Lessons learned from monitoring the stable water isotopic variability in precipitation and streamflow across a snow-dominated subarctic catchment

Steve W. Lyon, Stefan W. Ploum, Ype van der Velde, Gerard Rocher-Ros, Carl-Magnus Mörh, and Reiner Giesler

ABSTRACT

This empirical study explores shifts in stable water isotopic composition for a subarctic catchment located in northern Sweden as it transitions from spring freshet to summer low flows. Relative changes in the isotopic composition of streamflow across the main catchment and fifteen nested subcatchments are characterized in relation to the isotopic composition of precipitation. With our sampling campaign, we explore the variability in stream-water isotopic composition that originates from precipitation as the input shifts from snow to rain and as landscape flow pathways change across scales. The isotopic similarity of high-elevation snowpack water and early season rainfall water seen through our sampling scheme made it difficult to truly isolate the impact of seasonal precipitation phase change on stream-water isotopic response. This highlights the need to explicitly consider the complexity of arctic and alpine landscapes when designing sampling strategies to characterize hydrological variability via stable water isotopes. Results show a potential influence of evaporation and source water mixing both spatially (variations with elevation) and temporally (variations from post-freshet to summer flows) on the composition of stream water across Miellajokka. As such, the data collected in this empirical study allow for initial conceptualization of the relative importance of, for example, hydrological connectivity within this mountainous, subarctic landscape.

ARTICLE HISTORY

Received 28 June 2017
Revised 20 December 2017
Accepted 13 March 2018

KEYWORDS

Catchment hydrology; stable water isotopes; tracers; spring flood; freshet

Introduction

Freshet (spring flood) is an extreme period of the year in high-latitude, arctic, and subarctic systems. In these cold and snow-dominated regions, freshet is a period of rapidly melting snow and ice that typically produces the largest annual flows in rivers. Of course, the timing and magnitude of freshet has huge societal impacts for infrastructure and subsistence activities (Clement, Bengtson, and Kelly 2013), especially under a changing climate that is increasing precipitation in high-latitude regions. Spring flood and the subsequent recession into lower summer flows also influences biogeochemical cycling (Mann et al. 2016) and ecological health (Prowse et al. 2006). Climate change is also anticipated to shift precipitation from snow to rain, which could have considerable impacts on not only the amount of freshet water but also the chemical composition of freshet waters and streamflow throughout the year. This latter aspect is extremely important for arctic and subarctic aquatic ecosystems, because terrestrial-derived chemistry is often the main source of biological energy. As such, the composition of and any potential for changes in source water that enters into arctic and subarctic river systems may have considerable implications.

Recent studies have shown that flood extremes in cold regions are shifting or changing partially because of climate change, but the observed magnitude and direction of change can vary with location (Burn, Sharif, and Zhang 2010; Matti, Dahlke, and Lyon 2016; Wilson, Hisdal, and Lawrence 2010). This variability clearly reflects the complexity at play in cold regions where the phases of precipitation, temperature, and flow-path variability (i.e., because of frozen ground...
and the presence of snowpack) influence hydrological responses across scales. For example, precipitation shifts from snow to rain are anticipated to occur across several regions, such as the North American Rockies, where snowpacks have traditionally dominated water resources (Bales et al. 2006; Barnett, Adam, and Lettenmaier 2005). Harpold et al. (2017) recently highlighted how these changes in precipitation phases could alter streamflow timing and amounts (Berghuijs, Woods, and Hrachowitz 2014; Jepsen et al. 2016; Luce and Holden 2009), increase rain-on-snow flooding (McCabe, Clark, and Hay 2007), and impact the ability to accurately forecast water supplies (Milly et al. 2008).

Our understanding of how shifts in precipitation phases and how variability in frozen-ground patterns (Campbell et al. 2010) impact not only streamflow amounts but also stream-water chemistry and its sources is, unfortunately, still rather limited (Laudon et al. 2017).

Snowpack variability has increasingly been assessed via the changes in its isotopic composition as the pack develops and subsequently melts. Empirical investigations connecting variability in snowpack height, density, and isotopic composition are becoming more common (e.g., Gustafson et al. 2010; Lee et al. 2010; Rodhe 1998; Taylor et al. 2001); however, only a few such studies coincide detailed systematic and catchment scale observations of cryosphere interactions allowing for advancement of process-based understanding (Dahlke and Lyon 2013). Much progress has been made on understanding how snowpack melts and how this process (along with sublimation processes) imparts a distinct signature on the snowpack and meltwater isotopic composition. Traditionally, the first meltwaters draining from the snowpack are isotopically depleted relative to the average snowpack composition (Shanley et al. 1995; Stichler, Rauert, and Martinec 1981; Taylor et al. 2001), while subsequent meltwaters show a progressive isotopic enrichment. More recently, research such as that outlined in Ala-Aho et al. (2017) and Lyon et al. (2010a) has leveraged the “predictable” isotopic chemistry of the snowpack, which creates a traceable hydrological signal at freshet. This builds on studies using snow isotopic composition to estimate the contribution of snowmelt in groundwater recharge (Earman et al. 2006; Jasechko, Wassenaar, and Mayer 2017) and to understand the runoff generation processes (Carey and Quinton 2004; Laudon et al. 2004). Fractionation in the phase changes of sublimation/condensation and freeze/thaw during percolation through snow (O’Neil 1968) has the potential to change the isotopic signal in the original precipitation. The isotopic variability observed in the snowpack is usually marked both vertically in the profile, because of the persistence of isotopically different snowfall (Evans et al. 2016; Moser and Stichler 1974), and at various locations in the landscape (Dahlke and Lyon 2013; Schmieder et al. 2016).

