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Isotopic variation of snow cover and streamflow in response to changes in canopy structure in a snow-dominated mountain catchment

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Abstract

Isotopic composition of snow cover and streamflow was determined in a snow-dominated, forested watershed to quantify the spatial variability and processes that alter stable isotope (oxygen-18, ^{18}O and deuterium, ^{2}H) composition under different forest canopy conditions (clear-cut, partial-cut (thinned), and unimpacted forest). Snow sampling was carried out on 4 days in late winter and early spring 2006. Meteorological data, precipitation, and streamflow were continuously monitored during the study. Isotope analyses of precipitation samples were conducted weekly through the 2005–2006 snow season. Values of $\delta^{18}O$ varied between −22·0 and −9·5‰, and $\delta^{2}H$ varied between −170 and −76‰. Isotope concentrations from snowpack samples varied between −17·5 and −13·8‰ for $\delta^{18}O$, and between −129 and −102‰ for $\delta^{2}H$. These ranges reflect differences in precipitation, accumulation, sublimation, and melting of the snow cover. Streamflow samples were collected during the snowmelt season from two locations every alternate day from the beginning of April until the end of May. Streamflow and snow from a partial-cut and an uncut forest were enriched in the heavy isotopes (^{18}O and ^{2}H) relative to streamflow and snow from a clear-cut forest. Based on the low water contents of the snowpack under dense canopies, we infer that the isotope enrichment resulted primarily from sublimation of snow intercepted by the canopy, with more enrichment in denser canopies. There was no significant correlation between snowpack isotope concentration and altitude. Results indicate that variations in canopy structure can alter snow isotope composition. This finding will provide a useful index of snowpack sublimation, and thus, improved parameterization of distributed hydrological models.

Key Words snow hydrology; stable isotopes; spatial variability; snowmelt runoff; forest management practices

Introduction

Snowmelt is the primary contributor to runoff in snow-dominated systems, especially at high latitudes and elevations. Snow accounts for a large quantity of total precipitation (e.g. 50–90% in western US watersheds), and snow represents the largest water storage pool in the northwestern US—even larger than reservoirs (Mote *et al*., 2005). It is challenging to incorporate snowmelt processes into hydrological models because snow-cover dynamics are highly variable in space and time.

Stable isotopes (oxygen-18, ^{18}O and deuterium, ^{2}H) have been used extensively to study snow deposition and the subsequent alteration of snowpack characteristics. The solid phases of precipitation, snow and hail, do not undergo isotopic exchange with atmospheric water vapour as they fall; instead, they conserve the isotopic composition formed in the cloud (Gat, 1996). The process of snow formation shows a non-equilibrium effect that gives rise to precipitation with an elevated deuterium excess (DE) value (Gat, 1996). On the ground, the initial isotope signal of the snow layers may be modified by drifting, condensation of water vapour on the snowpack, deposition of rainwater, sublimation into the atmosphere, or partial melting and percolation of the melted water. Most commonly, metamorphism and the

subsequent melting of the snowpack reduces the initial isotopic variability in the snow cover (Cooper, 1998; Stichler and Schotterer, 2000).

These changes in isotopic variability are often studied using isotopic profiles in snow pits (Judy *et al*., 1970; Rodhe, 1987, 1998) or laboratory studies. Laboratory studies showed that initial snowmelt is depleted in heavier isotopes due to fractionation upon melting; the residual snow is thus enriched. As a consequence, when the residual snow melts, the water released is also enriched relative to the first water released (Arnason, 1969; Buason, 1972; Herrmann *et al*., 1981, Moser and Stichler, 1980; Stichler *et al*., 1981). Under field conditions, the difference between the isotope content of meltwater and mean snowpack also depends on the isotopic stratification of the snowpack. If the surface layer is enriched due to isotopically heavy snowfall in late winter, the meltwater may be enriched as compared to the mean snowpack. Across sites with a broad range of winter hydroclimatic regimes, snowmelt generally becomes progressively enriched in ^{18}O, with typical isotopic changes of 3–5% during a snowmelt event (Taylor *et al*., 2002). If the above changes are accounted for, it becomes possible to use stable isotope data to determine the snowmelt contribution to runoff in hydrograph separation studies (Cooper, 1998).

Hydrograph separations of spring snowmelt using isotopes have been carried out in many previous investigations (e.g. Dincer *et al*., 1970; Rodhe, 1987, 1998; Laudon *et al*., 2002, see Taylor *et al*. (2002) for a recent compilation). Various studies have recommended consideration of temporal variations of isotope concentrations in snowpack as tracer input in catchment studies (e.g. Laudon *et al*., 2002; Taylor *et al*., 2001, 2002; Unnikrishna *et al*., 2002). For hydrograph separations, the isotopic content of meltwater is needed as input, and therefore, it is recommended to directly measure the temporal trend of the isotope content of meltwater during the melting period. Meltwater can be sampled using snow lysimeters (Herrmann, 1978) if the devices are large enough to be unaffected by variability caused by the formation of preferential flow pathways in the snowpack and by canopy throughfall in forested areas.

Spatial variability of isotope concentrations in snow is generally not considered in the context of runoff separation and tracer-aided hydrological modelling at relatively small scales. Isotope concentrations in precipitation are generally correlated with altitude (Siegenthaler and Oeschger, 1980). Large-scale studies on origin and movement of moisture usually consider spatial isotopic distribution of the snowpack, e.g. in studies over Siberia (Kurita *et al*., 2005). Judy *et al*. (1970) recommended an evaluation of spatial variations in isotope content of a snow cover with large elevation differences before isotope variations can be applied to studies of snowmelt runoff. Carey and Quinton (2004) found random errors associated with spatial variability in snow isotope contents responsible for uncertainties in streamflow fraction separation when considering north- and south-facing slopes of sub-arctic catchments characterized by high sublimation rates.

In addition to variability in precipitation, spatial isotopic variability in snow layers can be caused by snow interception and subsequent sublimation from vegetation. Claassen and Downey (1995) measured and modelled evaporative enrichment of isotope concentrations in snow throughfall resulting from ablation of intercepted snow in evergreen forests. To our knowledge, no intensive study has been carried out addressing the extent of spatial isotope variability in snow cover of forested watersheds with considerable canopy structure variation.

