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Spatiotemporal variability of oxygen isotope compositions in three contrasting glacier river catchments in Greenland

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Abstract

Analysis of stable oxygen isotope (δ^{18}O) characteristics is a useful tool to investigate water provenance in glacier river systems. In order to attain knowledge on the diversity of spatio-temporal δ^{18}O variations in glacier rivers, we have examined three glacierized catchments in Greenland with different areas, glacier hydrology and thermal regimes. At Mittivakkat Gletscher River, a small river draining a local temperate glacier in south-east Greenland, diurnal oscillations in δ^{18}O occur with a three-hour time lag to the diurnal oscillations in runoff. Throughout the peak flow season the δ^{18}O composition is controlled by the proportion between snowmelt and ice melt with episodic inputs of rainwater and occasional storage and release of a specific water component due to changes in the subglacial drainage system. At Kuannersuit Glacier River on the island Qeqertarsuaq, the δ^{18}O characteristics were examined after the major 1995–1998 glacier surge event. Despite large variations in the δ^{18}O values of glacier ice on the newly formed glacier tongue, there were no diurnal oscillations in the bulk meltwater emanating from the glacier in the post-surge years 2000–2001. In 2002 there were indications of diurnal oscillations, and in 2003 there were large diurnal fluctuations in δ^{18}O. At Watson River, a large catchment at the western margin of the Greenland Ice Sheet, the spatial distribution of δ^{18}O in the river system was applied to fingerprint the relative runoff contributions from sub-catchments. Spot sampling indicates that during the early melt season most of the river water (64–73 %) derived from the Qinnguata Kuussua tributary, whereas the water flow on 23 July 2009 was dominated by bulk meltwater from the Akuliarusiarsuup Kuua tributary (where 7 and 67 % originated from the Russell Glacier and Leverett Glacier sub-catchments, respectively). A comparison of the δ^{18}O compositions from glacial river water in Greenland shows distinct differences between water draining local glaciers (between −17.4 and −13.7 ‰), large ice caps (between −23.0 and −17.8 ‰) and the Greenland Ice Sheet (between −29.9 and −23.2 ‰).

1 Introduction

Stable oxygen isotopes are natural conservative tracers in low-temperature hydrological systems (e.g. Moser and Stichler, 1980; Gat and Gonfiantini, 1981; Haldorsen et al., 1997; Kendall et al., 2013). Consequently, oxygen isotopes can be applied to determine the timing and origin of changes in water sources and flow paths because different water sources often have isotopically different compositions due to their exposure to different isotopic fractionation processes. Since the 1970s, this technique has been widely used for hydrograph separation (Dinçer et al., 1970). Most often a conceptual two-component mixing model is applied, where an *old water* component (e.g. groundwater) is mixed with a *new water* component (e.g. rain or snowmelt), assuming that both components have spatial and temporal homogeneous compositions. The general mixing model is given by the equation

$$QC = Q_1C_1 + Q_2C_2 + \ldots, \tag{1}$$

where the discharge Q and the isotopic value C are equal to the sum of their components. This simplified model has limitations when a specific precipitation event is analysed because the water isotope composition in precipitation (*new water*) may vary considerably during a single event (e.g. McDonnell et al., 1990) and changes in contributions from secondary *old water* reservoirs may occur (e.g. Hooper and Shoemaker, 1986). Nevertheless, water isotope mixing models still provide valuable information on spatial differences in hydrological processes on diurnal to annual timescales (Kendall et al., 2013).

A region where there is an urgent need for improving our understanding of the controls on water sources and flow paths is in Greenland. As in other parts of the Arctic, glacierized catchments in Greenland are highly sensitive to climate change (Milner et al., 2009; Blaen et al., 2014). In recent decades freshwater runoff from the Greenland Ice Sheet (GrIS) to adjacent seas has increased significantly (Hanna et al., 2005, 2008; Bamber et al., 2012; Mernild and Liston, 2012), and the total ice mass loss from the

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GrIS contributes with 0.33 mm sea level equivalent yr^{-1} to global sea level rise (1993–2010; Vaughan et al., 2013). In addition, ice mass loss from local glaciers (i.e. glaciers and ice caps peripheral to the GrIS; Weidick and Morris, 1998) has resulted in a global sea level rise of 0.09 mm sea level equivalent yr^{-1} (1993–2010; Vaughan et al., 2013). The changes in runoff are coupled to recent warming in Greenland (Hanna et al., 2012, 2013; Mernild et al., 2014), an increasing trend in precipitation and changes in precipitation patterns (Bales et al., 2009; Mernild et al., 2015a), and a decline in albedo (Bøggild et al., 2010; Tedesco et al., 2011; Box et al., 2012; Yallop et al., 2012; Mernild et al., 2015b). Also, extreme surface melt events have occurred in recent years (Tedesco et al., 2008, 2011; van As et al., 2012) and in July 2012 more than 97 % of the GrIS experienced surface melting (Nghiem et al., 2012; Keegan et al., 2014). In this climate change context, detailed catchment-scale studies on water source and water flow dynamics are urgently needed to advance knowledge of the potential consequences of future hydrological changes in Greenlandic river catchments. This knowledge has relevance on a local scale too because it will assist with water management such as flood control and hydropower production.