Clearly, understanding how the isotopic composition of a snowpack develops and evolves and reacts as a function of shifts from snow to rain is increasingly important because of its impact on stream-water composition. Stream-water sources and composition and hydrological tracers (e.g., stable water isotopes, geochemicals, and manufactured particles) have become a cornerstone for assessing how water moves through and mixes within a catchment. This has led to an increase in new modeling methods that seek to improve process understanding at the catchment scale (e.g., Harman 2015; Klaus et al. 2015; van der Velde et al. 2012). These new methods, in turn, push for new data to better characterize flow pathway activation under various conditions and across various geological settings (Birkel et al. 2012; Dahlke et al. 2015; Volkman et al. 2016). With regard to high-latitude, arctic, and subarctic systems, hydrological tracer-based and geochemical data are often limited in their spatiotemporal availability and coverage (Laudon et al. 2017; Lyon et al. 2016). Cryosphere tracer-based studies are becoming more common (Gustafson et al. 2010; Rodhe 1998; Taylor et al. 2001) and are starting to more often coincide with hydrologic catchments to support the development of process-based understanding (e.g., Dahlke and Lyon 2013). As such, even the simplest tracer-based approaches and datasets can still help to assess variability across catchment subsystems (Dunn, McDonnell, and Vache 2007) or provide baselines for regional comparisons (Lyon et al. 2010a; Tetzlaff, Seibert, and Soulsby 2009).

Arctic and subarctic regions are traditionally data poor and, projecting forward, are likely to become data poorer (Laudon et al. 2017). There is, thus, the need for investigation into the variability of streamflow across these regions. This is true not only from a physical magnitude and timing perspective but also with regards to stream-water composition. To this end, this empirical study explores the spatiotemporal variability in the stream-water isotopic response to spring freshet for a high-latitude, subarctic region in northern Sweden. Relative changes in the isotopic composition of streamflow across the Miellajokka catchment and fifteen nested subcatchments are characterized in relation to precipitation isotopic composition. Based on our initial sampling campaign we assess the potential to distinguish between snowmelt and rainfall contribution to streamflow across scales.
In addition, we seek to benchmark the hydrological response and isotopic composition across the study region as a basis for future catchment-scale modeling of biogeochemical cycling under current and potential future conditions. This provides a clear chance to outline key assumptions on interpreting data and highlight some lessons learned as a context to inform future sampling in this region that may be relevant to other arctic and alpine environments.

**Methods**

**Site description**

This study was performed in the Miellajokka catchment (53.5 km$^2$), which drains into Lake Torneträsk and is located near Abisko in northern Sweden, approximately 250 km north of the Arctic Circle (Figure 1). The catchment is oriented north-south and can be considered moderately to steeply sloped (Table 1). In the lowest part of the catchment the streams flow over old gravel and glacial deposits, and this porous terrain intermittently feeds some small meandering river beds that rejoin the main steam. The diffuse flow through this area may dampen high-flow events, such as the spring freshet. However, many of these small channels do not contain any water during average or low-flow conditions.

Three distinct elevation classes (lower, middle, and higher) can be distinguished across the catchment. The lower elevation class starts at the outlet in the most northern part of the catchment (375 m a.s.l.) and is covered mainly with mountain birch (Betula pubescens ssp. czerepanovii) forest. The middle elevation class (400–700 m a.s.l.) contains less dense mountain birch forest areas with patches of more open areas with shrubs and sparse wetlands. The highest elevation class (above 700 m a.s.l.) is mostly above the tree line such that the coverage is mainly dominated by tundra heath vegetation. Above approximately 1,300 m a.s.l. little vegetation is present and bare rock dominates. The vegetated areas in this highest elevation class are

![Figure 1. Site map showing the location of Miellajokka in Sweden and the positions of the snow survey efforts and synoptic sampling of discharge and stable water isotopes across the various subcatchments. Filled circles represent sites where discharge was measured, empty circles are sites of the synoptic sampling, and crosses are the snow sampling locations.](image-url)
dominated by dwarf shrubs, herbaceous and graminoid vegetation with taller Salix sp. shrubs in wet areas. A distinct landscape feature of the tundra in the middle and higher elevation classes are cryoturbated nonsorted circles (Becher, Olid, and Klaminder 2013). The soils are generally till soils and deposits of glacial outwash of varying depth. The catchment is located within a region of discontinuous permafrost (Johansson et al. 2006), implying that permafrost could be present particularly at higher elevations; however, permafrost has not been systematically mapped. The geology of Miellajokka consists mainly of metamorphic (gneiss and granitic) bedrock in the easternmost headwaters, and intrusive (amphibolite and eclogite) bedrock in the westernmost branch. The middle to lower elevations and main tributaries drain through regions of metamorphic (mica-rich schist) rock.

The subarctic climate in Miellajokka brings long, cold winters with as much as nine months of snow accumulation. The mean annual temperature typically ranges from approximately −3.6°C in the lower valley to −7.4°C in the mountains (Callaghan et al. 2010). Yearly average precipitation is approximately 350 mm, measured at the nearby meteorological station operated by the Abisko Scientific Research Station (https://polar.se/en/research-in-abisko/weather-data/), which is approximately 15 km northwest of the study region. Miellajokka has a low flow in the winter of approximately 0.05–0.10 m³/s, and peak discharges during the spring freshet exceed 15–20 m³/s.

Sample collection and analysis

Sampling campaigns were conducted from February to August 2015, focusing on hydrology as a complement to ongoing biogeochemical cycling investigations and monitoring in the region (Giesler et al. 2014; Lundin et al. 2016). The campaigns focused on assessing isotopic composition and variability across the catchment inputs as snow and rain, and catchment outputs through the stream water.

With regard to snowpack, isotopic composition and snow-water equivalent (SWE) were measured at three locations across Miellajokka (Figure 1). These locations correspond to the aforementioned elevation classes and were considered to be low (L) elevation at approximately 380 m a.s.l., middle (M) elevation at approximately 550 m a.s.l., and high (H) elevation at approximately 760 m a.s.l. At the lower and middle elevations, sampling was done both in forested (F) and bare/open-area (B) coverage positions. It is not possible to sample a forested coverage site at the highest elevation because it is above the tree line. At each site, snow cores were collected twice (May 4 and 22) during the campaign. These cores were divided to make them easier to transport, and were used to estimate SWE at each site. Concurrent with the SWE estimate, additional snow cores (one or two per site) were collected. These cores were composited and melted, and their water was used for isotopic analysis (see further on). For the rainfall input, rainwater was sampled per rain event (>5 mm), and bulk samples were collected between major events using a funnel-bottle system located at the Abisko Scientific Research Station. This funnel-bottle system consisted of a funnel mounted on a post and connected to a storage bottle via flexible tubing such that evaporative losses were likely minimal. This allowed us during site visits to collect rainwater samples stored in the bottle.

