original snowpack. Alternating melt and refreezing of a snowpack resulted in an initial meltwater composition 12.5‰ lighter than the original snowpack and the final meltwater was 8.3‰ heavier.

At 0°C, the equilibrium fractionation factors between ice and vapor are 1.0152 and 1.132 for $\delta^{18}O$ and δD, respectively (Majoube, 1971). Such fractionations may be observed under transient

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conditions in the natural environment where the vapor sublimed from the snow surface has been found to have δD values up to 110‰ lighter than the snow (Sommerfeld et al., 1991). Whether sublimation by itself can cause significant isotopic fractionation of the snowpack under steady-state conditions is a matter of debate (Friedman et al., 1991; Sommerfeld et al., 1991). For example, if sublimation simply strips away water molecules (Lawrence, 1987) or if temperature gradient metamorphism is strictly "hand to hand," no change in composition should occur (Sommerfeld et al., 1991). The observed large increase in the isotopic composition of snow during sublimation may be caused by the combination of sublimation and subsequent transport of vapor by diffusion, or by the cascading of many small sublimation/condensation cycles on growing snow crystals as the vapor travels upwards through the snowpack (Friedman et al., 1991; Sommerfeld et al., 1991). Partial condensation of vapor results in the formation of ice that is enriched relative to the residual vapor.

Individual snow layers may undergo isotopic fractionation at different rates prior to snowpack homogenization. For example, experimental snowpacks exposed to a thermal gradient showed $\delta^{18}O$ shifts of up to 10‰ in the both upper and lower layers (Sommerfeld et al., 1991). Exchange with isotopically heavy soil moisture as well as upward migration of lighter moisture from the bottom layers of the snowpack can also influence the isotopic signature of the layers within the snowpack (Friedman et al., 1991). Migration of moisture into the snowpack from the underlying soil can be as high as 10-35% of the of the moisture contained in the natural snowpack (Santeford et al., 1978; Friedman et al., 1991). Fractional condensation of water vapor upon growing snow crystals also appears to be a significant mechanism (Cooper, in press).

Precipitation may continuously modify the isotopic content of the snowpack. Isotopic composition of the precipitation inputs may vary considerably both during and between events (McDonnell et al., 1990). Typically, precipitation formed in colder temperatures (e.g., snow) will have a lighter isotopic composition than that formed in warmer temperatures (e.g., rain). Throughfall has been found to be generally heavier than the original rain (Kendall, 1993; DeWalle and Swistock, 1994) and snow (Claassen and Downey, in press) in a few catchments. Therefore, a heavily forested catchment may influence the isotopic content of the precipitation reaching the ground or snow surface.

The effects of environmental factors that control snowpack evolution, metamorphosis, and melt such as wind, vapor-pressure gradients, or temperature gradients are different under various cover types. For example, Federer and Leonard (1971) found windspeed in hardwood stands compared to open fields was reduced by half while temperature and relative humidity remained the same. They attributed differences in convection-condensation melt between the hardwood stand and open field to differences in turbulent transfer. High winds in open areas are found to increase ablation rates, snow crystallization changes, and water vapor exchange causing an increase in the isotopic composition of the snowpack relative to that in wind-sheltered areas (Cooper, 1993). Albert and Hardy (1993) found differences in mass loss and stratigraphy evolution at open and wooded sites.

The extent of isotopic exchange in snowpacks is dependent on conditions such as soil temperature, soil moisture, relative humidity, air temperature, the period of time the snowpack is present on the ground, and the isotopic fractionation processes associated with partial melt and refreezing (Cooper, in press). Because these conditions may also be controlled by the amount and type of vegetative cover, the isotopic composition of the snowpack and snowmelt may be significantly different under varying vegetative regimes. Snow in an open field is expected to be more exposed to environmental factors contributing to isotopic fractionation such as high winds, evaporation and melt-freeze cycling resulting in a consistently heavier isotopic composition than forested sites. Snow in coniferous stands is expected to be consistently lighter isotopically because of its isolation from the above potential fractionation mechanisms. The isotopic composition of snow in a deciduous stand is expected to be intermediate between the other two sites.