In glacier-fed river systems, the principal water sources to bulk runoff derive from ice melt, snowmelt, rainfall and groundwater components. Depending on the objectives of the study and on the environmental setting, hydrograph separation of glacial rivers has been based on assumed end-member isotope-mixing between two or three prevailing components (Behrens et al., 1971, 1978; Fairchild et al., 1999; Mark and Seltzer, 2003; Theakstone, 2003; Yde and Knudsen, 2004; Mark and McKenzie, 2007; Yde et al., 2008; Bhatia et al., 2011; Kong and Pang, 2012; Ohlanders et al., 2013; Blaen et al., 2014; Dahlke et al., 2014; Hindshaw et al., 2014; Meng et al., 2014; Penna et al., 2014; Rodriguez et al., 2014; Zhou et al., 2014). As glacierized catchments deviate in size, altitudinal range, hypsometry, degree of glaciation, and thermal and morphological glacier types, isotope hydrograph separation often requires that the primary local controls on runoff generation are identified in order to analyse the variability in isotope time-series. In detailed studies it may even be necessary to divide a main component

such as ice melt into several ice facies sub-components (Yde and Knudsen, 2004). However, in highly glacierized catchments the variability in oxygen isotope composition is generally controlled by seasonal snowmelt and ice melt with episodic inputs of rainwater, whereas contributions from shallow groundwater flow may become important in catchments, where glaciers comprise a small proportion of the total area (e.g. Blaen et al., 2014).

In this study, we examine the oxygen isotope composition in three Greenlandic glacier river systems, which are selected for this study because they are draining very different glaciological environments (Fig. 1): Mittivakkat Gletscher River (13.6 km^2) drains a local glacier in southeast Greenland; Watson River (∼ 9743 km^2) drains a sector of the GrIS in West Greenland; and Kuannersuit Glacier River (258 km^2) drains a local glacier on the island Qeqertarsuaq, West Greenland, that recently experienced a major glacier surge event. Our aim is to determine the magnitude and variability of the hydrological processes that govern the oxygen isotope composition in contrasting glacierized catchments with land-terminating glaciers. First, we present the results and interpretations from each glacier river setting. Then, we compare our findings with previous investigations to characterize the oxygen isotope composition in Greenlandic glacier rivers.

2 Study sites

2.1 Mittivakkat Gletscher River, Ammassalik Island, southeast Greenland

Mittivakkat Gletscher (65°41′ N, 37°50′ W) is the largest glacier complex on Ammassalik Island, southeast Greenland (Fig. 2a). The entire glacier covers an area of 26.2 km^2 (in 2011; Mernild et al., 2012a) and has an altitudinal range between 160 and 880 m a.s.l. (Mernild et al., 2013a). Bulk meltwater from the glacier drains primarily westwards to the proglacial Mittivakkat Valley and emanates into the Sermilik Fjord. The sampling site is located at a hydrometric station 1.3 km down-valley from the main subglacial meltwater portal and defines a hydrological catchment area of 13.6 km^2, of which 9.0 km^2 are glacierised (66 %). The maritime climate is Low Arctic with annual precipitation ranging from 1400 to 1800 mm water equivalent (w.e.) yr^{-1} (1998–2006) and a mean annual air temperature at 515 m a.s.l. of −2.2 °C (1993–2011) (updated from Mernild et al., 2008a). There are no observations of contemporary permafrost in the area, and the proglacial vegetation cover is sparse.

The glacier has undergone continuous recession since the end of the Little Ice Age (Knudsen et al., 2008; Mernild et al., 2011a). In recent decades the recession has accelerated and the glacier has lost approximately 29 % of its volume between 1994 and 2012 (Yde et al., 2014a), and surface mass balance measurements indicate a mean thinning rate of 1.01 m w.e. yr^{-1} between 1995/1996 and 2011/2012 (Mernild et al., 2013a). Similar to other local glaciers in the Ammassalik region, Mittivakkat Gletscher is severely out of contemporary climatic equilibrium (Mernild et al., 2012a, 2013b) and serves as a type location for studying the impact of climate change on glacierized river catchments in southeast Greenland (e.g. Mernild et al., 2008b, 2015b; Bárcena et al., 2010, 2011; Kristiansen et al., 2013; Lutz et al., 2014).

2.2 Kuannersuit Glacier River, Qeqertarsuaq, West Greenland

Kuannersuit Glacier (69°46′ N, 53°15′ W) is located in central Qeqertarsuaq (formerly Disko Island), West Greenland (Fig. 2b). It is an outlet glacier descending from the Sermersuaq ice cap and belongs to the Qeqertarsuaq–Nuussuaq surge cluster (Yde and Knudsen, 2007). In 1995, the glacier started to surge down the Kuannersuit Valley with a frontal velocity up to 70 m day^{-1} (Larsen et al., 2010). By the end of 1998 or beginning of 1999, the surging phase terminated and the glacier went into its quiescent phase, which is presumed to last more than hundred years (Yde and Knudsen, 2005a). The 1995–1998 surge of Kuannersuit Glacier is one of the largest land-terminating surge events ever recorded; the glacier advanced 10.5 km down-valley and approximately 3 km^3 of ice were moved to form a new glacier tongue (Larsen et al., 2010).

Kuannersuit Glacier River emanates from a portal at the western side of the glacier terminus and the sampling site is located 200 m down-stream (Yde et al., 2005a). The catchment area covers 258 km^2 of which Kuannersuit Glacier constitutes 103 km^2 of the total glacierized area of 168 km^2 with an altitude range of 100–1650 m a.s.l. (Yde and Knudsen, 2005a). The valley floor consists of unvegetated outwash sediment, dead-ice deposits and ice-cored, vegetated terraces. The proglacial area of the catchment is situated in the continuous permafrost zone (Yde and Knudsen, 2005b), and the climate is polar continental (Humlum, 1999). There are no meteorological observations from the area, but at the coastal town of Qeqertarsuaq (formerly Godhavn) located 50 km to the southwest the MAAT were −2.7 and −1.7 °C in 2011 and 2012, respectively (Cappelen, 2013).