Precipitation amounts and temperature were also monitored at the Abisko Scientific Research Station during this campaign in connection with the station and by the Swedish Meteorological and Hydrological Institute (SMHI). In addition, snow depths were monitored continuously by SMHI in the region at Katterjåkk (approximately 40 km northwest of the study region) at an elevation of 515 m a.s.l. and at

---

**Table 1.** Miellajokka main catchment (M1) and subcatchments (M2–M16) characteristics.

| Site | Area (km²) | Average Elevation (m) | Maximum Elevation (m) | Minimum Elevation (m) | Relief (m) | Average Slope (m/m) | Average Flow-Path Length (m) |
|------|------------|-----------------------|-----------------------|-----------------------|------------|--------------------|----------------------------|
| M1   | 51.5       | 947                   | 1,741                 | 381                   | 1,360      | 0.25               | 760                        |
| M2   | 13.7       | 871                   | 1,387                 | 389                   | 998        | 0.21               | 793                        |
| M3   | 34.7       | 1,017                 | 1,741                 | 389                   | 1,352      | 0.28               | 913                        |
| M4   | 30.2       | 1,076                 | 1,741                 | 502                   | 1,239      | 0.31               | 641                        |
| M5   | 27.3       | 1,102                 | 1,741                 | 661                   | 1,080      | 0.32               | 634                        |
| M6   | 1.8        | 948                   | 1,340                 | 747                   | 593        | 0.22               | 816                        |
| M7   | 6.8        | 1,232                 | 1,741                 | 703                   | 1,038      | 0.38               | 488                        |
| M8   | 20.0       | 1,067                 | 1,637                 | 731                   | 906        | 0.30               | 683                        |
| M9   | 10.9       | 1,080                 | 1,637                 | 800                   | 837        | 0.33               | 715                        |
| M10  | 8.6        | 1,070                 | 1,561                 | 815                   | 746        | 0.27               | 660                        |
| M11  | 5.9        | 1,294                 | 1,741                 | 882                   | 859        | 0.42               | 491                        |
| M12  | 8.7        | 1,119                 | 1,637                 | 948                   | 689        | 0.37               | 721                        |
| M13  | 0.9        | 1,011                 | 1,340                 | 842                   | 498        | 0.25               | 913                        |
| M14  | 0.4        | 927                   | 1,163                 | 827                   | 336        | 0.22               | 1,005                      |
| M15  | 0.1        | 947                   | 994                   | 925                   | 69         | 0.10               | 1,034                      |
| M16  | 0.7        | 403                   | 469                   | 385                   | 84         | 0.07               | 857                        |
Erange (approximately 80 km southeast of the study region) at an elevation of 328 m a.s.l.

Streamflow was synoptically sampled at the catchment outlet and across several subcatchments (Figure 1). Because discharge observations are difficult to make in this landscape, not every subcatchment was gauged during every synoptic discharge measurement campaign. Discharge was determined using the dilution of slug injections of salt at each location. Most flow measurements were made at the catchment outlet (site M1). Here, the observed streamflow data were used to calibrate SMHI’s HYPE hydrological model (Lindström et al. 2010) to provide an estimate of daily flows for the Miellajokka catchment during the 2015 calendar year. Calibration was done with a simple second-order polynomial regression ($R^2 = 0.66$).

In addition to streamflow measurements, we also grabbed sampled water at the outlets of fifteen subcatchments within the stream network (Table 1, Figure 1). Four synoptic sampling campaigns were conducted (June 30; July 15; July 28; August 12) with as many of the fifteen subcatchments visited as possible. For the region, topographic data were available from the Swedish University of Agricultural Sciences (SLU, http://maps.slu.se/) in the form of a digital elevation model (DEM) at a horizontal resolution of 2 m. These data were used to delineate subcatchment areas and to calculate topographically derived landscape characteristics. We used the D8 flow routing algorithm as implemented in Tarboton (1997) to define local slopes and flow pathway lengths for each nonstream network raster cell in the Miellajokka catchment to the stream network, which were then averaged over each subcatchment. While other spatial data are available in the region (i.e., Jantze et al. 2015), we limit detailed analysis here to these topographic data and simple derivative products (Table 1). More general characterizations regarding geology and vegetation coverages can be drawn from the site description.

All water samples collected were stored in sealed bottles without head space and were refrigerated from the day of collection until analysis for stable water isotopes. Samples were analyzed at the Stable Isotope Laboratory of Stockholm University with a Picarro L2140 Liquid Water Isotope Analyzer for stable water isotopes. Samples were analyzed at the Stable Isotope Laboratory. Regarding the snow cover from the May 4 survey, there was a lower SWE at the high elevation site relative to the middle and low elevation sites (Table 2). For the lower two elevation sites, both showed lower SWE measurements under forest coverage compared to the open coverage sites. By the second survey, on May 22, the snowpack was completely gone at the low elevation site, while the middle elevation pack had decreased by 57 percent and 42 percent for the open and forested coverage, respectively. The high elevation site was not accessible during the second campaign, but snow was visible in the vicinity of the site and at higher elevations. These survey observations were consistent with SMHI’s regional monitoring of snow depth, where the lower elevation monitoring station was snow free by mid-May 2015 while the higher elevation monitoring station was snow free by mid-June 2015 (Figure 2). The largest changes in snow cover were also consistent with the change from daily temperatures below freezing to daily temperatures above freezing, occurring in May 2015 (Figure 2). In addition, large early season rain events in

### Results and discussion

#### Hydroclimatic observations

Regarding the snow cover from the May 4 survey, there was a lower SWE at the high elevation site relative to the middle and low elevation sites (Table 2). For the lower two elevation sites, both showed lower SWE measurements under forest coverage compared to the open coverage sites. By the second survey, on May 22, the snowpack was completely gone at the low elevation site, while the middle elevation pack had decreased by 57 percent and 42 percent for the open and forested coverage, respectively. The high elevation site was not accessible during the second campaign, but snow was visible in the vicinity of the site and at higher elevations. These survey observations were consistent with SMHI’s regional monitoring of snow depth, where the lower elevation monitoring station was snow free by mid-May 2015 while the higher elevation monitoring station was snow free by mid-June 2015 (Figure 2). The largest changes in snow cover were also consistent with the change from daily temperatures below freezing to daily temperatures above freezing, occurring in May 2015 (Figure 2). In addition, large early season rain events in