This study examines $\delta^{18}O$ variability during snow accumulation and melt under three differing vegetative cover types during February - April 1994. Two hypotheses were tested:

(i) that cover type (deciduous, coniferous, or open) has no effect on the bulk isotopic compositions of snow and meltwater throughout accumulation and melt;

(ii) that the physical and isotopic composition of individual snow layers undergoes homogenization and metamorphism at the same rate among cover types.

SITE AND METHODS

Three study sites were located in Heiberg Memorial Forest, Tully, New York. The 1680 ha research forest is located 30 km south of Syracuse, New York (latitude 42°46' N, longitude 76°05' W) at an elevation of 600 m. Snow sampling sites were located approximately 100 m apart near the intersection of three vegetative cover types: an open field, a conifer stand, and a mixed hardwood stand (Figure 1).

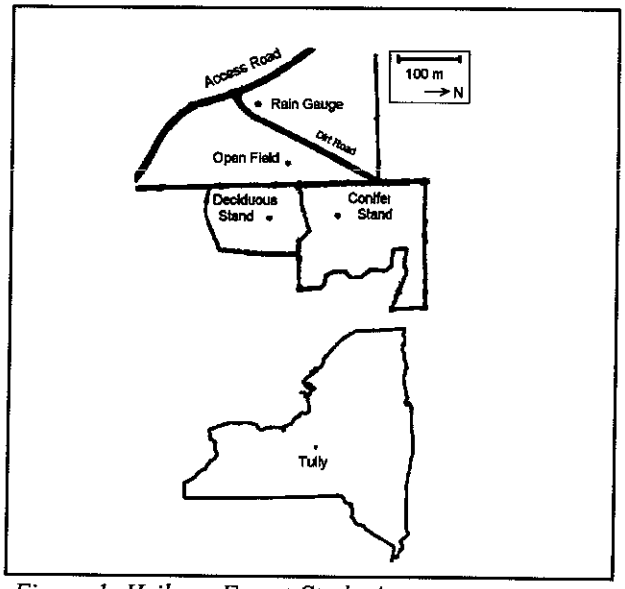

Figure 1. Heiberg Forest Study Area.

Soils are a moderately well-drained Mardin channery silt loam with a fragipan layer existing at 0.45-0.60 m. The open field site (53,000 m^2) is covered by 1 m high grasses in summer and is open to the north, south and west directions. The deciduous and coniferous stands bound the field to the east. Forty to fifty year-old dense red and norway spruce dominate the coniferous stand (400,000 m^2). The deciduous stand (23,000 m^2), which is less dense and of uneven age, is characterized by a mix of maple, beech and black cherry.

Meteorological Data

Hourly meteorological measurements were recorded from February 10 to April 18, 1994 with a Campbell CR10 data logger in the open field site. Thermocouples were placed 50 mm into the ground and positioned in the snowpack 0.5 m above the soil surface. A net radiometer and solarimeter were both fixed 1.5 m above ground. Two relative humidity gauges were placed at 1 m and 3 m heights and an anemometer installed at 3 m. A tipping bucket rain gauge was installed on March 17 at a 2 m height and correlated with daily precipitation measurements made by Heiberg Forest staff.

Snow Properties

A ten-point snow course was surveyed weekly from February 10 to April 15, 1994 in the deciduous stand. Snow depth and water equivalent were recorded using an Adirondack snow tube and a direct measurement snow scale. A snowpack of 708 mm depth existed at the time of the first survey. The snow course was located 30 m from the deciduous snow sampling site.

At each of the three study sites, a snow pit was excavated down to the soil surface. Each week a new vertical snow face was exposed approximately 200 mm away from the last exposed pit. A snow stratigraphy profile was developed using a standard mercury thermometer, tape measure, and a Taylor-Lachapelle Snow Density Kit. Different snow layers were delineated according to their depth, density, hardness, grain size and shape and temperature using the classification system described by Langham (1981). Powdered fluorescent dye (rhodamine WT and lissamine) and colored string were placed on the surface of the snowpack at the pit's edge to track the weekly snow layer positions. The snowpit face was then flagged for later relocation and the pit allowed to refill with new or blown snow.