2.3 Watson River, West Greenland

Watson River (67°00′ N, 50°41′ W) drains a sector of the Greenland Ice Sheet (GrIS) in central West Greenland (Fig. 2c). Hasholt et al. (2013) recently estimated the catchment area to 9743 km^2, but the dynamic nature of drainage flow-paths in ice sheets makes an accurate estimation difficult. The proglacial part of the river system is 25–35 km in length and consists of two tributaries: Akuliarusiarsuup Kuua to the north and Qinnguata Kuussua to the south. While Akuliarusiarssuup Kuua comprises the most well-examined land-terminating GrIS outlet glaciers (Russell Glacier and Leverett Glacier), no glacio-hydrological studies have yet been conducted in Qinnguata Kuussua.

The primary sampling site is located after the junction of the tributaries and ∼ 500 m from where Watson River drains into the fjord Kangerlussuaq (Søndre Strømfjord) (Yde et al., 2014b). Other sampling sites are situated along the river in Akuliarusiarsuup Kuua and at a site in Qinnguata Kuussua ∼ 700 m upstream from the junction (Fig. 2c). Sampling during the 1992 melt season took place at site #4 downstrem of Russell Glacier and 4 km from the glacier margin in Qinnguata Kuussua (Fig. 2c). At the mouth of Watson River, the 2001–2010 MAAT was −3.7 °C (Cappelen, 2013) and permafrost is continuously distributed in the proglacial area (van Tatenhove and Olsen, 1994; Christiansen et al., 2010). The climate is characterized as a polar desert with a mean annual precipitation of only 149 mm at the river mouth (1961–1990; Cappelen, 2013) and even drier conditions further inland (van den Broeke et al., 2009).

This sector of the ice sheet margin experienced a period of frontal advance between 1968 and 1999 (van Tatenhove, 1996; Knight et al., 2000). Since then, the ice sheet periphery has thinned without receding. Recently, several studies have examined the hydrology, hydrochemistry and glacial microbiology of the catchment (Bartholomew et al., 2010; Hodson et al., 2010; Mernild et al., 2010, 2011b, 2012b; Wimpenny et al., 2010, 2011; Cook et al., 2012; Cowton et al., 2012; Rennermalm et al., 2012, 2013; Ryo and Jacobson, 2012; Stibal et al., 2012a–d; Telling et al., 2012; van As et al., 2012; Yallop et al., 2012; Bellas et al., 2013; Chandler et al., 2013; Hasholt et al., 2013; Meierbachtol et al., 2013; Dieser et al., 2014; Graly et al., 2014; Hawkings et al., 2014; Hindshaw et al., 2014; Lawson et al., 2014; Yde et al., 2014b; Clason et al., 2015). In particular, jökulhlaups from ice-dammed lakes in the Akuliarusiarsuup Kuua tributary have received attention (Sugden et al., 1985; Russell and de Jong, 1988; Russell, 1989, 1993a, b, 2007, 2009; Russell et al., 1990, 1995, 2011; Česnulevičius et al., 2009; Mernild and Hasholt, 2009; Carrivick et al., 2013; Mikkelsen et al., 2013). Hence, the Watson River catchment and its sub-catchments are key locations for studies that provide significant improvements of our knowledge of hydrological, glaciological and ecosystem processes occurring at the GrIS margin.

3 Sampling and analysis

All water samples were collected manually in 20 mL vials. Snow and ice samples were collected in 250 mL polypropylene bottles or plastic bags before being slowly melted at room temperature and decanted to 20 mL vials. The vials were stored in cold (~ 5 °C) and dark conditions to avoid fractionation related to biological activity.

The relative deviations (δ) of wter isotope compositions ($^{18}O/^{16}O$ and D/H) were expressed in per mil (‰) relative to Vienna Standard Mean Ocean Water (0 ‰) (Coplen, 1996). The stable oxygen isotope analyses of all samples from Mittivakkat Glacier River and Kuannersuit River and most samples from Watson River were performed at the Niels Bohr Institute, University of Copenhagen, Denmark, using mass spectrometry with an instrumental precision of ±0.1 ‰ in the oxygen isotope ratio ($\delta^{18}O$) value. The 1992 samples from Watson River were analyzed at the Alfred Wegener Institute in Bremerhaven, Germany.

In this study, we focused on $\delta^{18}O$, but it should be kept in mind that hydrograph separations based on $\delta^{18}O$ or δD may not necessarily produce similar results (Lyon et al., 2009), despite their mutual relations to the local meteoric water line (Craig, 1961; Dansgaard, 1964). This deviation is likely to occur in dry environments such as in the Watson River catchment, where kinetic effects during evaporation and sublimation processes may cause deviations in the isotopic fractionation of $\delta^{18}O$ and δD (Johnsen et al., 1989). This issue with different results obtained by using different isotopes has not been addressed for glacier-fed river systems and the potential discrepancy is therefore not known.

Stage–discharge relationships were used to determine runoff at each study site. For details on runoff measurements we refer to Hasholt and Mernild (2006) for Mittivakkat Gletscher River and Yde et al. (2005) for Kuannersuit Glacier River. The accuracy of individual runoff measurements is within ±10–15 %.