### Table 2. Snow-survey observations for snow-water equivalent (SWE) and average snowpack water stable water isotope compositions across the three elevation zones at Miellajokka.

| Map ID | Description                          | May 4, 2015 | May 22, 2015 |
|--------|--------------------------------------|-------------|--------------|
|        | SWE (mm) | $\delta^{18}O$ (%) | $\delta D$ (%) | SWE (mm) | $\delta^{18}O$ (%) | $\delta D$ (%) |
| LB     | Low elevation, bare/open             | 718         | −21.6        | −157.9    | 0          | −             |
| LF     | Low elevation, forest                | 367         | −17.4        | −127.0    | 0          | −             |
| MB     | Middle elevation, bare/open         | 741         | −15.5        | −109.3    | 323        | −15.2        | −106.3       |
| MF     | Middle elevation, forest             | 287         | −16.1        | −115.9    | 283        | −17.3        | −125.5       |
| HB     | High elevation, bare/open           | 250         | −13.4        | −94.3     | −          | −             |
late May coincided with the observed loss of SWE between May 4 and 22, 2015 (Figure 2). Relative to the long-term average precipitation for May (13 mm) and June (22 mm), May 2015 (45 mm) and June 2015 (41 mm) were well above the averages for precipitation in the region (Callaghan et al. 2010). These early season rain events, particularly rain-on-snow events, contributed to the quick snowmelt and the loss of SWE that was seen across the catchment (Table 2).

The temperature shift, snowmelt, and rainfall in May through June triggered a freshet that began in the middle of May (Figure 2). There were two high-flow periods during this spring flood period. The first had peak discharge consistently above 5 m$^3$/s for several days at the outlet of the Miellajokka catchment in early June. This corresponded to the melting of the majority of low-to-middle elevation snow and some rain-on-snow events that followed across all elevations. After this initial high-flow period, a colder period followed with lower flow conditions below 5 m$^3$/s. Then, at the end of June, a 35 mm rain event falling on the high-elevation snow caused the second high discharge period. This period was shorter in duration but had high flows over 20 m$^3$/s at M1.

Looking into the synoptic observations of flow across the subcatchment (Table 3), there was larger specific discharge (flow normalized by catchment area) coming from the M3 catchment relative to the M2 catchment early in the freshet period. This range diminishes going from the wet spring period to the lower-flow summer period, as does the relative variability in specific discharge amounts across the monitored headwaters. Site
M7, which drains the highest valley in the Miellajokka system, did appear to have slightly higher specific discharge later in the season than the other subcatchments where flow could be measured. However, it should be noted that this is based on only a few direct synoptic observations across the region.

Isotopic spatiotemporal variability

Observations of isotopic composition

The spatiotemporal variations of the stable water isotopes $\delta^{18}$O and $\delta$D across the Miellajokka catchment showed clear response to precipitation based on observations (Figure 3). The response observed in the streams followed the variability observed in the isotopic composition of snowpack (Table 2) and rainfall (Table 4) water. Snowpack water exhibited similar $\delta^{18}$O and $\delta$D compositions compared to the early season rainfall water, but tended to exhibit lower, for example, more depleted, isotopic compositions relative to the later-season rainfall water (Figure 3). During the entire period of sampling, snowpack water $\delta^{18}$O composition averaged $-16.6$ percent and $\delta$D composition averaged $-119.2$ percent, while rainfall water $\delta^{18}$O composition averaged $-11.0$ percent and $\delta$D composition averaged $-82.5$ percent. The response to precipitation variability can be seen clearly, albeit dampened, in the higher-temporal resolution sampling at the catchment outlet (M1; Figure 3). Specifically, $\delta^{18}$O and $\delta$D values measured in the stream water at M1 decreased (depleted) during the freshet period, corresponding to increased snowmelt at lower elevations and rain-on-snow events. As snowmelt progressed and rainfall precipitation began, the isotopic compositions at M1 reached their minimum, at $-15.9$ percent for $\delta^{18}$O and $-114.7$ percent for $\delta$D, already at approximately

| Site | May 29, 2015 q (mm/d) | June 5, 2015 q (mm/d) | July 7, 2015 q (mm/d) | July 15, 2015 q (mm/d) | July 22, 2015 q (mm/d) | August 12, 2015 q (mm/d) |
|------|----------------------|-----------------------|----------------------|------------------------|------------------------|--------------------------|
| M1   | 22.5                 | 13.4                  | 8.8                  | 4.5                    | -                      | 2.7                      |
| M2   | 17.9                 | 12.5                  | 9.9                  | -                      | -                      | -                        |
| M3   | 29.5                 | 11.5                  | 9.5                  | -                      | 7.8                    | 2.6                      |
| M4   | -                    | 7.5                   | 7.2                  | -                      | 9.2                    | -                        |
| M5   | -                    | -                     | 6.6                  | 8.5                    | -                      | -                        |
| M7   | -                    | -                     | 7.6                  | 11.1                   | -                      | -                        |
| M8   | -                    | -                     | -                    | 6.4                    | 8.7                    | -                        |

Figure 3. Time series of observed $\delta^{18}$O composition, $\delta$D compositions, and deuterium excess. Black dots are for M1 stream-water samples and gray dots are for M2–M16 synoptic stream-water samples. Triangles show the snowpack water isotopic compositions and stars show the rainfall water isotopic composition. The dashed line in the bottom panel highlights synoptic sampling from the M10 site.
Table 4. Observed rainfall water isotopic compositions collected across this study.

| Date (2015) | δ18O (%) | δD (%) |
|-------------|-----------|--------|
| May 18      | −8.5      | −66.9  |
| May 25      | −19.6     | −145.4 |
| May 29      | −14.0     | −104.0 |
| June 1      | −7.4      | −56.8  |
| June 2      | −14.2     | −107.0 |
| June 8      | −11.0     | −84.6  |
| June 11     | −11.3     | −88.6  |
| June 17     | −5.5      | −44.9  |
| June 24     | −10.4     | −72.0  |
| July 13     | −10.7     | −76.8  |
| July 29     | −10.4     | −74.6  |
| August 17   | −9.5      | −68.6  |

May 28, 2015. Stream-water isotopic values at M1 then remained relatively low (depleted) until mid-June, after which they begin to increase (enrich) for both δ18O and δD.