Snow Isotope Sampling

Bulk snowpack samples (entire snowpack column) were collected weekly near each of the three snowpit sites using an Adirondack snowtube. Samples were sealed in plastic bags, later melted at room temperature (20°C) and transferred into 30 ml glass vials. These samples were analyzed for $\delta^{18}O$ at the USGS Water Resources Division Stable Isotope Laboratory in Menlo Park, CA with an analytical precision of 0.05‰. Isotopic compositions are given as ratios of the relative difference of the O^{18}/O^{16} ratios from the Standard Mean Ocean Water (SMOW) (Craig, 1961) and expressed in permil (‰). Snow meltwater was collected with snow lysimeters (230 x 330 mm plastic trays) placed at the snowpack base and drained into plastic containers sunk below the soil surface. Containers were checked weekly for meltwater accumulation. Upon the onset of snowmelt, accumulated meltwater was collected every second day. Collected

meltwater was bottled in 30 ml glass vials for isotopic analysis. Snow samples (200 cm^3) were weekly taken from the top, middle and bottom layers of the exposed snow pit faces. The top layer sample was taken from within 50 mm of the snow surface and the bottom layer was taken from within 50 mm of the snow/soil interface. The middle sample was taken from the physical center of the snowpack profile. Layer samples were handled in the same manner as the bulk snow samples for isotopic analysis.

Rainfall was collected in a totalizing rain gauge in the open field, approximately 500 m from the open field survey site. A film of oil on the surface of the collected water prevented evaporative fractionation. During site visits, samples were drawn from the rain gauge by syringe and bottled for isotopic analysis. Rain samples were collected within 24 h of the rain event.

RESULTS AND DISCUSSION

Average yearly snowfall at Heiberg Forest from 1971 to 1989 was 3050 mm. Snowcover typically existed from late December until mid-March (SUNY-ESF, unpublished data). The 1993-1994 winter season was the second snowiest in central New York history and the Heiberg Forest snowpack persisted until mid-April. During the 1993-1994 season, the 4115 mm total snowfall surpassed the mean by 1065 mm and was second only to the 4877 mm snowfall of 1992-1993. Snowpack depth and snow water equivalent (SWE) were both double the mean values for snow seasons from 1977-1989. A maximum SWE of 261 mm was recorded on March 17. The largest snowfall event during the study period occurred on March 4 totalling 610 mm (38.1 mm SWE), adding an average of 450 mm to all three snowpacks. Unexpectedly, significant snow drifting was observed at the deciduous snowpit which was 50 m downwind of the open field. Blown snow accumulated in the vicinity of the snowpit where the treeline separating the open field from the deciduous stand acted as a snow fence.

A period of unseasonably warm temperatures accompanied by a rain-on-snow event occurred during the week of February 17-24. Temperatures peaked at 12.4° C on February 19 with 10 mm of rain recorded on February 24 (Figure 2a). This atypical week was further accentuated by preceding and subsequent periods of below normal temperatures. Rain-on-snow events were also recorded on March 8 (5.6 mm), March 15 (2 mm), March 22 (12 mm) and during the final period of the study, April 7 - 15 (34.6 mm) (Figure 2b).

Bulk Snow Samples

Although none of the three sites displayed consistently distinctive snowpack $\delta^{18}O$ signatures throughout the study period, snow at all sites experienced an isotopic enrichment in ^{18}O until April 8 when a late season snowfall of 50.8 mm occurred; this snowfall (not analyzed) may have influenced the final bulk sample taken on April 15 (Figure 3a). Prior to the snowfall, open site $\delta^{18}O$ compositions increased a total of 0.8‰, the coniferous 2.0‰, and the deciduous 2.8‰, indicative of the strong effect of ablation on isotopic composition.

The initial samples collected February 10 showed a 2.5‰ range in the $\delta^{18}O$ values of the snowpacks among the cover types. Because of the lack of sampling from late December to early February, it is unknown whether this variability was caused by original differences in the snow deposited at the sites or results from differences in processes that occurred during ablation. It is likely that the pre-February snowpack was originally lighter in isotopic composition than was observed during the study period. Although the results of the experiment showed meaningful differences in $\delta^{18}O$ values between the three sites (greater than 0.5‰), additional snow survey pits in each cover type would provide stronger confirmation of this isotopic spatial variability.