The objectives of this study were to (i) quantify the isotope distribution of a snowpack in relation to differing canopy structures (e.g. clear-cut, partial-cut and fully forested sites), (ii) quantify the spatial variability and effect of altitude on the isotopic composition (^{18}O, ^{2}H) of a snow cover, and (iii) correlate the isotopic composition of the snowpack with that of spring runoff.

Study Site and Methods

The Mica Creek Experimental Watershed (MCEW) is located in northern Idaho, approximately 80 km northeast of Moscow, Idaho (47 10′N, 116 17′W, 975–1725 m a.s.l.). Mica Creek is a tributary of the St. Joe River and predominantly drains forested mountainous terrain. The watershed size is 97 km^2. It contains three small headwater research catchments with total area of about 10 km^2 (Figure 1). Hillslopes range from 20 to 40% and stream gradients range from 5–14%, approximately (Hubbart *et al*., 2007). The climate of the region is characterized by a mix of continental and maritime conditions. Mean annual precipitation and air temperature was approximately 1450 mm and 4·5 C respectively, calculated for the period from 1992 to 2006. Precipitation occurs mainly during the period from November through May, and approximately 70% of the precipitation occurs as snow (Hubbart *et al*., 2007).

The winter climate conditions of the MCEW are characterized by a continental/maritime climate regime common to inland northwestern regions. Winters in northern Idaho are typically long with moderate temperatures, though they are colder than the more maritime Cascade Mountains to the west. The continental/maritime winter climate regime is characterized by frequent interruptions of cold dry air masses (continental) by warm moist frontal systems (maritime) and subsequent warming. This often results in rain-on-snow events in lower elevations and in the transient snow zone; thus, winter snowmelt is not uncommon in this region (Haupt, 1972). In the MCEW, snow water equivalent (SWE) is spatially variable and the snow season typically spans at least 6 months from mid-November to early May. Daily minimum, maximum, and mean temperatures averaged over the months of December–February (the snow deposition period) were −5·6, 0·3, and −3·1 C, respectively. Daily minimum, maximum, and mean temperatures during the months of March–May (the snow

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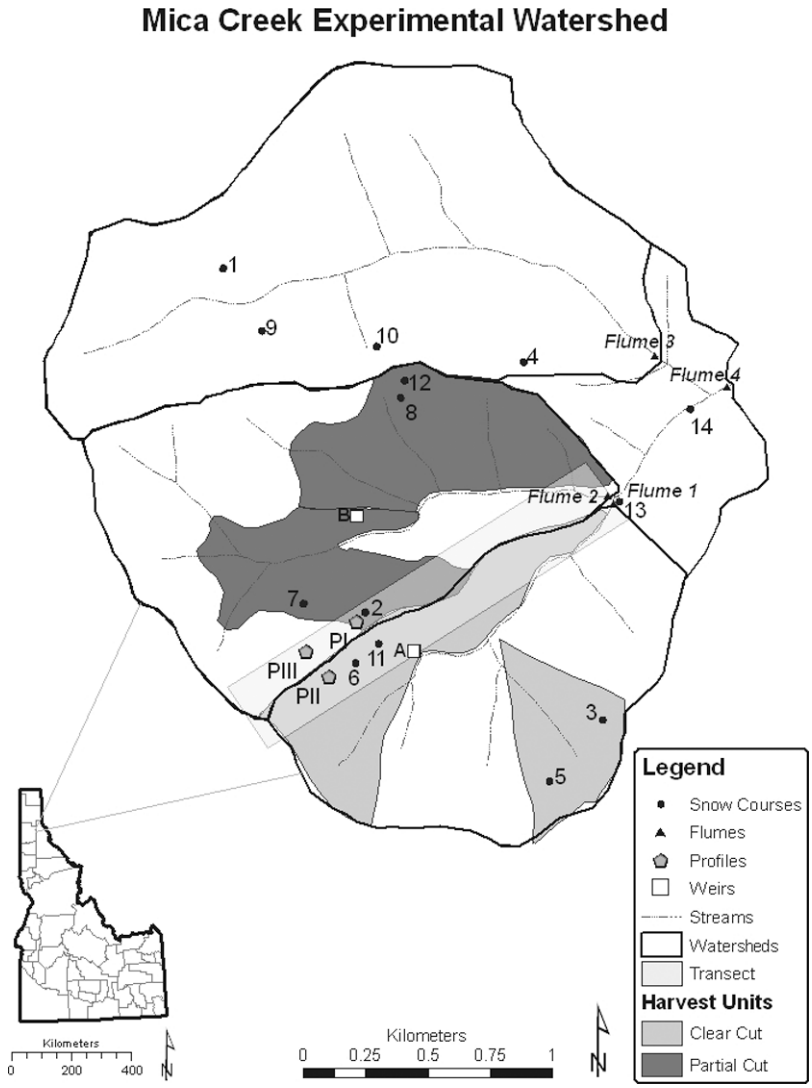

Figure 1. Location of the Mica Creek Experimental Watershed (MCEW) in northern Idaho (insert), forest treatments (clear-cut, partial-cut and control forest) and sampling sites: transect, snow profile (PI, PII and PIII), snow course (1–14), weirs (A, B) and flume sites (flume 1–4)

ablation period) were −0·7, 10·2, and 3·4 C, respectively. These means were estimated from 1990 to the present, using data from the Natural Resources Conservation Service (NRCS) Mica Creek Snow Telemetry SNOTEL (http://www.wcc.nrcs.usda.gov/snow/) site located within the MCEW at 1448 m a.s.l. Average peak SWE was 62 cm (±23 cm standard deviation, $n = 16$) on water year day 173 (22nd March) (±13 days standard deviation).

Radiation loading is assumed to be a major contributor to spatial variation of snowmelt processes as a result of slope and aspect in the MCEW. For example, as solar angle increases during snowmelt months (March–May), more direct solar radiation reaches slope facets that were either self- or terrain-shaded earlier during the snow deposition phase (November–February). Simultaneous warming of continental and maritime air masses during the melt season also increases the sensible heat flux, which in combination with increased incident solar radiation, results in increased melt and subsequent streamflow. Advected energy resulting from occasional rain-on-snow events may also contribute to snowmelt and streamflow during the melt phase.

Geology in the MCEW consists primarily of the metamorphic Prichard and Wallace Formations of the Belt Super group (Griggs, 1973). The dominant rock is the Wallace gneiss with some areas of Prichard quartzite. The primary soils are the Boulder Creek Series and the Marble Creek Series (USGS, 2003). Hillslope soil layers are approximately 1 m deep with a moderate (∼3 cm) humus layer. The first 50 cm is silt loam, with an average field capacity of approximately 0·33 $cm^3\ cm^{-3}$, and wilting point 0·13 $cm^3\ cm^{-3}$ of volumetric soil water content.