From the observations available, the two high-flow periods on the spring freshet hydrograph cannot be seen in the isotopic composition of the stream water at M1. However, it may be that the second high-flow period at M1 has its isotopic signal masked because of the mixing of high elevation snowmelt-water and rainfall-water contributions (Figure 3). Such is common in situations where the mixing of input water with various isotopic compositions can mask output responses in streamflow (e.g., Lyon, Desilets, and Troch 2009). The potential for such masking can be seen more clearly in the deuterium excess time series (defined here as \( \delta D - 8 \times \delta^{18}O \)) for M1 (Figure 3). The maximum deuterium excess value thus occurred between early June and early July.

For the synoptically sampled streams (M2–M16), this pattern of potentially dampened isotopic signal was repeated and can be seen as a shift in the maximum deuterium excess value that tends to occur later in the season for M2–M16 relative to M1 (Table 5). This potential shifted maximum deuterium excess can be seen, for example, at the M10 catchment that drains through higher elevations (Figure 3). However, given the temporal resolution of the synoptic sampling (Table 5), it is not possible to determine the precise timing of this maximum deuterium excess (or, alternatively, minimum \( \delta^{18}O \) and \( \delta D \) isotopic values) for each individual subcatchment. Interestingly, the isotopic composition and deuterium excess values showed an increasing range for the synoptic samples moving from the first sampling campaign (June 30) to last campaign (August 12; Figure 3, Table 5). For example, the range in stream-water deuterium excess across all the catchments changed from 1.9 percent at the first sampling to 4.3 percent at the last sampling. While there was more spread in the deuterium excess at the last campaign relative to the first, the order of the streams from highest to lowest values when considering their isotopic compositions remained relatively constant (Table 5).

### Isotopic water lines

The spatiotemporal isotopic compositions observed for the snowpack and rainfall water samples were further considered via their relative positioning in \( \delta D-\delta^{18}O \) space and the linear relationships these define—the so-called water lines in a dual-isotope plot (Figure 4). In general, the snowpack water isotopic compositions were lower (more depleted) than rainwater compositions; however, there was some overlap because of relatively low isotopic composition early season rain events. Looking at the snow samples collected in bare/open coverage, there was a clear separation between the low-elevation samples and the middle- and high-elevation samples (Figure 4). This pattern of separation by elevation was less clear in the forest-coverage samples. It was interesting that the low-elevation snow samples were isotopically more negative than those at higher

Table 5. Observed stream-water isotopic compositions and deuterium excess across this study for the subcatchments at Miellajokka during the synoptic campaigns.

| Site | June 30, 2015 | July 15, 2015 | July 28 | August 12 |
|------|---------------|---------------|---------|-----------|
|      | \( \delta^{18}O \) (%) | \( \delta D \) (%) | Deuterium Excess | \( \delta^{18}O \) (%) | \( \delta D \) (%) | Deuterium Excess | \( \delta^{18}O \) (%) | \( \delta D \) (%) | Deuterium Excess |
| M1   | −14.6         | −104.1        | 12.7    | −14.3     | −102.3       | 12.1    | −14.0     | −99.7       | 12.3    | −13.6     | −97.2       | 11.6    |
| M2   | −14.1         | −100.6        | 12.2    | −14.3     | −102.1       | 12.3    | −13.7     | −97.5       | 12.1    | −13.3     | −94.8       | 11.6    |
| M3   | −14.3         | −102.8        | 11.6    | −14.0     | −100.0       | 12.0    | −14.1     | −99.7       | 13.1    | −13.8     | −97.6       | 12.8    |
| M4   | −14.5         | −103.9        | 12.1    | −14.3     | −101.9       | 12.5    | −14.0     | −98.9       | 13.1    | −13.8     | −97.2       | 13.2    |
| M5   | −14.4         | −103.9        | 11.3    | −14.3     | −101.5       | 12.9    | −13.9     | −98.4       | 12.8    | −13.8     | −96.8       | 13.6    |
| M6   | −14.7         | −105.5        | 12.1    | −14.6     | −104.2       | 12.6    | −14.3     | −101.8       | 12.6    | −14.1     | −99.7       | 13.1    |
| M7   | −15.0         | −107.7        | 12.3    | −14.9     | −106.4       | 12.8    | −13.8     | −97.2       | 13.2    | −13.6     | −95.9       | 12.9    |
| M8   | −14.3         | −102.8        | 11.6    | −14.0     | −100.0       | 12.0    | −13.8     | −97.6       | 12.8    | −13.5     | −96.1       | 11.9    |
| M9   | −14.3         | −102.6        | 11.8    | −13.8     | −98.9        | 11.5    | −13.9     | −97.2       | 13.2    | −13.6     | −95.9       | 12.9    |
| M10  | −14.6         | −104.1        | 12.7    | −14.5     | −102.3       | 13.7    | −13.9     | −97.2       | 14.0    | −13.6     | −95.4       | 13.4    |
| M11  | −15.2         | −109.5        | 12.1    | −15.2     | −107.4       | 14.2    | −14.4     | −101.3       | 13.9    | −14.1     | −99.4       | 13.4    |
| M12  | −14.2         | −102.0        | 11.6    | −13.7     | −98.3        | 11.3    | −13.8     | −97.5       | 12.9    | −13.5     | −96.7       | 11.3    |
| M13  | −14.1         | −101.0        | 11.6    | −14.1     | −100.6       | 12.2    | −14.2     | −100.4       | 13.2    | −13.9     | −99.1       | 12.1    |
| M14  | −15.3         | −109.2        | 13.2    | −15.1     | −108.4       | 12.4    | −14.8     | −105.6       | 12.8    | −13.9     | −100.5      | 10.7    |
| M15  | −13.8         | −99.4         | 11.0    | −13.8     | −98.6        | 11.8    | −12.9     | −92.5        | 10.7    | −12.5     | −90.5       | 9.5     |
| M16  | −14.6         | −103.7        | 13.1    | −14.3     | −101.4       | 13.0    | −13.8     | −98.7        | 11.7    |
elevations. This could be because of atmospheric inversion processes coupled with weather-system variability at the larger scale (e.g., Moser and Stichler 1974), or general wind-driven redistribution of snow coupled with variations of incoming solar radiation at more local scales (e.g., Gustafson et al. 2010). Given our sampling resolution, it is not possible to isolate a clear mechanism here. For the rainfall water samples, there was a tendency for increasing (enriching) δ¹⁸O and δD values with time across the sample period (Figure 3, Table 4). The early season rain events (May and June 2015) were, however, isotopically similar to the middle- and high-elevation snowpack water samples (Figure 4). The slope of the snowpack water line (slope = 7.8) and the rainfall water line (slope = 7.2) were rather consistent with the local meteoric water line (LMWL; slope = 7.1), considering both snowpack and rainfall water isotopic compositions.