To facilitate comparisons of changes in $\delta^{18}O$ with physical changes in the snowpack, the study period was divided into three subperiods with characteristic snowpack conditions and isotopic compositions: the initial conditions will be referred to as period 1 (February 10 to March 3), the post-storm conditions as period 2 (March 4-21), and the isothermal conditions as period 3 (March 22 to April 14).

Snowpacks in the three different sites did not exhibit parallel development within each of these periods. For the first period, the open field site was consistently heavier than the forested stands. This relationship reversed in the second period when the open site became and remained lighter than either forested site. The coniferous snowpack $\delta^{18}O$ values were generally intermediate between those of the other two sites (Figure 3a). At the conclusion of the third period, the isotopic signatures showed that the open site was 2.5‰ lighter than the forested sites. Homogenization brought the final deciduous and conifer bulk samples to within 0.4‰.

Snowpack enrichment was expected to continue

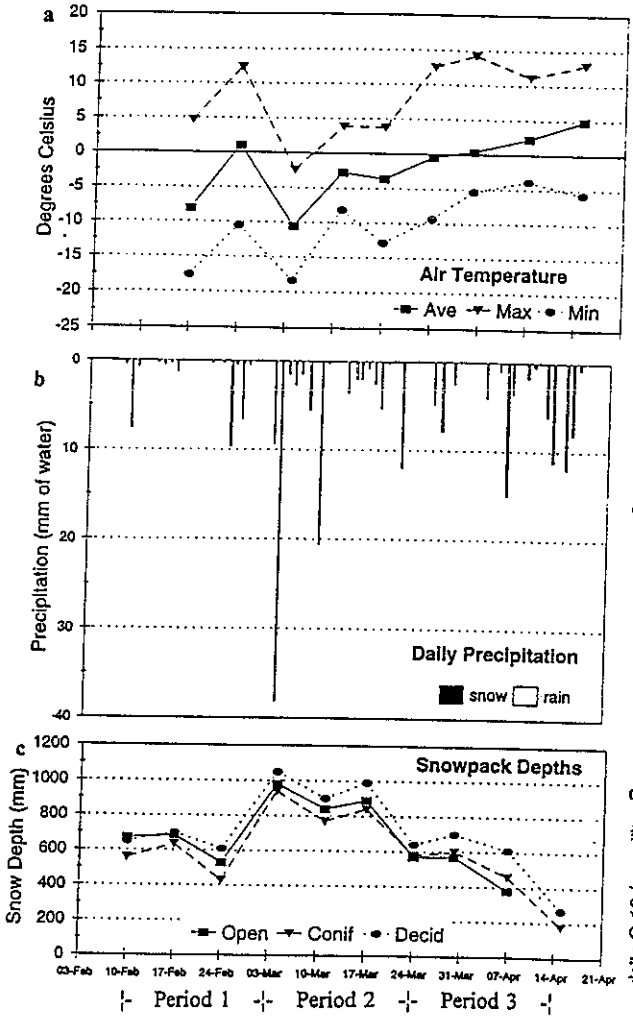

Figure 2. (a) Air Temperature; (b) Daily Precipitation; (c) Snowpack Depths.

