Stable Water Isotope (O and H) Evolution of a Boreal Snowpack

KRYSTOPHER J. CHUTKO,[1] APRIL JAMES,[1] AND BRITTANY RUNDLE[1]

EXTENDED ABSTRACT

Keywords: stable water isotopes, snowpack, snowmelt.

BACKGROUND

Stable water isotopes are used in a variety of hydrograph separation and mixing analysis techniques (Klaus and McDonnell, 2013). In regions of seasonal snowcover, snowmelt can be a significant source of water influx, typically associated with a spring freshet, and is therefore an important potential component of two-or-more component mixing analyses. Defining the isotopic signature of snowmelt and its contribution to streamflow continues to be a challenge. The spatial and temporal heterogeneity of snowcover is well documented, as is the variability of the isotopic signature of the snowpack. To define the isotopic signature of the snowmelt contribution to surface waters, several studies have relied on snow cores or other means of bulk snow sampling (e.g. Rhode, 1981; Bottomley *et al*., 1986; St. Amour *et al*., 2005; Turner *et al*., 2010). However, many studies have identified a disconnect between the signatures of the snowpack *vs*. the snowmelt (i.e. the water leaving the snowpack) (e.g. Taylor *et al*., 2001; Laudon *et al*., 2002; Unnikrishna *et al*., 2002), suggesting that bulk snowpack signatures are inadequate inputs to hydrograph separation techniques or hydrological models. The objective of this study is to more accurately determine the isotopic signature of the snowmelt end-member for use in various hydrological modelling techniques, as well as to assess the isotopic evolution of the snowpack in a relatively typical Canadian Shield environment. This analysis will examine both the intra- and interannual variability of snowpack and snowmelt isotopic signatures.

STUDY SITE & METHODS

Snow courses were established in 2013 and 2014 at three sites in an approximately 100 km radius around North Bay, Ontario, Canada, from which bulk snowpack cores were collected biweekly from January through April (8 samples each) for snow water equivalence (SWE) and stable water isotopes (SWI). In 2014, a snowpit array, snow course, and snow board for more detailed study was established near the centre of this area on the Nipissing University campus, along with an Onset HOBO weather station, precipitation samplers, and snowmelt lysimeters. Sampling started on 7-January and continued through 22-April, when all snow at the site was melted. There was a total of 32 sampling days at the central site; samples were collected by a group of student volunteers. For all sites, bulk snowcore SWE is presented as an average of 10 snowcores extracted vertically along a 100 m transect, while bulk snowcore SWI is derived from a single representative snowcore taken along the transect. Snowpits were dug in undisturbed snow

[1] Department of Geography, Nipissing University, 100 College Dr., North Bay, ON, P2A 8L7, Canada

and SWE and SWI samples were extracted with a horizontal sampler at 10 cm depth intervals; SWE and SWI are presented as averages of two or more samples per depth interval. Snow samples from all sources were melted slowly at 5 °C and sub-sampled for SWI analysis, performed in the Watershed Analysis Centre, Nipissing University. Analytical precision and accuracy was better than 0.14‰ and 0.13‰ for $\delta^{18}O$ and 0.72‰ and 0.68‰ for $\delta^{2}H$, respectively.

SNOWPACK EVOLUTION

In 2014, 178 isotope samples were recovered from snowpits across 32 sampling dates. $\delta^{2}H$ and $\delta^{18}O$ ranged from -95.34 to -211.39‰ and -14.42 to -28.22‰, respectively (Fig. 1). The lightest (most negative) samples correspond with surface snow recovered after snowfall during the coldest periods of winter, while the heaviest (least negative) samples correspond to precipitation (rain and snow) inputs during warm weather. Brief periods of surface melt followed by refreezing (13-January (day 13) and 22-February (day 53)) resulted in two distinct ice layers forming at ~35 cm and ~55 cm depth, respectively. These layers were isotopically heavier than layers above and below, corresponding to the melting and refreezing process. Relatively warm basal conditions (-5 to 0 °C) throughout the winter promoted minor melting and a concentration of heavier meltwater above the frozen ground surface. Rising air and snowpack temperatures in late-March/early-April (approximately day 79 onwards) promoted isothermal conditions followed by isotopic homogenization, a result of snowpack metamorphism processes, snowmelt infiltration, and rainfall (Unnikrishna *et al*., 2002). In general, the entire snowpack became isotopically heavy during the snowmelt, potentially due to a loss of lighter isotopes through evaporation and transport.