The variation in snowpack isotopic composition can be seen in the stream network (Figure 5). For M1, there was a clear temporal pattern, such that early samples plotted higher in a dual isotope plot relative to the samples coinciding with the maximum deuterium excess period. Later in the season, the M1 isotopic composition increased, returning (resetting) to pre-freshet values. All stream-water samples plotted above the observed LMWL for the M1 site. This was rather unexpected and could indicate an inability to capture the full range of isotopic variability of the precipitation across the Miellajokka catchment. For example, we do not have a good understanding of the potential for dew formation and trace and/or occult rainfall in the region, which can be a significant contribution (Woo and Steer 1979). Further, the LMWL will continue to develop as more samples are collected in both space and time. A lack of full characterization in inputs would translate to an incomplete view of the water that is driving runoff source-water mixing in the region—this highlights the need for capturing true end members if our goal is to truly allocate stream source waters (e.g., Buttle 1994). The slope of this surface water line for M1 (slope = 7.4) does not deviate considerably from that of the LMWL (slope = 7.1) in the region.

Across the synoptic sampling campaigns for the subcatchments (Table 5), there was a general decreasing pattern in the campaign stream water line slopes and intercepts; that is, where the line crosses the δD axis (Figure 5). Such a pattern in intercept would be consistent with the melting of snow from the lower elevations during late spring followed by melting at higher elevations and increased rainfall precipitation later in the season. The shift in stream water line slopes across the campaign could also be consistent with an increased impact of evapotranspiration on the source water contributing to streamflow across the subcatchments. These changes in the slope of the campaign stream water lines could, however, be somewhat confounded by (1) fundamental shifts in precipitation phase and (2) our limited ability to represent the full extent of isotopic input variability across the entire Miellajokka catchment.

Potential controls on stream-water isotope variability

To further explore the potential controls on spatiotemporal variability of stable water isotopes across the Miellajokka region, we also considered the relationships between stream water lines for each individual subcatchment (Table 6) and the topographically derived characteristics available (i.e., Table 1). There was a significant \( p < 0.05 \) negative linear relationship between the slopes of the subcatchment stream water lines and the average flow-path length in each catchment (Figure 6). Conceptually, one would expect subcatchment stream water line slopes to decrease as the impacts of evaporation on recharging water increases. Because there is a general inverse relationship between average elevation and flow-path length across Miellajokka, catchments with longer flow paths likely integrate over areas with more evaporation impacts as temperatures increase across lower elevations in the region.
Such an interpretation would also be consistent with the increasing control of flow-path length on the deuterium excess observed for these data moving further into the summer low-flow period (i.e., from the first to last sampling campaign) as average temperatures increase (Figure 7). Longer flow paths could potentially also integrate across areas where opportunities for evaporation readily occur (e.g., as groundwater upwells to the surface because of bedrock outcropping and/or within saturated frost boils). There could be a potential interplay with these flow pathway distributions and the general soil frost in the regions, which has been shown to influence the storage-discharge relationships regionally (Ploum 2016).

There was also a significant ($p < 0.05$) positive linear relationship between the slopes of the subcatchment stream water lines and the topographic relief (i.e., the difference between maximum and minimum elevation) of each catchment (Figure 6), albeit with some scatter around the relationship ($R^2 = 0.31$). Conceptually, this positive linear relation suggests that higher relief catchments span larger ranges of precipitation and snow accumulation variability. This would be somewhat consistent with observed lower SWE and longer periods of snow coverage at high elevations relative to low elevations (Table 2). For example, high relief catchments can experience low elevation snowmelt events early in the season relative to high elevation snowmelt events that occur later in the season. Higher relief catchments should also see larger impacts of isotopic “rain out” as rainfall systems move up in elevation throughout the season.

### Interpretations, assumptions, and lessons learned

There was observable change in the stream-water isotopic composition because of precipitation phase shift from snow to rain across Miellajokka (Figure 3). The streams across the Miellajokka catchment reflect the spatiotemporal variability of the isotopic composition of the precipitation input; namely, the snowpack water and rainfall water isotopic variability (Figure 4). Based on the sampling available, the similarity in the isotopic composition of high elevation snow and early season rainfall makes it difficult to fully isolate the potential impact of a shift in the regions that experience snow accumulation and melt. Further, this similarity limits our ability to describe input isotopic signatures in order...
to characterize and quantify the extent of mixing within the catchment (e.g., Birkel et al. 2012; Heidbüchel, Troch, and Lyon 2013; van der Velde et al. 2015) or the timing of snowmelt-water movement through the system across scale (Lyon et al. 2010a). Regardless of such limitations, we can still distill relevant first-order information about catchment processes from the systematic isotopic variation exhibited by this initial sampling.

For example, we can see potential increased influence of evaporation across the subcatchments moving from those with longer average flow paths (lower elevation) to those with shorter average flow paths (higher elevation) via the systematic variation in subcatchment stream water line slopes (Figure 6). This could indicate that there are more opportunities for water flowing through catchments with longer flow paths to evaporate relative to water flowing through catchments with shorter flow paths. For example, more occurrences of bedrock outcrops and thin soils where groundwater can well up to the surface could allow for more evaporation, particularly as air temperature increases moving to lower elevations. This not only holds across the individual subcatchments (spatial variation) but also appears consistent across the season, moving from the post-freshet period to late summer sampling (temporal variations) as temperatures increase when considering the slopes of the campaign stream water lines (Figure 5). Such a process interpretation of potential increased evaporation impact on source water in both space (i.e., moving up in elevation) and time (i.e., moving from freshet to summer flows) would be mechanistically consistent with previous alpine region studies (e.g., Blanken et al. 2009; Knowles et al. 2014; Molotch et al. 2007).