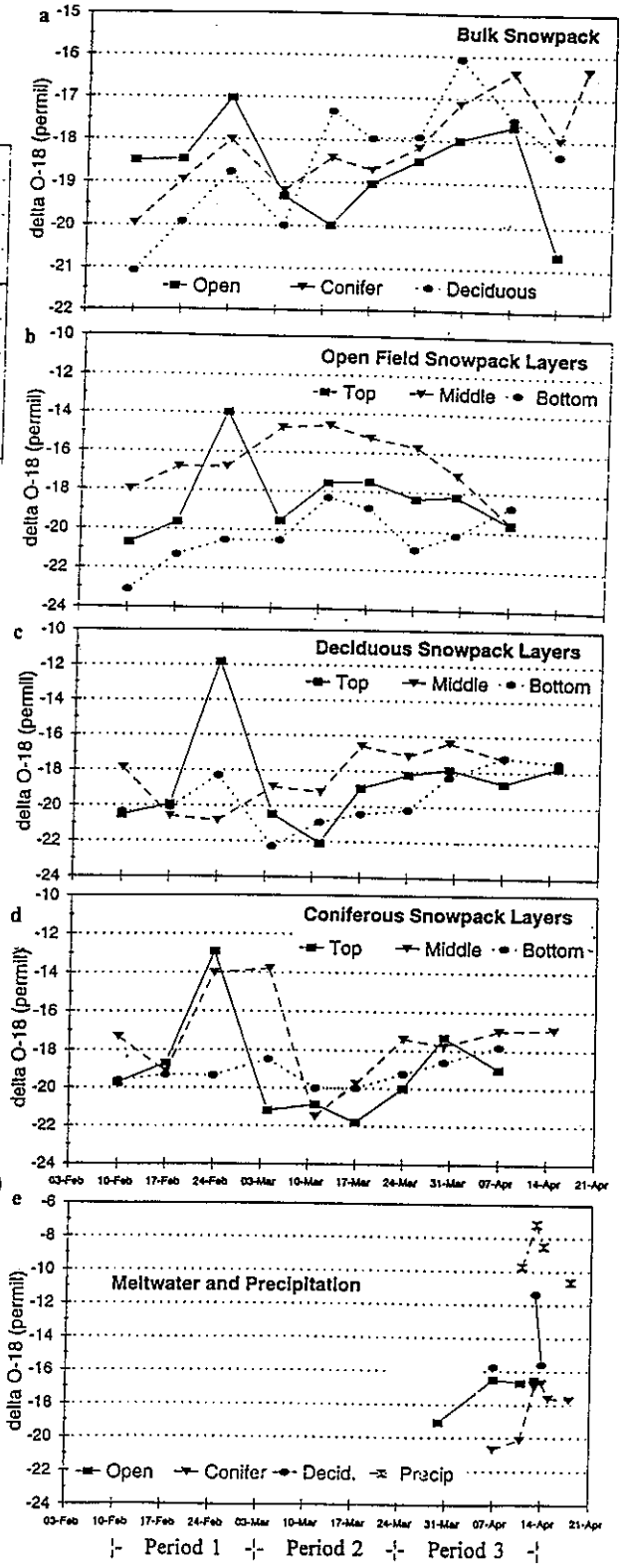

Figure 3. Isotopic Compositions of: (a) Bulk Snowpack; (b) Open Field Snowpack Layers; (c) Deciduous Snowpack Layers; (d) Coniferous Snowpack Layers; (e) Meltwater and Precipitation.

until complete ablation (Judy et al., 1970). The week of February 17-24 exhibited a substantial enrichment in ^{18}O, producing a distinctive "spike" in the data (Figures 3a, 3b, 3c, 3d). The rapid enrichment in ^{18}O corresponds to a period of snowpack ablation caused by a 10-mm rain-on-snow event during a four day period when average temperatures were well above 0°C. The open, deciduous and conifer sites experienced a 160 mm, 200 mm and 90 mm loss respectively (Figure 2c). Despite this ablation, no meltwater was observed. The succeeding week (February 24 to March 4) was characterized by heavy snows and average temperatures of -10.5°C (7°C below normal). During this period the open site snowpack increased 450 mm in depth, the coniferous 510 mm and the deciduous 440 mm (Figure 2c). Though not sampled, new snow was apparently isotopically lighter than the existing snowpacks, decreasing the bulk $\delta^{18}O$ composition by 1 to 2‰. The top layers of each snowpack showed a depletion of 6 to 10‰ during this period, strongly suggesting that the new snow was light relative to the existing snowpack (Figure 3b, 3c, 3d). The uncertainty of the isotopic inputs to the snowpack highlights the need for isotopic sampling of each precipitation event to provide insight into the isotopic evolution of the snowpack.

Vertical Variability

Analysis of three layers of each snowpack throughout the study period provided some insight into the bulk snowpack homogenization processes. The top layer is thought to reflect the isotopic composition of recent precipitation events and condensation of atmospheric vapor. During period 1 the $\delta^{18}O$ values of the top snow layer for the three sites were less variable (Figure 3b, 3c, 3d) than during period 2, with the open field site being generally heavier and the coniferous site lighter. Wind effects, more pronounced radiative effects and greater diurnal temperature fluctuations at the open site may explain this greater fractionation at the top snow layer. Since the deciduous stand was affected by winds and solar radiative fluxes (although to a lesser extent than in the open site) the $\delta^{18}O$ values of its top snow layer were more similar to those of the open site values. The top layers converged again to within 1‰ during period 3.