Vegetation on the site is dominated by 65- to 75-year-old naturally regenerated conifer stands. Remnant old-growth western red cedar (*Thuja plicata*) remains along the upper tributaries of the West Fork of Mica Creek. Current vegetation community status is the result of extensive logging that took place during the 1920s and 1930s. Since that time, there were no major anthropogenic disturbances in the watershed until 2001. Dominant overstory

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vegetation within the watershed includes western larch (*Larix occidentalis*), grand fir (*Abies grandis*), western red cedar (*Thuja plicata*), western white pine (*Pinus monticola*), western hemlock (*Tsuga heterophylla*), and Engelmann spruce (*Picea engelmannii*). Understory vegetation is largely comprised of grasses, forbs, and shrubs (Hubbart *et al*., 2007).

Forest management practices at the MCEW have produced substantial canopy variations across a set of three sub-catchments. Fifty percent of the area under catchment 1 was clear-cut with two harvest units on the north (∼23 ha) and southeast (∼43 ha) facing slopes. Fifty percent in catchment 2 was partially cut with approximately 50% canopy removal on the northeast (∼34 ha) and southeast (∼49 ha) facing slopes (Figure 1). These treatments have substantially changed the canopy structure, which we describe in terms of leaf area index (LAI).

Four gauge stations equipped with Parshall flumes designed to accommodate 50-year return interval flow events were installed in 1990 and 1991. Flume stations 1 and 2 monitor flows from the clear-cut and partial-cut catchments, respectively, while flume station 3 monitors streamflow from the untreated control catchment. Station 4 monitors the cumulative effects of treatments in catchments 1 through 3.

Samples of precipitation, snow cover and streamflow, were collected and analysed. Weekly precipitation volumes were collected in Moscow, ID (80 km southwest of the MCEW) to determine the seasonal trend of isotope concentrations in the region. Samples were collected using a sampling device consisting of a 15 l plastic container with plastic funnel and interior tubing to prevent evaporation (IAEA 2001).

Snow samples collected in the research catchments consisted of (i) detailed vertical profiles in each of the forest canopy structures, (ii) vertically integrated samples at snow courses spanning a range of aspects and canopy structures, and (iii) an elevational transect from the ridgetop to valley bottom (Figure 1). Vertical snow profile samples for isotope analyses were collected with a Snowmetrics volumetric snow sampler from the walls of a snow pit, which also enabled the quantification of SWE over 10 cm intervals (Colbeck *et al*., 1990). Snow temperature was measured with a dial stem thermometer at 10 cm increments in all profiles. Fourteen 20-m-long snow courses replicated by treatment, aspect, and stratified by elevation were sampled every 2 m for snow depth and density and provided a vertically integrated core sample for subsequent isotope analyses. Snow courses were sampled using a Federal snow sampling tube to obtain incremental snow core samples. LAI was measured early in spring at the 14 snow courses to provide an indication of canopy structure. LAI values were determined from canopy light transmission using an AccuPAR ceptometer (Model PAR-80, Decagon Instruments). An extinction coefficient of 0·52 was assumed, which is typical of forests of this species composition in this region (Duursma *et al*., 2003). The elevational transect-sampling (Figure 1) included snow cores sampled from the top to the bottom of the watershed. These samples were collected at least 50 m from the canopy edges to avoid edge effects.

Field sampling was carried out on four separate days: 19 February (3 profiles and 14 snow courses), 23 March (3 profiles, 14 snow courses and transect-sampling), 6 April (3 profiles, 14 snow courses and transect-sampling) and 20 April, 2006 (14 snow courses and transect-sampling) (indicated in Figure 2, vertical lines). All snow samples were sealed and stored in plastic bags (ZipLoc), melted at room temperature, weighed, and stored in sealed glass bottles for subsequent isotope analyses.

Streamflow samples originating from the clear-cut site (weir A) and partial-cut site (weir B) were collected every 48 h from 30 March until 31 May using automated water samplers (Teledyne ISCO). All sample bottles were spiked with mineral oil prior to sampling to prevent evaporation. Additionally, grab samples of streamflow were collected monthly at flume sites 1–4.

All isotope analyses were conducted at the Idaho Stable Isotope Laboratory (ISIL), located at the University of Idaho, Moscow. For ^{18}O a headspace-equilibration technique was used (26 C for 20 h with a GasBench II). The equilibrated CO_2 was transferred by continuous flow technique into a Finnigan Delta XP IRMS. Deuterium was measured using a Finnigan H-Device (chromium reduction at 900 C) connected to a Finnigan Delta Plus in dual inlet mode. All isotope concentrations were expressed as δ-values in ‰ against the international standard V-SMOW. Precision of $\delta^{18}O$ and $\delta^{2}H$ analyses was approximately 0·2 and 1‰ respectively.

Results

The winter season of 2005–2006 was characterized by the precipitation, snow depth, temperature, and streamflow conditions shown in Figure 2. During the period from 1 November 2005 to 31 May 2006, a precipitation total of 1034 mm was recorded. This total is approximately 7% below the 15-year average for the same time period (Nov 1–May 31) of approximately 1119 mm. Snow depth and SWE derived from snow core measurements during the four sampling dates are summarized in Table I. Mean snow depths derived from snow core sampling in the catchment were about 50 cm less than those observed at the Mica Creek SNOTEL site. Mean values of SWE observed in the catchment varied between 17 and 33 cm (maxima between 25 and 61 cm, minima between 1 and 18 cm), reflecting a high degree of variability within the catchment. For the period of the current study (i.e. water year 2006), daily minimum, maximum, and mean temperatures for the snow deposition and ablation periods were −4·9, 0·0, −2·5, and 0·6, 10·5, and 4·2 C, respectively. Streamflow increased slightly in response to temperature increases in mid-December and at the end of February. The largest streamflow occurred during the seasonal period of snowmelt, which began in mid-March and was complete in early May (Figure 2 lower panel).