Positive air temperatures driving snowmelt out of the snowpack occurred during two brief periods during the 2014 winter (mid-January and late-February), but primarily during the spring melt. Meltwater samples collected during these melt periods show a depletion of heavy isotopes ($\delta^{18}O$ and $\delta^{2}H$ become more negative) through time (seasonally, Fig. 2). However, overall, the snowmelt isotopic signature ranged from -12 to -20‰ while the snowpack signature ranged from -17 to -23‰. This difference is important when considering which signature to use in hydrograph separation techniques and hydrologic models.

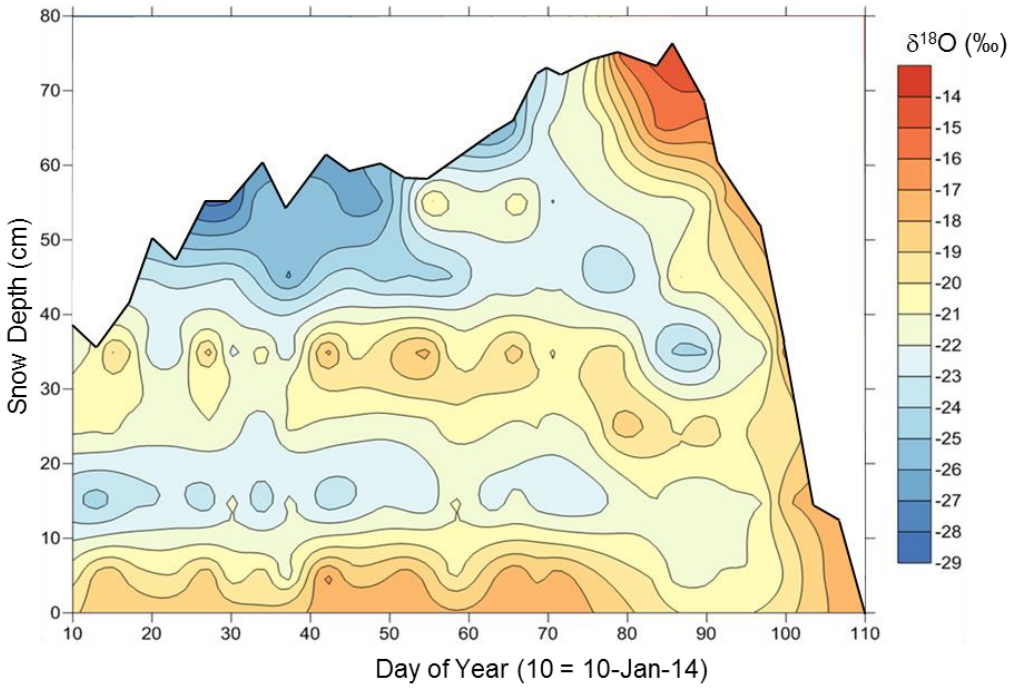

Figure 1. Interpolated snowpit $\delta^{18}O$ from 10-January to 22-April.

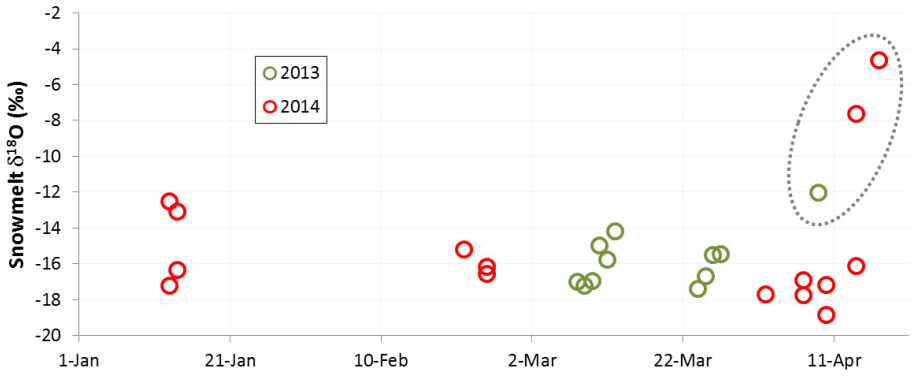

Figure 2. $\delta^{18}O$ of snowmelt collected in snowmelt lysimeters, 2013 and 2014. Samples within the dashed ellipse reflect melt season rainfall events which were partially mixed with snowmelt.