Because the middle layer samples were not taken from the same snow layer each week, these samples might be expected to show the greatest $\delta^{18}O$ variability among the study sites (Figure 3b, 3c, 3d); however, the top layers that are most affected by new snow generally show the most scatter. At the beginning of the study, middle layers of the snowpacks were 2 to 3‰ heavier than the top layers and 2 to 4‰ heavier than the bottom layers. The open field showed consistently heavy middle layers and the least variation from week to week. The coniferous site showed higher variability.

At the end of March, the middle layer $\delta^{18}O$ values of all three sites converged within a range of 2‰. The general enrichment of the middle layers may be related to the presence of several ice layers within this section of the snowpack; the ice layers represent either zones of condensation or zones of earlier partial melting and subsequent refreezing; both of these mechanisms would cause isotopic enrichment. An alternate explanation is that the enrichment merely reflects the original composition of the middle layer. Ice layers regulate the transport of water vapor and free water through the snowpack.

The bottom layers were generally lighter than the middle and top layers, perhaps because the isotopic composition of the first snowfalls of the season may have been lighter than subsequent snowfalls. The bottom snow layers show progressive enrichment in ^{18}O during the entire study (Figure 3b, 3c, 3d). This may reflect condensation of relatively heavy water vapor flux from the soil into the bottom layers of the snowpack as shown by Friedman et al. (1991). The bottom layers show much less temporal variability in $\delta^{18}O$ values than the top and middle layers. For example, the unusual weather conditions of February 17-24 have little effect on the bottom layers. By April 7, the three bottom layers were within 2‰ of each other. After this date, the open snowpack began to disappear first, followed by the coniferous and the deciduous snowpacks.

Cover Types

The differences in $\delta^{18}O$ values of the three cover types demonstrate spatial variability in the homogenization of the three snowpacks. The middle and bottom layers in the open field site maintain a consistent 3 to 5‰ difference throughout almost the entire study (Figure 3b). Although the bottom was found to have larger, metamorphosed grains including depth hoar, it proved to be the most isotopically depleted of the three sampled layers during the entire period. A rapid convergence of $\delta^{18}O$ values during the third and final period brought the snow layers within 1‰, indicating snowpack homogenization. The forested sites showed more variability among their layers from

week to week than did the open site. The main difference between the open and forested sites was that the open field was subject to higher winds, blowing and drifting snow, and sintering of the top layer of snow forming a thin ice lens.

The snow layers at the deciduous site exhibited a smaller isotopic range than at the open site, generally about 3‰ (Figure 3c). After the large March 4 snowfall, the deciduous bulk samples were heavier than at the other sites and showed consistently heavy middle layers and light bottom layers. This relationship was similar to that developed in the open field. The deciduous site was also subject to high winds, blowing and drifting snow, but showed little surface crusting. The three layers converged to within 1.7‰ by April 7. The last samples of the top and bottom layers taken on April 15 of the small remaining snowpack were virtually identical.

The coniferous layers values did not show a consistent difference in $\delta^{18}O$, but generally showed a narrower range than the open site samples (Figure 3d). The three layers were usually within 2‰ of each other, jumping to a 7‰ difference only during February 17-24. By the end of the study period the three layers were 2.8‰ apart.

Both the bulk samples and most of the individual layers showed the same general progressive enrichment in ^{18}O during the study period. Superimposed on this general trend is the rapid increase in $\delta^{18}O$ caused by the February 24 rainfall. Other than these, there was almost no correspondence between patterns seen in bulk and layer samples. Clearly, sampling of only three points in the snowpack is not sufficient for defining the processes responsible for snowpack homogenization. Repeated sampling of each observed layer is needed to track the temporal and spatial isotopic variations within the snowpacks. Additional uncertainty in analyzing differences between cover types arises from the limitations imposed by having only a single sampling point within each cover type. Intra-site variability cannot be accounted for accurately.