$\delta^{18}O$ of precipitation was observed on a weekly basis in Moscow, Idaho, and compared to long-term mean

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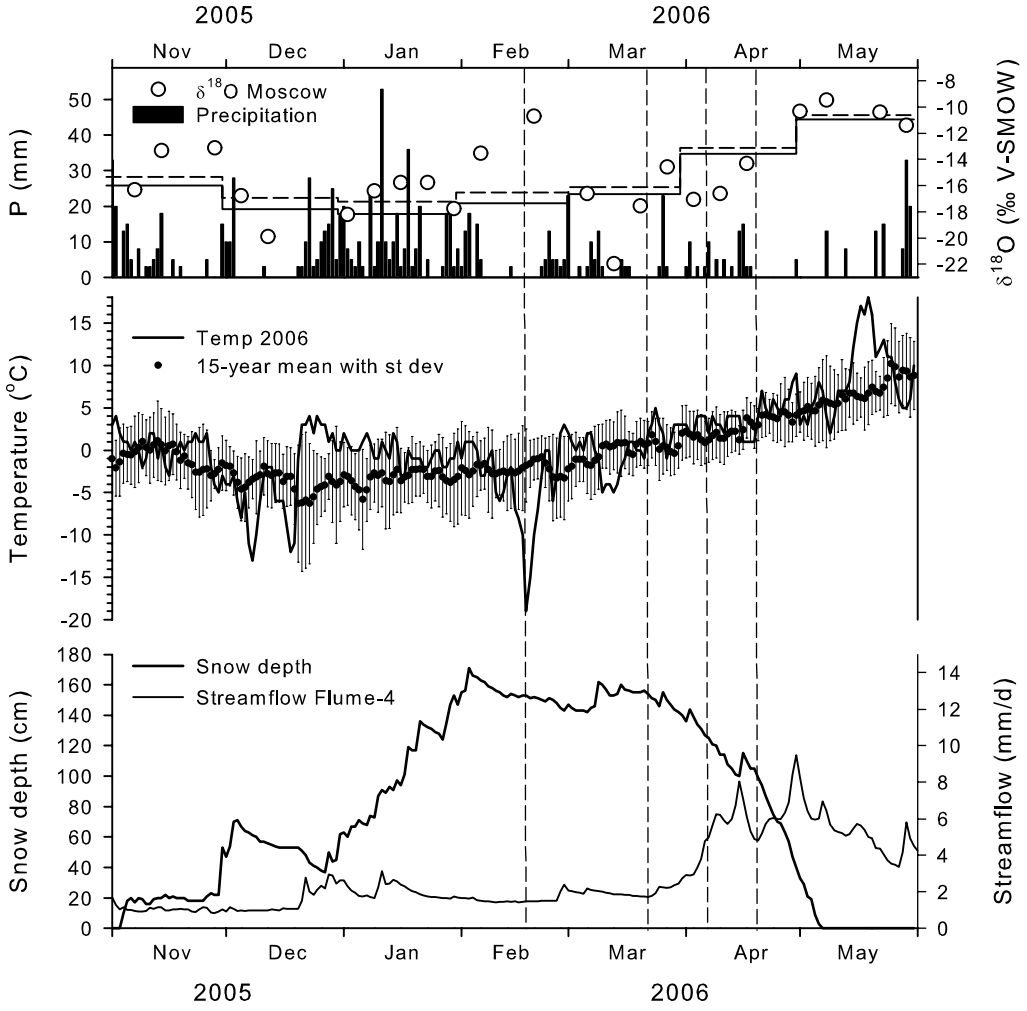

Figure 2. Upper graph: daily precipitation (black bars), weekly $\delta^{18}O$ values of precipitation measured in Moscow (grey circles), mean monthly $\delta^{18}O$ values of precipitation calculated after www.waterisotopes.org for Moscow mountain (dashed line) and Mica Creek (solid line); middle graph: air temperature (line) for 1 October 2005 until 31 May 2006 and long-term mean temperature (dots) (1991–2004) with standard deviation (bars); lower graph: snow depth (thick line) and streamflow at flume-4 (thin line) at MCEW

Table I. Mean snow depth, and mean, maximum, and minimum snow water equivalent (SWE) for snow courses and transects collected during HY 2006 at the Mica Creek experimental Watershed

Date		Number of samples	Snow depth (cm)	SWE mean ± SD (cm)	max SWE (cm)	min SWE (cm)
19 Feb 2006	Snow course*	14	114	30 ± 11	54	18
23 Mar 2006	Snow course*	14	98	33 ± 13	61	17
	Transect	24	80	20 ± 3	25	12
7 Apr 2006	Snow course*	14	72	26 ± 15	56	8
	Transect	19	76	23 ± 12	40	3
20 Apr 2006	Snow course*	14	53	20 ± 16	55	1
	Transect	19	51	17 ± 10	43	4

* Snow course WE was collected every 2 m over a 20-m snow course ($n = 10$ for each snow course).

monthly values calculated after Bowen and Revenaugh (2003) (www.waterisotopes.org) for Moscow mountain (1433 m a.s.l.) and the Mica Creek SNOTEL site (1448 m a.s.l.) (Figure 2). The mean monthly values differ by about 0·5‰. They follow a seasonal trend with depleted values during the winter months and more enriched values during the summer months (data not shown). The weekly values, which were not weighted by precipitation amount, indicate greater variability than the monthly mean values derived from Bowen and Revenaugh (2003) (www.waterisotopes.org).

Figure 3 shows the $\delta^{18}O$ and SWE of three snow profiles plotted against snow depth measured on 19 February 2006, 23 March 2006, and 7 April 2006 at the clear-cut, partial-cut and control forest sites. The arrows in Figure 3 represent the mean isotope concentrations