BULK SNOWCORES *VS.* SNOWPIT

Concurrent bulk snowpack and snowpit measurements of depth, SWE, and SWI were used to assess the difference between these techniques in estimating a mean snowpack SWI signature. In 2014, a total of 32 pairs of snowcore transects and snowpits were compared, up to and including patchy snow conditions just prior to complete snow loss. In the snowpits, individual layer $\delta^{18}O$ was weighted with the corresponding layer SWE to produce a SWE-weighted bulk $\delta^{18}O$ value to compare directly with the depth-integrated snow course $\delta^{18}O$ values (Fig. 3). The relationship between bulk snowcore and stratigraphic snowpit measures falls close to a 1:1 correspondence for both SWE and SWI suggesting that little accuracy was gained from the more labour-intensive snowpit method of sampling. However, observations of liquid water draining from the bulk snowpack sampling tube during late season sampling suggest that this relationship may be more tenuous during the peak melt period. The horizontal sampling technique used in the snowpits did not result in the same "leaking" effect.

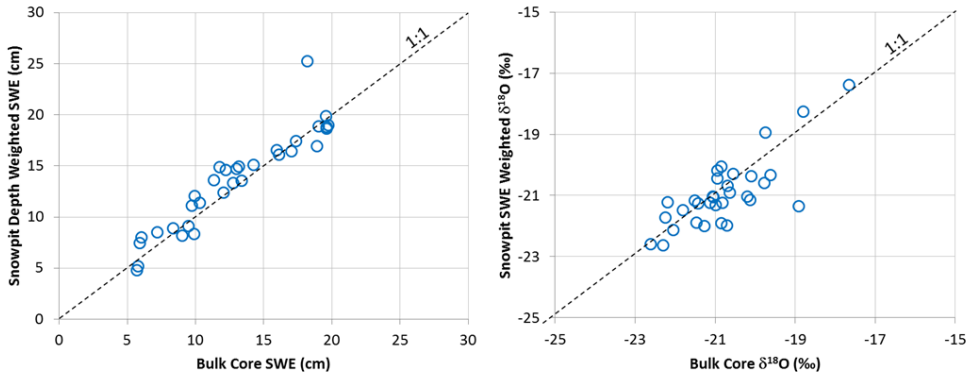

Figure 3. Comparison between bulk snowpack sampling and stratigraphic snowpit sampling techniques for determining SWE and SWI.

INTERANNUAL VARIABILITY: SNOWPACK AND SNOWMELT

Snowpack conditions varied between 2013 and 2014. At the four snowcourse transects, maximum snow depth was 62.2 cm and 86.9 cm and maximum SWE was 14.4 cm and 20.9 cm for 2013 and 2014, respectively (Fig. 4). The isotopic signature of the bulk snowpack was

significantly different ($p < 0.001$) between years, with average $\delta^{18}O$ values of -17.2‰ and -20.8‰ in 2013 and 2014, respectively. A likely explanation of the large difference in isotopic signature between years is the difference in observed weather conditions. Average JFM air temperature in North Bay during 2013 was -6.7 °C while it was -11.1 °C in 2014. Colder air temperatures lead to stronger fractionation rates of water isotopes, with colder temperatures resulting in lighter (i.e. more negative) ratios. Despite the significant difference in bulk snowpack isotopic signature, snowmelt isotopic signature was not different. Snowmelt lysimeter samples recorded average signatures of -15.8‰ and -16.3‰, respectively (Fig. 2). While it was expected that snowmelt would release water of a heavier signature than that of the snowpack (due to the typical fractionation process), the fact that the snowmelt signatures were similar in both years, despite significantly different snowpack signatures, remains unexplained.