4 Results and discussion

4.1 Mittivakkat Gletscher River

The Mittivakkat Gletscher River catchment makes an ideal site for investigating temporal variations in the oxygen isotope composition of glacial river water due to the potential for linking these investigations to other ongoing studies. For instance, information

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on $\delta^{18}O$ is valuable for validating the proportional contributions of snowmelt and ice melt in dynamic glacier models, which aim to elucidate future climate-driven changes in glacier volume and runoff generation. On Mittivakkat Gletscher, three snow pits were excavated at different altitudes in May 1999, showing a mean $\delta^{18}O$ composition of -16.5 ± 0.6 ‰ in winter snow (Dissing, 2000). Also, two ice-surface $\delta^{18}O$ records of 2.84 and 1.05 km in length (10 m sampling increments) were obtained from the glacier terminus towards the equilibrium line (Boye, 1999). The glacier ice $\delta^{18}O$ ranged between -15.0 and -13.3 ‰ with a mean $\delta^{18}O$ of -14.1 ‰, and the theoretical altitudinal effect (Dansgaard, 1964) of higher $\delta^{18}O$ towards the equilibrium line altitude (ELA) was not observed. The reasons for an absence of a $\delta^{18}O$ lapse rate are most likely due to the limited size and altitudinal range of Mittivakkat Gletscher, but ice dynamics, ice age and meteorological conditions, such as frequent inversion (Mernild and Liston, 2010), may also have an impact. Based on these observations it is evident that end-member snowmelt has a relatively low $\delta^{18}O$ compared to end-member ice melt and that these two water source components can be separated. The $\delta^{18}O$ of summer rain has not been determined in this region, but at the coastal village of Ittoqqortoormiit, located ~ 840 km to the north of Mittivakkat Gletscher, observations show monthly mean $\delta^{18}O$ in rainwater of -12.8, -9.1 and -8.8 ‰ in June, July and August, respectively (data available from the International Atomic Energy Agency database WISER).

Oxygen isotope samples were collected from Mittivakkat Gletscher River during the years 2003–2009 (Table 1). Most of the sampling campaigns were conducted in August at the end of the peak flow period (i.e. the summer period with relative high runoff), where the mean annual $\delta^{18}O$ value was -14.68 ± 0.18 ‰ (here and elsewhere the uncertainty of $\delta^{18}O$ is given by the standard deviation). We conducted three multi-sample tests at 14:00 LT (local time) on 9, 15 and 21 August 2004 to determine the combined uncertainty related to sampling and analytical error. The tests show standard deviations of 0.08 ‰ ($n = 25$), 0.06 ‰ ($n = 5$) and 0.04 ‰ ($n = 10$), respectively, which are lower than the instrumental precision.

In the years 2005 and 2008, meltwater was also collected during the early melt season (i.e. the period before the subglacial drainage system is well-established) to evaluate the seasonal variability in the $\delta^{18}O$ signal. In 2005, the onset of ice melt had commenced before the early melt season sampling campaign, as reflected in $\delta^{18}O$ ranging from -15.16 ‰ in late May to -14.35 ‰ in mid-June (Fig. 3a). During this period $\delta^{18}O$ increased by 0.04 ‰ per day, which is equal to a daily increase of 1.7 in the ice melt-to-snowmelt ratio, assuming end-member $\delta^{18}O$ compositions of snowmelt and ice melt as observed in snow and ice samples. In contrast, the 2008 onset of ice melt was delayed and snowmelt totally dominated the bulk composition of the river water, except on 30 May 2008 where a rainfall event (19 mm in the nearby town of Tasiilaq; Cappelen, 2013) caused a positive peak in $\delta^{18}O$ of ~ 1 ‰ (Fig. 3b). Episodic effects on $\delta^{18}O$ by precipitation seem common. For instance, another short-term change occurred on 14–15 August 2005 (Fig. 3a), where a negative peak in $\delta^{18}O$ of ~ 2 ‰ coincided with a snowfall event (14 mm in Tasiilaq; Cappelen, 2013) and subsequent elevated contribution from snowmelt.

The most intensively sampled period was from 8 to 22 August 2004, where sampling was conducted with a 4 h frequency supplemented by short periods of higher frequency sampling. We use these 2004 data to assess oxygen isotope dynamics in the Mittivakkat Gletscher River during the peak flow period when the subglacial drainage system is assumed to be well-established, transporting the majority of meltwater in a channelized network. In Fig. 4, the 2004 $\delta^{18}O$ time-series is shown together with runoff (at the hydrometric station), air temperature (at a nunatak at 515 m a.s.l.) and electrical conductivity (at the hydrometric station; corrected to 25 °C). There was no precipitation during the entire sampling period, except for some drizzle on 8 August prior to the collection of the first sample. The time-series shows characteristic diurnal variations in $\delta^{18}O$ composition, e.g. on 9–10 and 16–18 August 2004. However, the diurnal pattern was severely disturbed at around 03:00 LT on 11 August. The hydrograph shows that during the falling limb the runoff suddenly remained constant, coinciding with an air temperature increase and a change in $\delta^{18}O$ from decreasing to slightly in-

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creasing values. The runoff stayed almost constant until a rapid 39 % increase in runoff occurred at 13:00 LT on 12 August, accompanied by an increase in δ^{18}O and decrease in electrical conductivity. Thereafter, runoff remained at an elevated level for more than two days before retaining the diurnal oscillation pattern again. Hydrograph separation of water sources is a helpful tool to elucidate the details of this event.