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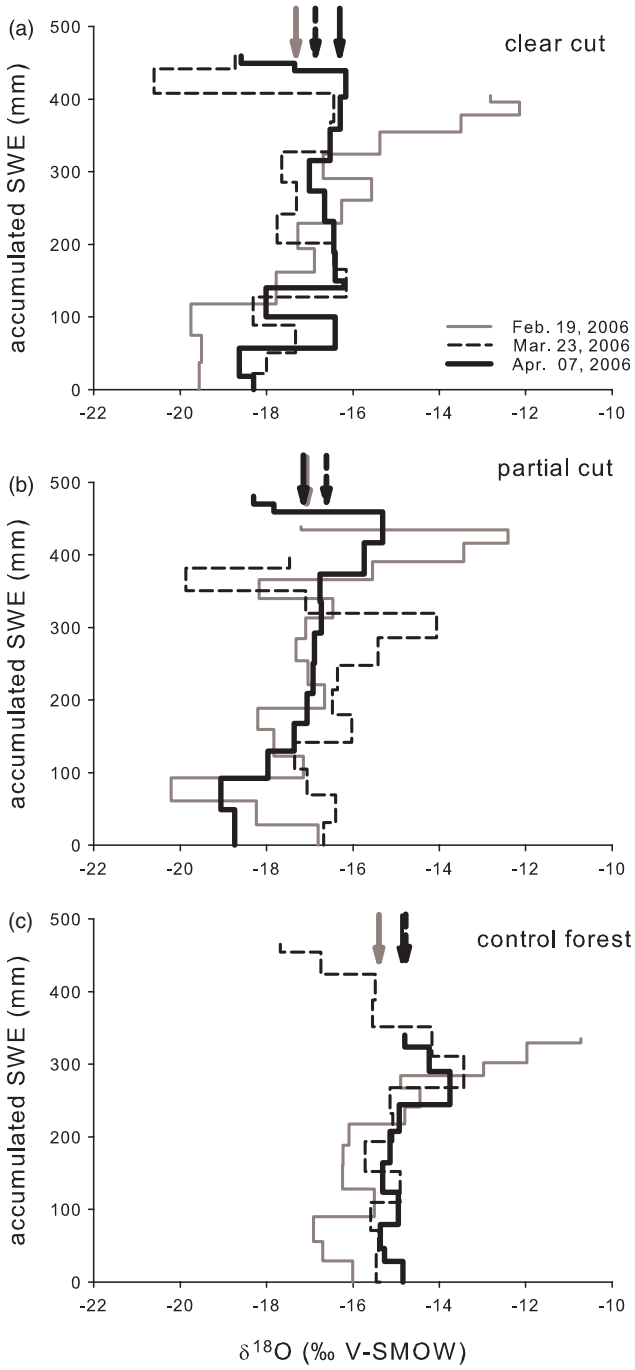

Figure 3. Accumulated snow water equivalent (SWE) versus δ^{18}O values of snow samples for snow profiles collected at clear-cut, partial-cut, and control sites during the winter seasons. Arrows indicate mean isotope values of the profiles for time-steps indicated in Figure 2

calculated by weighting the concentration of each horizon with the appropriate measured SWE of each horizon.

The snowpack varied considerably among treatments. Both, the depth and SWEs were lowest at the control site, and progressively greater at the partial-cut and clear-cut sites (Hubbart, 2007). Snow profile temperatures varied between −12 and 0 C at an air temperature of −8 C and a soil temperature of +1 C during the first sampling date (19 February 2006), and became isothermal at 0 C thereafter (snow temperature data not shown). The snow surface was enriched in ^{18}O at the first sampling date. Subsequent depleted values at the second sampling date reflect the isotope concentrations of recent precipitation (Figure 2). The isotope concentrations within the snow profiles varied between −21 and −11‰ (Figure 3(a)–(c)) and plotted within a similar range as the previous precipitation. Mean isotope values observed for the profiles at the clear-cut site as well as for the partial-cut site were between −17·5 and −16‰, whereas the values for the control forest were more enriched, between −15·5 and −14·5‰.

δ^{18}O versus δ^{2}H values of integrated snow samples collected at the snow courses are plotted in Figure 4(a) in comparison to the global and local meteoric water lines. In Figure 4(b) and (c) δ^{18}O values of integrated snow samples collected at the snow courses and over the elevational transect (1200–1500 m a.s.l.) are plotted against elevation. In Figure 4(d), (e) and (f) the correlation of δ^{18}O, δ^{2}H and DE to LAI at the snow course locations are shown. Correlations range from 0·33 to 0·77 for ^{18}O and from 0·41 to 0·82 for ^{2}H, respectively, over the four sampling dates.

The δ^{18}O values of the monthly streamflow samples for the streams draining the clear-cut, partial-cut, control, and cumulative catchments (1–4, respectively) are plotted in Figure 5(a). The values generally decrease from February to May in response to the melting of more depleted winter precipitation. Streamflow at flumes 3 and 2 show more enriched values than flume 1, except in May. δ^{18}O values of streamflow samples collected from weirs below the clear-cut (A) and partial-cut (B) are shown in Figure 5(b). The δ^{18}O values of water samples collected from the partial-cut weir were in general about 0·5‰ more enriched in comparison to the ones collected at the clear-cut weir.

Weighted mean δ^{18}O values were calculated for each of the snow profiles. Values of SWE were determined for each horizontal layer and multiplied by the appropriate isotopic concentrations; these products were integrated over the entire snowpack profile and divided by the total SWE of the snow profile (Unnikrishna *et al.*, 2002). Weighted mean values from the different snow profiles (Figure 3 vertical arrows) indicate successive isotopic enrichment over the three sampling dates. This enrichment is obvious for the clear-cut and control site, but not as evident for the partial-cut site where the integral value for the profile from 7th April again shows a more depleted value. The control site is consistently more enriched in ^{18}O in comparison to the partial-cut and clear-cut sites. These results agree with the vertically integrated samples collected at the snow courses and elevational transects. Means, standard deviations and ranges of the values at each sampling date are plotted against precipitation and streamflow in Figure 6.

Discussion

Results of this research indicate modification of the isotope content of snow cover as a function of canopy structure. These effects were translated into the isotopic