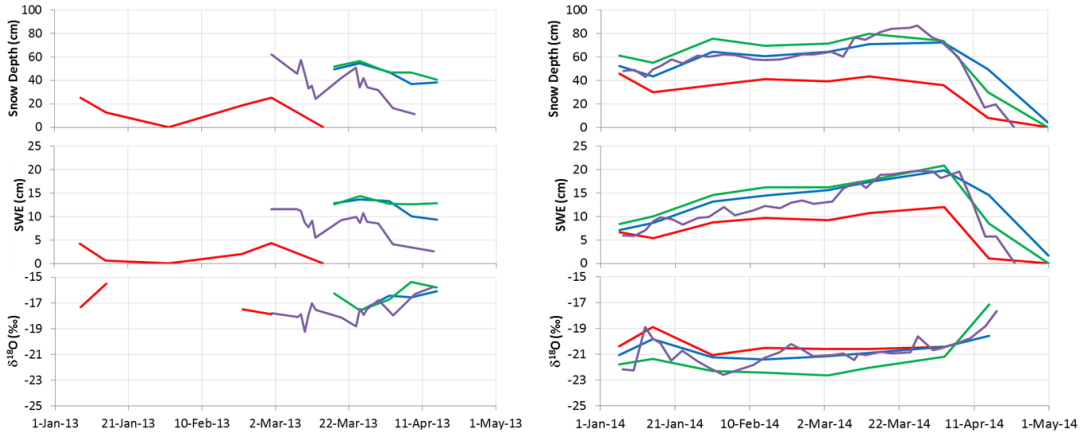

Figure 4. Snow depth, SWE and $\delta^{18}O$ of bulk snowcores collected at four sites (red: Wasi; blue: Tilden; green: Glen Afton; purple: Nipissing) in 2013 and 2014. Cores were collected with an aluminum MSC tube.

SUMMARY

High frequency spatial sampling of the 2014 boreal snowpack illustrates the isotopic variation in precipitation input and the persistence of these layers through to the ultimate homogenizing event of end of season smowmelt. Estimates of mean snowpack SWI signature were similar whether sampled via standard snowcore or SWE-weighted snowpit measurements, although the use of snowcores became problematic during the late season melt with observed water loss from the sampling tube. With much colder temperatures in 2014, there was a large interannual variability in snowpack SWI signatures, however snowmelt isotopic signatures did not show a commensurate difference between years. Further research will strengthen the sampling of snowmelt water through the use of passive wick samplers (Penna *et al.*, 2014) which continuously extract meltwater from the base of the snowpack and from below the soil surface. Soil moisture and temperature sensor arrays will also be added to the central field site to further our understanding of snowpack and snowmelt isotopic signatures and ultimately their use in hydrograph separation techniques.

REFERENCES

Bottomley DJ, Craig D, Johnston LM. 1986. Oxygen-18 studies of snowmelt runoff in a small Precambrian Shield watershed: implications for streamwater acidification in acid-sensitive terrain. *Journal of Hydrology* **88**: 213-234.

Klaus J, McDonnell JJ. 2013. Hydrograph separation using stable isotopes: review and evaluation. *Journal of Hydrology* **505**: 47-64.

Laudon H, Hemond HF, Krouse R, Bishop KH. 2002. Oxygen 18 fractionation during snowmelt: implications for spring flood hydrograph separation. *Water Resources Research* **38**: 1258.

Penna D, Ahmad M, Birks SJ, Bouchaou L, Brencic M, Butt S, Holko L, Jeelani G, Martinex DE, Melikadze G, Shanley J, Sokratov SA, Stadnyk T, Sugimoto A, Vreca P. 2014. A new method of snowmelt sampling for water stable isotopes. *Hydrological Processes*, doi: 10.1002/hyp.10273.

Rhode A. 1981. Spring flood – meltwater or groundwater? *Nordic Hydrology* **12**: 21-30.

St. Amour NA, Gibson JJ, Edwards TWD, Prowse TD, Pietroniro A. 2005. Isotopic time-series partitioning of streamflow components in wetland-dominated catchments, lower Liard River basin, Northwest Territories, Canada. *Hydrological Processes* **19**: 3357-3381.

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**: 759-769.

Turner KW, Wolfe BB, Edwards TWD. 2010. Characterizing the role of hydrological processes on lake water balances in the Old Crow Flats, Yukon Territory, Canada, using water isotope tracers. *Journal of Hydrology* **386**: 103-117.

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