We apply time-series cubic spline interpolation to estimate δ^{18}O at one-hour time-step increments, matching the temporal resolution of the runoff observations. This approach allows a better assessment of the diurnal δ^{18}O signal. For instance, it shows that the δ^{18}O signal lags three hours behind runoff ($r^2 = 0.66$; linear correlation without lag shows $r^2 = 0.58$), indicating the combined effect of the two primary components, snowmelt and ice melt, on the δ^{18}O variations. The diurnal amplitude in δ^{18}O ranged between 0.11 ‰ (11 August 2004) and 0.49 ‰ (16 August 2004). However, there was no statistical relation between diurnal δ^{18}O amplitude and daily air temperature amplitude ($r^2 = 0.28$), indicating that other forcings than variability in surface melting may have a more dominant effect on the responding variability in δ^{18}O.

Based on the assumption that snowmelt and ice melt reflect their end-member δ^{18}O compositions, a hydrograph showing contributions from snowmelt and ice melt is constructed for the 2004 sampling period (Fig. 5). The ice melt component constitutes 82 ± 5 % of the total runoff and dominates the observed variations in total runoff ($r^2 = 0.99$). This is expected late in the peak flow season, where the subglacial drainage mainly occurs in a channelized network in the lower part of the glacier. The slightly decreasing trend in the daily snowmelt component is likely a consequence of the diminishing snow cover on the upper part of the glacier. The snowmelt component peaks around 10:00–13:00 LT each day, reflecting the long distance from the melting snowpack to the proglacial sampling site and the existence of an inefficient distributed subglacial drainage network in the upper part of the glacier.

The most likely reason for an abrupt change in glacial runoff, such as the one observed during the early morning of 11 August 2004 followed by the sudden release of water 34 h later, is a roof collapse causing ice-block damming of a major subglacial

channel. The hydrograph separation (Fig. 5) shows that the proportion between ice melt and snowmelt remains almost constant after the event commenced, indicating that the bulk water derived from a well-mixed part of the drainage system, which is unaffected by the large diurnal variation in ice melt generation. This suggests that the functioning drainage network transports meltwater from the upper part of the glacier with limited connection to the drainage network on the lower part. Meanwhile, ice melt is stored in a dammed section of the subglacial network located in the lower part of the glacier, and suddenly released when the dam breaks at 13:00 LT on 12 August (Fig. 5). In the following hours ice melt comprised up to 94 % of the total runoff. On 13 August the snowmelt component peaked at noon but then dropped markedly and in the evening it only constituted 4 % of the total runoff. On 14 August there were still some minor disturbances in the lower drainage network, but from 15 August the drainage system had stabilized and the characteristic diurnal glacionival oscillations had taken over (Figs. 4 and 5).

4.2 Kuannersuit Glacier River

During five field seasons in July 2000, 2001, 2002, 2003 and 2005, oxygen isotope samples were collected from Kuannersuit Glacier River (Table 2). The observed mean annual δ^{18}O was -19.58 ± 0.55 ‰ (the uncertainty is given by the standard deviation). A consequence of the surge event was that the glacier front was relocated from a position at an altitude of ~ 500 to 100 m a.s.l., while a significant part of the glacier surface in the accumulation area was lowered by more than 100 m to altitudes below the ELA (~ 1100–1300 m a.s.l.). A helicopter survey in July 2002 revealed that the post-surge accumulation area ratio was less than 20 % (Yde et al., 2005a). Hence, we assume that the primary post-surge water source during the peak flow period is ice melt, particularly from ablation of the new glacier tongue. However, longitudinal and transverse ice sample transects on the new glacier tongue show large fluctuations in δ^{18}O (Fig. 6). The longitudinal transect was sampled along the centreline but showed unsystematic fluctuations on a 500 m sampling increment scale. In contrast, the transverse transect, which was sampled 3250 m up-glacier with 50 m increments, showed a more systematic trend where relatively high $\delta^{18}O$ values were observed along both lateral margins. From the centre towards the western margin an increasing trend of 0.46 ‰ per 100 m prevailed, whereas the eastern central part showed large fluctuations in $\delta^{18}O$ between −22.69 and −20.08 ‰. The total range of measured $\delta^{18}O$ in glacier ice along the transverse transect was 4.14 ‰. A possible explanation of this marked spatial variability may be that the ice forming the new tongue derived from different pre-surge reservoirs on the upper part of the glacier. If so, it is very likely that the marginal glacier ice was formed at relatively low elevations (high $\delta^{18}O$ signal), whereas the glacier ice in the western central part mainly derived from high elevation areas of Sermersuaq ice cap (low $\delta^{18}O$ signal). At present, there are no comparable studies on transverse variations in $\delta^{18}O$ across glacier tongues. It is therefore unknown whether a high variability in $\delta^{18}O$ is a common phenomenon or related specific circumstances such as surge activity or present of tributary glaciers.

During the surge event, a thick debris-rich basal ice sequence was formed beneath the glacier and exposed along the glacier margins and at the glacier terminus (Yde et al., 2005b; Roberts et al., 2009; Larsen et al., 2010). The basal ice consisted of various genetic ice facies, where different isotopic fractionation processes during the basal ice formation resulted in variations in the $\delta^{18}O$ composition. The $\delta^{18}O$ in massive stratified ice was -16.6 ± 1.9 ‰ ($n = 10$); in laminated stratified ice it was -19.6 ± 0.7 ‰ ($n = 9$) and in dispersed ice it was -18.8 ± 0.6 ‰ ($n = 41$) (Larsen et al., 2010). The glacier ice above the profiles showed $\delta^{18}O$ of -19.4 ± 0.9 ‰ ($n = 20$; lower section with debris layers formed by thrusting) and -19.8 ± 1.1 ‰ ($n = 37$; upper section without debris layers) (Larsen et al., 2010). Also, during the termination of the surge event in the winter 1998/1999 proglacial naled (extrusive ice assemblage formed in front of the glacier by rapid freezing of winter runoff and/or proglacial upwelling water mixed with snow) was stacked into ∼ 3 m thick sections of thrust-block naled at the glacier front, as the glacier advanced into the naled (Yde and Knudsen, 2005b; Yde et al., 2005b; Roberts et al., 2009). A profile in a thrust-block naled section showed a $\delta^{18}O$ of