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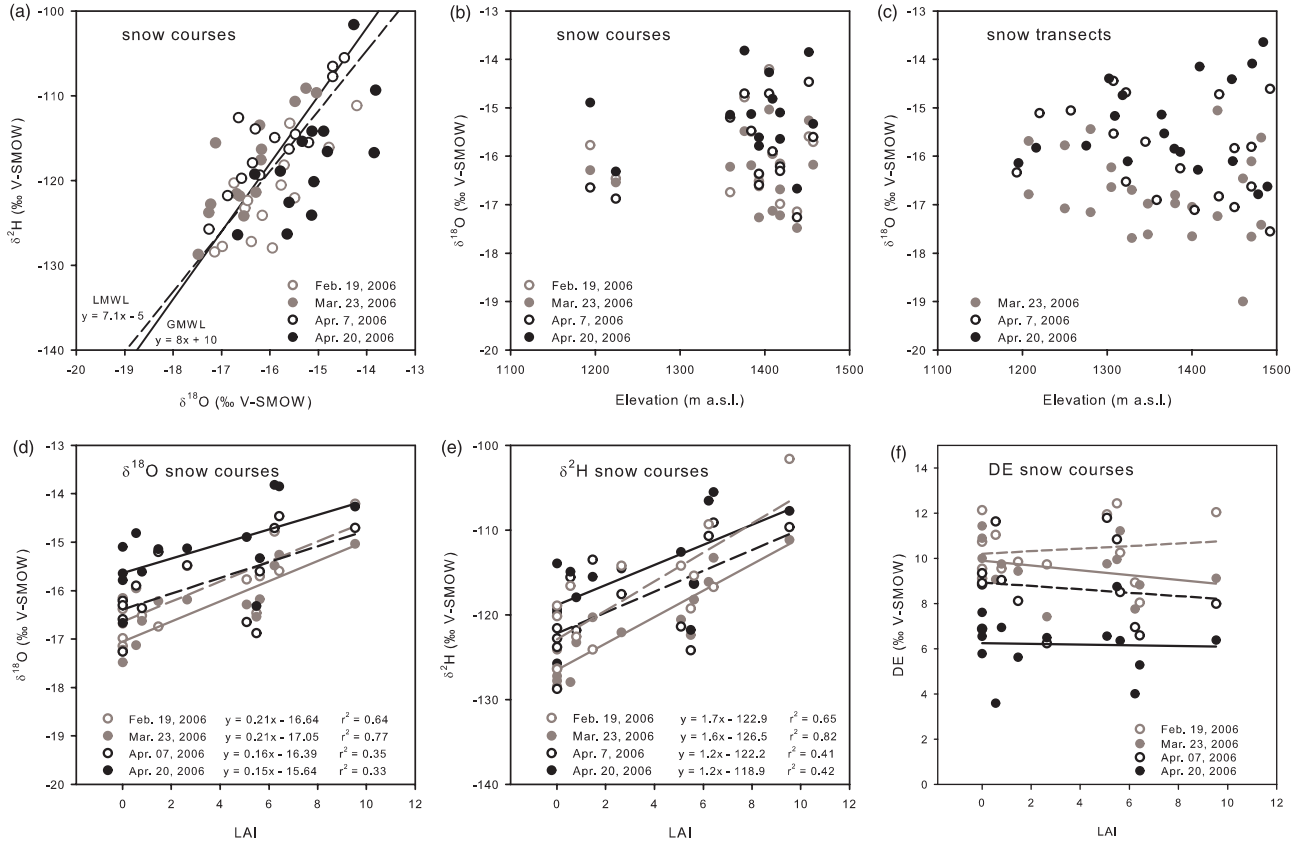

Figure 4. $\delta^{18}O$ versus $\delta^{2}H$ of snow course samples (a), correlations of $\delta^{18}O$ with altitude for snow courses (b) and snow transects (c), and correlation of $\delta^{18}O$ (d), $\delta^{2}H$ (e) and deuterium excess (f) with LAI for the snow course samples

composition of the streamflow draining the research catchments. In the snow and stream water, the heavy isotopes of oxygen and hydrogen (^{18}O and ^{2}H) were progressively enriched as canopy density increased.

Streamflow isotopic enrichment was similar to the isotopic composition of the vertically integrated snow samples. Monthly grab samples from flumes 1, 2, and 3 showed this expected tendency, but the response was somewhat damped in relation to the variation in the snowpack, probably because only half of each of the watersheds above the flumes had undergone canopy alteration. $\delta^{18}O$ values of streamflow from grab samples taken in February, March and April reflect the variation in the snowpacks among the treatments. Samples taken in May show lower isotopic variation, which may have been caused by a combination of rainfall, condensation inputs, and by a difference in the timing of snowmelt (Figure 5(a)).

Differences in flow paths or residence time distributions among the watersheds could potentially give rise to the observed isotopic differences. However, the drainage areas of the forest treatments are so small, similar, and steep that differences in flow paths or residence time distributions are not likely to explain the observed isotope differences in streamflow. Moreover, high-density sampling during the peak of snowmelt (Figure 5(b)) indicated relatively stable trends in streamflow isotopic composition. There is little direct information on groundwater dynamics in the watersheds because bedrock is relatively shallow (1–2 m), and monitoring wells were difficult to install in the remote, mountainous study site. A set of piezometers installed near the drainages in one of the clear-cut watersheds was unable to detect an elevated water table above the bedrock during the peak of snowmelt (Brooks and Boll, personal communication), suggesting that the flow paths may be rapid and short. Future studies on behaviour and residence times of base flow should provide additional insights on this topic.

A study of this type raises questions about the detectability of isotope concentration differences. The precision of $\delta^{18}O$ isotope measurements are usually better than 0·2‰ on a long-term scale, and better than 0·1‰ within single sequence runs. The snow and streamflow data presented in Figure 5 are mean values calculated from several samples. A signal of 0·5‰ is therefore large enough to interpret. It would, however, be valuable for future studies to verify these results during the winter season in other catchments.

No correlation was observed between $\delta^{18}O$ in snow samples and elevation in the MCEW. An altitude effect of 0·2‰/100 m for precipitation in the Alps (Siegenthaler and Oeschger, 1980) was not observed in this catchment largely because the catchment is located on the leeward side of a ridge, and snowfall likely occurred out of the same clouds after they passed over the main ridge at the highest elevation. Similar results were found in other studies. Gurney and Lawrence (2004) found no differences for samples collected between 740 and 970 m