Stratigraphy

Snow stratigraphic profiles provided additional physical evidence of the relation between snow metamorphism and snow isotopic evolution. Snow density measurements showed periods of snowpack consolidation and layer metamorphism. Well-defined ice layers, which may regulate vapor movement, developed in response to high wind, rain-on-snow events and melt-freeze episodes, and persisted in the snowpacks at each site up until snowmelt. The most notable stratigraphic changes observed during the study took place during February 17 to March 4, the three-week period containing the $\delta^{18}O$ "spike" of February 24 (Figure 4). Over the course of the study period a trend in increasing density was noted with ^{18}O enrichment.

Meltwater Samples

Snowmelt first occurred in the open field on March 30 (Figure 3e). The initial meltwater sample $\delta^{18}O$ value was -19.1‰, which was 1‰ heavier than the lower layer and 1.1‰ lighter than the total remaining (bulk) snowpack. During the following week (April 7), initial melt was observed from the deciduous stand with a $\delta^{18}O$ of -15.7‰ (2‰ heavier than the lower layer and 1.8‰ heavier than its snowpack) and subsequently the conifer stand at -20.7‰ (2.7‰ lighter than the lower layer and 4.3‰ lighter than its snowpack). At this time, only the coniferous site had meltwater isotopically lighter than its corresponding bulk snow sample, since the April 7 open site meltwater sample was 1.1‰ heavier than the corresponding bulk sample.

By April 11, the soil pits containing the open and deciduous lysimeter collection bottles had been flooded with meltwater, precipitation and possibly shallow groundwater and no longer provided reliable representations of snowpack meltwater. The grab sample taken from water standing in the open field lysimeter pit on April 11 was isotopically similar to the open lysimeter sample indicating possible contamination of the lysimeter sample. The lysimeter sample collected in the deciduous site on April 13 was heavy (-11.4‰) indicating probable contamination by precipitation. Precipitation samples collected from April 11 to 18 were extremely enriched in ^{18}O, ranging in value from -7‰ to -10‰. For these reasons, lysimeter sample data from the open and deciduous sites are not considered valid after April 11.

The coniferous site, which did not experience flooding during the melt period, provided the most consistent lysimeter readings. These meltwater samples displayed the expected gradual enrichment in ^{18}O toward the isotopic content of the homogeneous snowpack during the final melt phase. From April 7 to April 14 the lysimeter samples approached bulk samples, from a 4.3‰ difference to within 1.3‰.