Further, the increased spread in the deuterium excess across all catchments, moving from early season to late season sampling (Figure 3), likely reflects the
The spatial isotopic input variability in cold regions can manifest itself as a positive relationship with altitude for snow and as a negative relationship with altitude for rainfall that must be resolved to identify source-water allocation to streams across elevation gradients.

- The difference between isotopic composition (and SWE) of snow under forest versus open fields, coupled with the isotopic variability in rainfall with time, must be resolved if we want to isolate process variability that changes with season (such as evapotranspiration or flow-pathway connectivity).
- The estimated LMWL can deviate from what would be anticipated because of limitations in observations across the full range of the variability in inputs (both snow and rain), and we cannot ignore the potential for other precipitation phases, such as dew, fog, and trace/occult rainfall.
- We do see clear isotopic stream-water freshet signal at all scales sampled, but given the interplay of the earlier lessons, it is not possible to uniquely pinpoint the source of stream-water variability. As the most isotopic difference between scales for stream water was seen at end of the season, the end-of-season measurements (low flows) were most informative for subcatchment characterization.

As such, the main lesson learned comes from the isotopic complexity and variability at play in this landscape. These conditions warrant special consideration as we seek to use stable water isotopes to characterize hydrological mixing. Because complexity in the timing and phase shift of the input signals combines with the inherent complexity of the landscape and storage-discharge dynamics, sampling strategies need to be explicitly designed in a manner relevant for arctic and alpine settings.

**Conclusion**

A clear lesson learned from this study was that the complexity of the Arctic and alpine landscape that exists in Miellajokka requires a dedicated sampling design to capture the real spatial and temporal variability in the isotopic composition of precipitation and snowmelt. Explicitly, this must include sampling of both snow and rainwater (i.e., input) isotopic variability at spatiotemporal scales capable of isolating the seasonality of these inputs from each other. It also must include sampling of stream-water (i.e., outflow) isotopic variability at spatiotemporal scales capable of separating the change from snowmelt to rainfall inputs both seasonally and across elevation ranges (i.e., the phase shift of inputs).

As we develop and expand our process understanding of how water mixes and moves through arctic and subarctic landscapes, there is clear value in empirical exploration, because it can feed into
future analysis and field studies targeting the remaining unknown parts of the hydrological system. Given the remote nature of the Miellajokka region, even first-order information about the processes surrounding the major mode of hydrological responses are helpful to begin unraveling mechanisms relevant for biogeochemical cycling and weathering interactions across scale. However, adopting sampling strategies—for example, from temperate or lowland systems—that cannot see nor capture the true complexity and variability of the precipitation and snowmelt input may limit our ability to isolate the subarctic landscape controls on streamflow. As we continue to explore the ways in which various storage-discharge conditions influence internal catchment mixing, empirical characterization of isotopic variability in streamflow and precipitation inputs, such as that presented here for the snow-dominated, subarctic Miellajokka catchment, help set boundaries to constrain water movement through landscapes and help inform future strategies for monitoring. Given the importance and uncertain projected future of northern high-latitude research catchments (Laudon et al. 2017), this may be more true now than ever.

Acknowledgments

We acknowledge the Abisko Scientific Research Station, where large parts of the field preparation were done, and the Stable Isotope Lab (SIL) at the Department of Geological Sciences at Stockholm University and its lab manager Heike Siegmund, where most sample analysis was done.

Funding

This study was supported by the Swedish Research Council (VR;2013-5001) and the Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning (FORMAS;2014-970). Additional support was provided through the Netherlands Polar Programme (NWO Project 15.60.00) and the Hendrik Muller Fonds. For help in the field we acknowledge Albin Bjärhall, Belen Diaz Collante, and Max Schuchardt.

References

Ala-Aho, P., D. Tetzlaff, J. P. McNamara, H. Laudon, P. Kormos, and C. Soulsby. 2017. Modeling the isotopic evolution of snowpack and snowmelt: Testing a spatially distributed parsimonious approach. *Water Resources Research* 53:5813–30. doi:10.1002/2017WR020650.

Bales, R. C., N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier. 2006. Mountain hydrology of the western United States. *Water Resources Research* 42: W08432. doi:10.1029/2005wr004387.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* 438:303–9. doi:10.1038/nature04141.

Becher, M., C. Olid, and J. Kliminder. 2013. Buried soil organic inclusions in non-sorted circles fields in northern Sweden: Age and paleoclimatic context. *Journal of Geophysical Research: Biogeosciences* 118:1–8. doi:10.1002/jgrg.20016.

Berghuis, W. R., R. A. Woods, and M. Hrachowitz. 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change* 4:583–86. doi:10.1038/nclimate2246.

Birkel, C., C. Soulsby, D. Tetzlaff, S. Dunn, and L. Spezia. 2012. High-frequency storm event isotope sampling reveals time-variant transit time distributions and influence of diurnal cycles. *Hydrological Processes* 26 (2):308–16. doi:10.1002/hyp.8210.

Blanken, P. D., M. W. Willliams, S. P. Burns, R. K. Monson, J. Knowles, K. Chowanski, and T. Ackerman. 2009. A comparison of water and carbon dioxide exchange at a windy alpine tundra and subalpine forest site near Niwot Ridge, Colorado. *Biogeochemistry* 95:61–76. doi:10.1007/s10533-009-9325-9.

Burn, D. H., M. Sharif, and K. Zhang. 2010. Detection of trends in hydrological extremes for Canadian watersheds. *Hydrological Processes* 24 (13):1781–90. doi:10.1002/hyp.7625.

Buttle, J. M. 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progress in Physical Geography* 18:16–41.

Callaghan, T. V., F. Bergholm, T. R. Christensen, C. Jonasson, U. Kokkelt, and M. Johansson. 2010. A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. *Geophysical Research Letters* 37:L14705. doi:10.1029/2009GL042064.

Campbell, J. L., S. V. Ollinger, G. N. Flerchinger, H. Wicklein, K. Hayhoe, and A. S. Bailey. 2010. Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire. *Hydrological Processes* 24:2465–80.