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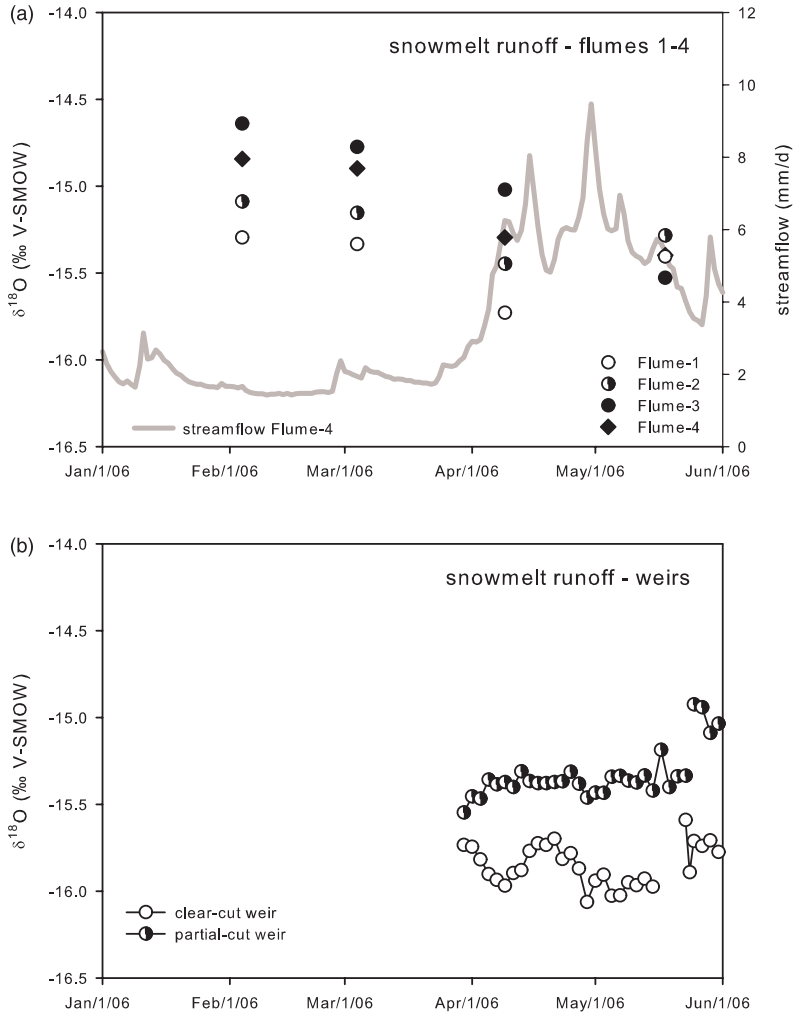

Figure 5. $\delta^{18}O$ of streamflow at (a) flume sites 1–4 and (b) at the clear-cut and partial-cut weir during snowmelt for samples collected every second day during the melting period (1 April 2006–31 May 2006). In (a) streamflow data measured at flume-4 is plotted on the right axis (grey line)

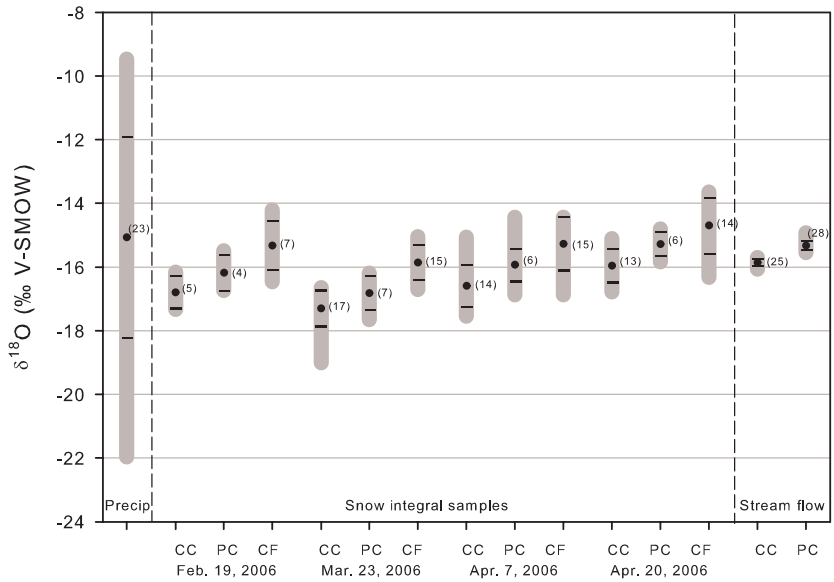

Figure 6. Mean values (dots) with number of samples in brackets, standard deviation (horizontal marks) and range (grey bars) of isotope concentrations measured in the vertically integrated snow samples at a clear-cut site (CC), partial-cut site (PC), and control forest site (CF), and precipitation (7 November 2005–31 May 2006) and streamflow (30 March 2006–31 May 2006) during WY 2006

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a.s.l. in a sub-arctic, mountainous, but non-glaciated, catchment in northern Norway. Mast *et al*. (1995) found no correlation of $\delta^{18}O$ with elevation, snow depth, or water content of snow samples at 15 snow cores in an alpine watershed in Colorado, USA.

The cause of the observed isotopic enrichment in denser forest canopies is likely to be higher sublimation rates due to greater, longer-term exposure of canopy-intercepted snow loads to atmospheric drying. Claassen and Downey (1995) measured winter throughfall in evergreens in the Snowshoe Mountains, Colorado, that was enriched on the order of 2·1 and 13‰ for $\delta^{18}O$ and $\delta^{2}H$ respectively, relative to precipitation. We were unable to estimate a change of isotope values due to this process, because we did not attempt to collect drip water or meltwater (e.g. with lysimeters) during this study. However, $\delta^{18}O$ enrichment at the control site versus the clear-cut site was in the order of 2‰ (Figure 6). This is similar to the findings of Claassen and Downey (1995). It seems likely that the isotope enrichment was caused by sublimation in the tree crowns and, if sublimation were occurring at such high rates, it seems reasonable that it would enrich the heavy isotopes in the residual snowpack, as observed here. This point is supported by observations of peak SWE (Figure 3) and streamflows from the experimental areas. Peak SWE averages from 4 snow courses in the clear-cut, partial-cut and control forest were 43, 33, and 24 cm, respectively (Hubbart *et al*., 2007). Average streamflows during the melt season, defined as the period from March through June, increased from the clear-cut and partial-cut catchments by 35 and 22%, respectively, as a result of canopy removal (Hubbart *et al*., 2007). These results of experimental manipulations further support the assertion that the observed isotope concentration differences are due to differences in snow sublimation.

Conclusions

Stable isotope enrichment in the snow cover was correlated with increasing canopy density across catchments characterized by a range of canopy densities resulting from contemporary forest harvest practices. No significant correlation of isotope concentration was found with altitude. We found significantly enriched isotope values both in vertically integrated snow profiles and in streamflow samples in a partial-cut and an untreated control site. Snowmelt is the main input to the soil water reservoir, the main source of transpired water from the vegetation, and the main source of base flow in this catchment. Snow isotopic composition can provide a useful parameter to improve snowmelt hydrograph separations and to assess snowpack ablation under varying forest management and climate scenarios.