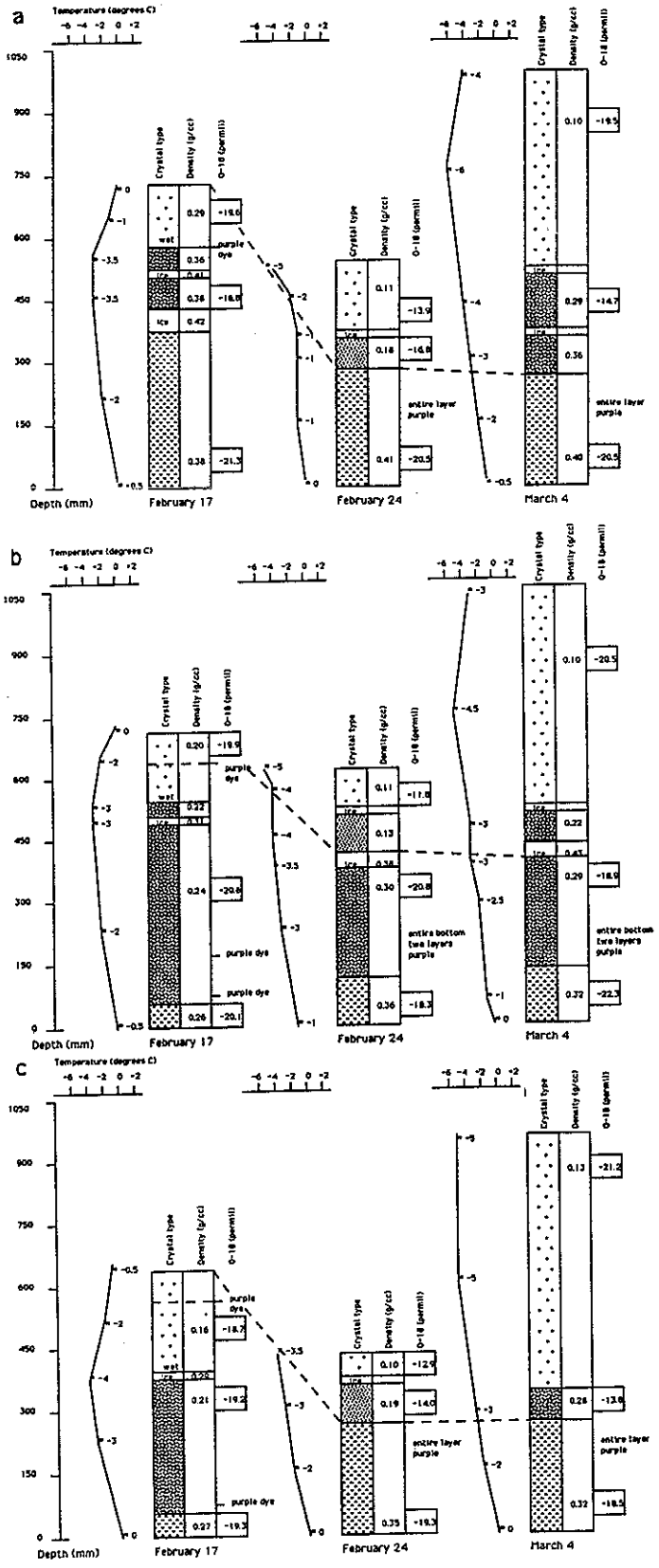

Figure 4. Selected snow profiles from the Heiberg Forest study area: (a) Open Field; (b) Deciduous Stand; (c) Coniferous Stand. Position of $\delta^{18}O$ values represents the location of the samples. The dashed line illustrates the weekly movement of colored string used as profile markers.

Impact of Meltwater Variability on Isotope Hydrograph Separations

Let us consider the effect of the isotopic variability observed in this study on a simple two-component hydrograph separation model (McDonnell et al., 1990). If the April 7 open field meltwater sample ($\delta^{18}O$ = -16.5‰) was utilized as the new- water component, and the estimated $\delta^{18}O$ values of groundwater and measured streamflow in the catchment were -12‰ and -14‰, respectively, then the relative groundwater and meltwater contributions to runoff would be 56% and 44%. Alternatively, using the April 7 conifer meltwater sample (-20.7‰), the relative groundwater and meltwater contribution to runoff would be calculated as 77% and 23%. Therefore, a difference of 4.2‰ in the estimation of meltwater $\delta^{18}O$ could result in a 20% miscalculation of new water contribution to streamflow. These differences in the timing of melt and the isotopic contributions to melt from the three sites may have a significant impact on the calculation of old and new water contributions to streamflow in hydrograph separations. These preliminary results suggest that additional investigation of the potential spatial and temporal variation in meltwater composition and its contribution to spring runoff is needed.

CONCLUSIONS

The $\delta^{18}O$ values of bulk snow samples from the three cover types (open field, coniferous and deciduous stands) showed considerable differences in composition among the three sites throughout the study period. In addition, both meltwater composition and the timing of its release from the snowpacks of the three cover types were found to be different. Additional work will be required to determine the potential for spatial variability in the isotopic composition of the snowpack under a uniform cover type. However, it is clear that the spatial and temporal variability in snowpack isotopic composition needs to be considered when estimating snowmelt contributions to runoff using multi-component static end member mixing models. Periodic sampling of snowmelt collected in multiple, carefully positioned, pan lysimeters is by far the best method of assessing the potential temporal and spatial variability in the isotopic composition of the new-water end member.

Although no consistent pattern was discernable among the three sites, short-term trends were noted. Isotopic data confirmed that the snowpacks at the three sites became enriched in ^{18}O during the study period from February 10 to April 14. Isotopic analysis of individual snow layers indicate isotopic homogenization of the snowpack during the melt period. The top, middle and bottom layer $\delta^{18}O$ samples and snowpack stratigraphic profiles provided evidence of dissimilar metamorphic processes controlling isotopic evolution in the snowpacks of the three cover types.

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