Carey, S., and W. Quinton. 2004. Evaluating snowmelt runoff generation in a discontinuous permafrost catchment using stable isotope, hydrochemical and hydrodymetric data. *Hydrology Research* 35:309–24.

Clement, J. P., J. L. Bengtson, and B. P. Kelly. 2013. Managing for the future in a rapidly changing Arctic. A report to the President. Interagency Working Group on Coordination of Domestic Energy Development and Permitting in Alaska (D.J. Hayes, Chair), Washington, DC.

Coplen, T. B. 2011. Guidelines and recommended terms for expression of stable-isotope-ratio and gas-ratio measurement results. *Rapid Communications in Mass Spectrometry* 25 (17):2538–60.

Dahlke, H. E., and S. W. Lyon. 2013. Early melt season snowpack isotopic evolution in the Tarfala valley, northern Sweden. *Annals of Glaciology* 54 (62):149–56. doi:10.3189/2013AoG62A232.

Dahlke, H. E., M. T. Walter, S. W. Lyon, A. Sharma, S. Leung, and A. Williamson. 2015. Using concurrent DNA tracer injections to infer glacial flow pathways. *Hydrological Processes* 29 (25):5257–74. doi:10.1002/hyp.10679.
terrestrial dissolved organic matter from optical measurements. Frontiers in Earth Science 4 (25):1–18. doi:10.3389/feart.2016.00025.

Matti, B., H. E. Dahlke, and S. W. Lyon. 2016. On the variability of cold region flooding. Journal of Hydrology 534:669–79. doi:10.1016/j.jhydrol.2016.01.055.

McCabe, G. J., M. P. Clark, and L. E. Hay. 2007. Rain-on-snow events in the western United States. Bulletin of the American Meteorological Society 88:319–28. doi:10.1175/bams-88-3-319.

McGuire, K. J., and J. J. McDonnell. 2006. A review and evaluation of catchment transit time modeling. Journal of Hydrology 330:543–63. doi:10.1016/j.jhydrol.2006.04.020.

McNamara, J., D. Chandler, M. Seyfried, and S. Achet. 2005. Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment. Hydrological Processes 19:4023–38. doi:10.1002/hyp.5869.

Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer. 2008. Stationarity is dead: Whither water management? Science 319:573–74. doi:10.1126/science.1151915.

Molotch, N. P., P. D. Blanken, M. W. Williams, A. A. Turnipseed, R. K. Monson, and S. Margulis. 2007. Estimating sublimation of intercepted and sub-canopy snow using eddy covariance systems. Hydrological Processes 21 (12):1567–75. doi:10.1002/hyp.6719.

Moser, H., and W. Stichler. 1974. Deuterium and oxygen-18 contents as an index of the properties of snow covers. International Association of Hydrological Sciences Publication 114:122–35.

O’Neil, J. R. 1968. Hydrogen and oxygen isotope fractionation between ice and water. Journal of Physical Chemistry 72:3683–84.

Ploum, S. 2016. Thawing and snowmelt effects on streamflow recessions in a large sub-arctic catchment. MSc Thesis, Utrecht University.

Prowse, T. D., F. J. Wrona, J. D. Reist, J. J. Gibson, J. E. Hobbie, L. M. J. Lévesque, and W. F. Vincent. 2006. Climate change effects on hydroecology of Arctic freshwater ecosystems. Ambio 35 (7):347–58. doi:10.1579/0044-7447(2006)35[347:CCEOHO]2.0.CO;2.

Rodhe, A. 1998. Snowmelt-dominated systems. In Isotope tracers in catchment hydrology, ed. C. Kendall and J. J. McDonnell, 391–434. Amsterdam: Elsevier.

Schmieder, J., F. Hanzer, T. Marke, J. Garvelmann, M. Warscher, H. Kunstmann, and U. Strasser. 2016. The importance of snowmelt spatiotemporal variability for isotope-based hydrograph separation in a high-elevation catchment. Hydrology and Earth System Sciences 20 (12):5015–33. doi:10.5194/hess-20-5015-2016.

Shanley, J. B., C. Kendall, M. R. Albert, and J. P. Hardy. 1995. Chemical and isotopic evolution of a layered eastern U.S. snowpack and its relation to stream-water composition. In Biogeochemistry of seasonally snow-covered catchments, ed. K. A. Tennessen, M. W. Williams, and M. Tranter, 329–38. IAHS publication 228. Wallingford: IAHS Press.

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

Tarboton, D. G. 1997. A new method for the determination of flow directions and contributing areas in grid digital elevation models. Water Resources Research 33 (2):309–19.

Taylor, S., X. Feng, J. W. Kirchner, R. Osterhuber, B. Klaue, and C. C. Renshaw. 2001. Isotopic evolution of a seasonal snowpack and its melt. Water Resources Research 37 (3):759–69. doi:10.1029/2000WR900341.

Tetzlaff, D., J. Seibert, and C. Soulsby. 2009. Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland. Hydrological Processes 23 (13):1874–86. doi:10.1002/hyp.7318.

van der Velde, Y., I. Heidbüchel, S. W. Lyon, L. Nyberg, A. Rodhe, K. Bishop, and P. A. Troch. 2015. Consequences of mixing assumptions for time-variable travel time distributions. Hydrological Processes 29 (16):3460–74. doi:10.1002/hyp.10372.

van der Velde, Y., P. J. F. Torfs, S. E. A. T. M. van der Zee, and R. Uijlenhoet. 2012. Quantifying catchment-scale mixing and its effects on time-varying travel time distributions. Water Resources Research 48:W06536. doi:10.1029/2011WR011310.

Volkman, T. H. M., K. Haberer, A. Gessler, and M. Weiler. 2016. High-resolution isotope measurements resolve rapid ecohydrological dynamics at the soil-plant interface. New Phytologist 210:839–49. doi:10.1111/nph.13868.

Wilson, D., H. Hisdal, and D. Lawrence. 2010. Has streamflow changed in the Nordic countries? Recent trends and comparisons to hydrological projections. Journal of Hydrology 394 (3–4):334–46. doi:10.1016/j.jhydrol.2010.09.010.

Woo, M., and P. Steer. 1979. Measurement of trace rainfall at a high Arctic site. Arctic 32 (1):80–84. http://www.jstor.org/stable/40508945.