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References

Arnason B. 1969. The exchange of hydrogen isotopes between ice and water in temperate glaciers. *Earth and Planetary Science Letters* **6**: 423–430.

Bowen GJ, Revenaugh J. 2003. Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research* **39**(10): 1299, DOI:10·129/2003WR002086.

Buason T. 1972. Evaluations of isotope fractionation between ice and water in a melting snow column with continuous rain and percolation. *Journal of Glaciology* **11**: 387–405.

Carey SK, Quinton WL. 2004. Evaluating snowmelt runoff generation in a discontinuous permafrost catchment using stable isotope, hydrochemical and hydrometric data. *Nordic Hydrology* **35**(4): 309–324.

Claassen HC, Downey JS. 1995. A model for deuterium and oxygen isotope changes during evergreen interception of snowfall. *Water Resources Research* **31**(3): 601–618.

Cooper LW. 1998. Isotopic fractionation in snow cover. In *Isotope Tracers in Catchment Hydrology*, Kendall C, McDonnell JJ (eds). Elsevier: Amsterdam; 119–136.

Colbeck S, Akitaya E, Armstrong R, Gubler H, Lafeuille J, Lied K, McClung D, Morris E. 1990. The international classification for seasonal snow on the ground. *The International Commission on Snow and Ice of the International Association of Scientific Hydrology, World Data Center A for Glaciology*. University of Colorado: Boulder, CO.

Dincer T, Payne BR, Florkowski T, Marinec J, Tongiorgi T. 1970. Snowmelt runoff from measurements of tritium and oxygen-18. *Water Resources Research* **6**: 110–118.

Duursma RA, Marshall JD, Robinson AP. 2003. Leaf area index inferred from solar beam transmission in mixed conifer forests on complex terrain. *Agricultural Meteorology* **118**: 221–236.

Gat JR. 1996. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences* **24**: 225–262.

Griggs AB. 1973. Geologic map of the Spokane quadrangle, Washington, Idaho, and Montana. MAP I-768. USGS Misc. Geologic Investigations.

Gurney SD, Lawrence DSL. 2004. Seasonal trends in the stable isotopic composition of snow and meltwater runoff in a subarctic catchment at Okstindan, Norway. *Nordic Hydrology* **35**(2): 119–137.

Haupt HF. 1972. The release of water from forest snow packs during winter. USDA Forest Service Research Paper INT-114, Intermountain Forest and Range Experiment Station, Ogden, Utah.

Herrmann A. 1978. A recording snow lysimeter. *Journal of Glaciology* **82**(20): 209–231.

Herrmann A, Lehrer M, Stichler W. 1981. Isotope input into runoff systems from melting snow covers. *Nordic Hydrology* **12**: 309–318.

Hubbart JA. 2007. Measuring and modeling hydrologic responses to timber harvest in a continental/maritime mountainous environment, PhD thesis, Department of Forest Resources, University of Idaho, Moscow; 156.

Hubbart JA, Link TE, Gravelle JA, Elliot WJ. 2007. Timber harvest impacts on hydrologic yield in the continental/maritime hydroclimatic region of the United States. *Forest Science* **53**(2): 169–180.

Judy C, Meiman JR, Friedman I. 1970. Deuterium variations in an annual snowpack. *Water Resources Research* **6**: 125–129.

Kurita N, Sugimoto A, Fujii Y, Fukazawa T, Makarov V, Watanabe O, Ichiyanagi K, Numaguti A, Yoshida N. 2005. Isotopic composition and origin of snow over Siberia. *Journal of Geophysical Research* **110**: Doi: 10·1029/2004JD005053.

Laudon H, Hemond HF, Krouse R, Bishop KH. 2002. Oxygen-18 fractionation during snowmelt: implications for spring flood hydrograph

separation. *Water Resources Research* **38**(11): 1258–1267. DOI:10·1029/2002WR001510, 2002.

Mast MA, Kendall C, Campbell DH, Clow DW, Back J. 1995. Determination of hydrologic pathways in an alpine-subalpine basin using isotopic and chemical tracers, Loch Vale Watershed, Colorado, USA. *Biogeochemistry of Seasonally Snow-covered Catchments. Proceedings of a Boulder Symposium*. Publication 228, International Association of Hydrological Sciences, Wallingford; 263–270.

Moser H, Stichler W. 1980. Environmental isotopes in ice and snow. In *Handbook of Environmental Isotope Geochemistry*, Vol. 1, Fritz P, Fontes JC (eds). Elsevier: Amsterdam; 141–178.

Mote PW, Hamlet AF, Clark MP, Lettenmaier DP. 2005. Declining mountain snowpack in Western North America. *Bulletin of the American Meteorological Society* **86**(1): 39–49, DOI: 10·1175/BAMS-86-1-39.

Rodhe A. 1987. The origin of stream water traced by oxygen-18, Diss. Dept. Earth Sci., Hydrol., Uppsala Univ., Uppsala, Sweden, 333.

Rodhe A. 1998. Snowmelt-dominated systems. In *Isotopes in Catchment Hydrology*, Kendall C, Mc Donnell JJ (eds). Elsevier: Amsterdam; 391–434.

Siegenthaler U, Oeschger H. 1980. Correlation of $\delta\ ^{18}O$ in precipitation with temperature and altitude. *Nature* **285**: 314–316.

Stichler W, Schotterer U. 2000. From accumulation to discharge: modification of stable isotopes during glacial and post-glacial processes. *Hydrological Processes* **14**: 1423–1438.

Stichler W, Rauert W, Martinec J. 1981. Environmental isotope studies of an alpine snowpack. *Nordic Hydrology* **12**: 297–308.

Taylor S, Feng X, Williams M, McNamara J. 2002. How isotopic fractionation of snowmelt affects hydrograph separation. *Hydrological Processes* **16**: 3683–3690.

Taylor S, Feng X, Kirchner JW, Osterhuber R, Klaue B, Renshaw CE. 2001. Isotopic evolution of a seasonal snowpack and its melt. *Water Resources Research* **37**(3): 759–769.

Unnikrishna PV, McDonnell JJ, Kendall C. 2002. Isotope variations in a Sierrra Nevada snowpack and their relation to meltwater. *Journal of Hydrology* **260**: 38–57.

USGS. 2003. United States Geological Survey, Soil Conservation Service. Soil Survey Geographic (SSURGO) database for St. Joe Area, Idaho, Parts of Benewah and Shoshone Counties, Idaho.