-20.05 ± 0.52 ‰ ($n = 60$; excluding a outlier polluted by rainwater; Yde and Knudsen, 2005b). In general, the basal ice and incorporated naled showed higher $\delta^{18}O$ than glacier ice at the central part of the tongue, but $\delta^{18}O$ of basal ice and naled were within the $\delta^{18}O$ range of marginal glacier ice. Hence, the ice melt component in bulk runoff comprised water from several ice facies sub-component sources with various $\delta^{18}O$ values and spatial variability. It was not possible to access snow on the upper part of the glacier, so no $\delta^{18}O$ values on snowmelt were measured. Rainwater was collected during rainfall events in July 2002, showing a wide range in $\delta^{18}O$ between −18.78 and −6.57 ‰ and a median $\delta^{18}O$ of -10.32 ± 4.49 ‰ ($n = 7$).

With the large $\delta^{18}O$ variations from different sources in mind, it is interesting to analyse the post-surge diurnal $\delta^{18}O$ signal. Figure 7 shows the diurnal $\delta^{18}O$ variations during four July days in the years 2000–2003. There was no diurnal oscillation in 2000 and 2001, but a tendency appeared in 2002 with low $\delta^{18}O$ (∼ −19.4 ‰) between 09:00 and 15:00 LT and high $\delta^{18}O$ (∼ −18.8 ‰) in the evening (20:00–02:00 LT). In 2003, the fluctuations were much larger than in the preceding years, but the highest $\delta^{18}O$ (−19.03 ‰) was measured at 21:00 LT and low $\delta^{18}O$ prevailed during the night (∼ 21.0 ‰). The trend in diurnal variability was also evident in the standard deviations, which increased from ±0.07 ‰ in 2000 to ±0.11, ±0.23 and ± 0.70 ‰ in 2001, 2002 and 2003, respectively. In comparison, multi-sampling tests were conducted in 2001, 2002 and 2003, showing a standard deviation variability of ±0.16 ‰ ($n = 5$), ±0.13 ‰ ($n = 17$) and ±0.44 ‰ ($n = 22$), respectively. This indicates that the glacier runoff was not well-mixed in 2003, probably because different parts of the drainage system merged close to the glacier portal.

Based on the available data, it is not possible to conduct hydrograph separation in the years following the surge event. The lack of strong diurnal oscillations indicates either a mono-source system, a well-mixed drainage network or a multi-source system, where the primary components have similar $\delta^{18}O$ compositions. The expected primary component, glacier ice melt, has lower $\delta^{18}O$ than bulk runoff and there must be additional contributions from basal ice melt (similar $\delta^{18}O$ composition as runoff), snowmelt (unknown $\delta^{18}O$ composition) or precipitation (higher $\delta^{18}O$ composition than runoff). We therefore hypothesize that the presence of a well-mixed drainage network is the most likely reason for the observed $\delta^{18}O$ signal in the bulk runoff from Kuannersuit Glacier.

During the surge event the glacier surface became heavily crevassed and the pre-existing drainage system collapsed (Yde and Knudsen, 2005a). It is a generally accepted theory that the drainage system of surging glaciers transform into a distributed network where meltwater is routed via a system of linked cavities (Kamb et al., 1985; Kamb, 1987), but little is known about how subglacial drainage systems evolve into discrete flow systems in the years following a surge event. In the initial quiescent phase at Kuannersuit Glacier, ongoing changes in the drainage system were evident by frequent loud noises from roof collapses inside the drainage system and episodic export of ice blocks from the portal. A consequence of these processes is also visible on the glacier surface, where circular collapse chasms formed above marginal parts of the subglacial drainage system (Yde and Knudsen, 2005a). In Fig. 8, some of the episodic damming and meltwater release events are seen as peaks on the runoff curve from July 2001. The 2001 runoff measurements showed diurnal oscillations with minimums around 10:00–12:00 LT and maximums at 19:00–20:00 LT, correlating with reversed oscillations in solutes (Yde et al., 2005a) and poorly with suspended sediment concentrations (Knudsen et al., 2007). However, the variability of $\delta^{18}O$ did not correlate with any of these variables.

4.3 Watson River

Sampling at Watson River was conducted in May, July and August in the years 2005, 2007 (a single sample), 2008 and 2009 (Table 3). In the peak flow period (e.g. July–August), the interannual mean $\delta^{18}O$ was -24.17 ± 0.20 ‰. The peak flow $\delta^{18}O$ deviated significantly from the mean $\delta^{18}O$ of -26.79 ± 0.40 ‰ in early melt season flow samples collected in May 2009. This is interesting because we would expect proglacial snowmelt

to have higher $\delta^{18}O$ than ice melt, as indicated by the mean $\delta^{18}O$ of -10.65 ± 1.24 ‰ in 14 local lakes (Yde, unpublished data) and $\delta^{18}O$ values ranging between -18.7 and -15.5 ‰ and -16 and -11 ‰ in ice-marginal snow samples collected at Paakitsup Akuliarusersua (275 km to the north; Reeh and Thomsen, 1993) and at "N Glacier" (117 km to the north; Bhatia et al., 2011), respectively. A potential provenance for meltwater with low $\delta^{18}O$ is the marginal zone of the ice sheet, which consists of an exposed basal ice sequence and an outer 300–400 m band of dark Pleistocene ice (locally referred to as velvet ice). The basal ice comprises various ice facies, which cover a wide range of $\delta^{18}O$ values between -32.7 and -24.6 ‰ (Knight, 1987, 1989; Yde et al., 2010). Reeh et al. (2002) compiled an 880 m ice-surface $\delta^{18}O$ record (2–10 m sampling increments) from the ice sheet margin in the Watson River catchment. The record showed an outer band of Pleistocene ice with a $\delta^{18}O$ of -33.0 ± 0.5 ‰ followed by an abrupt transition after 350 m to Holocene ice with a $\delta^{18}O$ of -28.0 ± 0.1 ‰ (Reeh et al., 2002). The $\delta^{18}O$ values of the Pleistocene ice in this record were consistent with a short ice-surface record sampled by Knight (1989), which showed the $\delta^{18}O$ values of Pleistocene ice ranging between -34.5 and -32.3 ‰. Based on the $\delta^{18}O$ compositions of these potential water sources and the fact that the catchment is located in a dry climate, where local summer precipitation is unlikely to contribute significantly to bulk runoff, we propose that river water in the early melt season derived from mixed proglacial snowmelt and ice-marginal ice melt. As the snowline rises towards the ELA, the $\delta^{18}O$ value in progressively exposed surface ice is expected to increase, while the $\delta^{18}O$ value in snowmelt above the snowline progressively decreases (Reeh and Thomsen, 1993). In combination, the altitudinal effect and a continental effect infer that as a precipitating cloud moves further inland on the GrIS, the $\delta^{18}O$ value of precipitating snow decreases (Dansgaard et al., 1973). The consequence of changing $\delta^{18}O$ in the primary water sources is that peak flow hydrograph separation based on assumed fixed end-member $\delta^{18}O$ compositions of snowmelt and ice melt is complicated in large ice sheet catchments.

Based on a strategy of two samples per day (morning and evening), there were no distinct diurnal oscillations in $\delta^{18}O$ during the peak flow periods of 2008 and 2009 in Watson River. However, in July 1992 two diurnal time-series from the river in front of Russell Glacier (sampling site #4) and one diurnal time-series from the Qinnguata Kussua tributary were obtained with a two-hour sampling frequency (Fig. 9). The 15/16 July 1992 time-series from Qinnguata Kuussua showed a diurnal signal in $\delta^{18}O$ with an amplitude of 2.71 ‰. At the sub-catchment of Russell Glacier, a diurnal $\delta^{18}O$ amplitude of 1.75 ‰ was observed on 30/31 July 1992, whereas no distinct signal was present on 22/23 July 1992. Also, Hindshaw et al. (2014) observed weak diurnal oscillations of 0.21 ± 0.15 ‰ in the sub-catchment of Leverett Glacier (based on two samples per day). It is likely that diurnal oscillations in $\delta^{18}O$ exist periodically in sub-catchment waters, but at the Watson River outlet mixing of water masses from sub-catchments with differences in transit time may obliterate the $\delta^{18}O$ signal, or the $\delta^{18}O$ signal may not have been captured by the time of sampling.

In the Watson River system the most useful application of stable water isotope analysis is likely to estimate the relative contributions from major sub-catchments. On three days in 2009 $\delta^{18}O$ samples were collected from Watson River and its two tributaries Akuliarusiarsuup Kuua (sampling site #7) and Qinnguata Kuussua (sampling site #8) all within a couple of hours of each other. Calculations of the relative contributions indicate that during the early melt season most of the water in Watson River (73 and 64 % on 26 and 28 May 2009, respectively) derived from the Qinnguata Kuussua system, whereas during the peak flow period most water (74 % on 23 July 2009) derived from the Akuliarusiarsuup Kuua system (Table 4). It must be emphasized that these results are based on a few spot samples and are therefore unlikely to show the full story of the seasonal dynamics in the river system. However, the results indicate that large variations in the relative proportion of water flow from the two tributaries do occur. This encourages further research on processes causing diurnal and seasonal scale variations in addition to analyses on rapid shifts in the relative proportion in water flow caused by

hydro-meteorological or hydrological episodic events such as extreme ablation on the ice sheet and catastrophic drainage of ice-marginal lakes.

The Akuliarusiarsuup Kuua tributary system consists of two major sub-catchments: the Russell Glacier and Leverett Glacier sub-catchments. The headwaters of the Russell Glacier sub-catchment (sampling site #1) had $\delta^{18}O$ values ranging between −28.79 and −26.86 ‰ during the peak flow period (Table 5), indicating that the dominating meltwater provenance was near-marginal melting of basal ice, Pleistocene ice and early Holocene ice (for details on this sampling site see Dieser et al., 2014). Two transects of the spatial variations in $\delta^{18}O$ downstream along the river in Akuliarusiarsuup Kuua show that during the early melt season (27 May 2009) the $\delta^{18}O$ values of the Akuliarusiarsuup Kuua tributaries were similar to the $\delta^{18}O$ value of Watson River after the junction with the Qinnguata Kuussua (Table 6). In contrast, there was a large discrepancy of 2.31 ‰ between the low $\delta^{18}O$ of the Russell Glacier tributary (sampling site #4) and the higher $\delta^{18}O$ after the junction with the Leverett Glacier tributary (sampling site #5) in the peak flow transect (28 July 2007). Assuming that the $\delta^{18}O$ value of the Leverett Glacier tributary was similar to the mean $\delta^{18}O$ of -23.90 ± 0.16 ‰ ($n = 74$) in July 2009 measured by Hindshaw et al. (2014), 76 % of the water in the Akuliarusiarsuup Kuua tributary derived from the Leverett Glacier sub-catchment on 28 July 2007 (Table 4). We can make a similar hydrograph separation for 23 July 2009 by using the morning $\delta^{18}O$ of −23.85 ‰ from the Leverett Glacier sub-catchment (Hindshaw et al., 2014), the $\delta^{18}O$ of −24.18 ‰ from the Akuliarusiarsuup Kuua tributary (Table 4) and assuming that the $\delta^{18}O$ of the Russell Glacier sub-catchment was similar to measured $\delta^{18}O$ of −27.19 ‰ on 4 August 2009. This calculation indicates that on 23 July 2009 the Leverett Glacier sub-catchment contributed with 67 % of the total water in the Watson River, whereas the Russell Glacier sub-catchment contributed with 7 % and the Qinnguata Kuussua tributary with 26 % (Table 4). This backs up earlier modelling studies, which suggest that the relatively small Russell Glacier sub-catchment receives meltwater sourced in the lower ablation area of the ice sheet (van de Wal and Russell, 1994).

The contribution from the proglacial area to Watson River is negligible compared to the contribution from bulk glacial meltwater. The largest input of non-glacial water comes from the lake Aajuitsup Tasia to the river in front of Russell Glacier (Fig. 2c). Although water from Aajuitsup Tasia had a high δ^{18}O of −11.94 ‰ on 27 May 2009, it did not cause any downstream changes in bulk δ^{18}O of the meltwater sampled upstream and downstream of the input source (Table 6). Also, field observations indicate that in recent years the discharge from Aajuitsup Tasia has ceased during the peak flow period.

4.4 Variability of δ^{18}O in glacier rivers

It is clear from the results above that glacier rivers in Greenland may have different δ^{18}O compositions. The bulk meltwater from Mittivakkat Gletscher has a δ^{18}O composition similar to the water draining the nearby local glacier Hobbs Gletscher and to waters from studied valley and outlet glaciers in Scandinavia, Svalbard, European Alps, Andes and Asia (Table 7). Meltwater in the early melt season is dominated by snowmelt with relatively high δ^{18}O, whereas diurnal oscillations with an amplitude between 0.11 and 0.49 ‰ exist during the peak flow period due to mixing of a dominant ice melt component and a secondary snowmelt component. Diurnal oscillations in δ^{18}O are common in meltwater from small, glacierized catchments; for instance, at Austre Okstindbreen, Norway, the average diurnal amplitude is approximately 0.2 ‰ (Theakstone, 1988; Theakstone and Knudsen, 1989, 1996a, b; Theakstone, 2003). However, at Glacier de Tsanfleuron, Switzerland, sampling in the later melt season (23–27 August 1994) showed no diurnal variations in δ^{18}O, which was interpreted by Fairchild et al. (1994) as a consequence of limited altitudinal range (less than 500 m) of the glacier. An alternative explanation may be that snowmelt only constituted so small a proportion of the meltwater in the late melt season that backscattering rendered water source discrimination impossible.

Lack of diurnal δ^{18}O oscillations was also observed at Kuannersuit Glacier during the initial quiescent phase after the major 1995–1998 surging event, although the last

results from 2005 indicate a progressive trend from isotopic homogeneous conditions in the emanating bulk meltwater towards the development of diurnal δ^{18}O oscillations. This is likely a consequence of stabilization of both the structure of the subglacial drainage system and a more permanent supraglacial routing of meltwater as the glacier surface changes from chaotically crevassed to a smooth surface (Yde and Knudsen, 2005a). The observed interannual variability at Kuannersuit Glacier River was larger than at the two other study sites, showing an interannual mean δ^{18}O of -19.58 ± 0.55 ‰ during the peak flow period. This may be explained by annual differences in the proportion of snowmelt. The large variability in δ^{18}O values in the transverse profile across the glacier tongue is another observation that requires more attention. The preliminary interpretation is that it is due to ice movement from different up-glacier reservoirs, but it is unknown whether this is a common phenomenon on large glacier with lateral tributary glaciers. At present, there are no similar stable water isotope studies of surge-type or large outlet glaciers. However, the δ^{18}O composition of Kuannersuit Glacier is similar to the δ^{18}O composition of the glacier Killersuaq, an outlet glacier from the ice cap Amitsulooq, which is located c. 100 km south of Watson River (Table 7). Here, Andreasen (1984) found that diurnal oscillations in δ^{18}O were prominent during the relatively warm summer of 1982, whereas no diurnal δ^{18}O oscillations were observed in 1983 because the glacier was entirely snow-covered throughout the ablation season, due to low summer surface mass balance caused by the 1982 El Chichón eruption (Ahlstrøm et al., 2007).

From the margin of the GrIS in West Greenland, we now have several studies on δ^{18}O dynamics in river water (Reeh and Thomsen, 1986, 1993; Yde and Knudsen, 2004; Bhatia et al., 2011; Hindshaw et al., 2014). In general, the δ^{18}O composition in bulk meltwaters from the ice sheet is much lower than in meltwaters draining glaciers and ice caps (Table 7). At small-scale GrIS catchments such as at Imersuaq and "N Glacier", the diurnal amplitudes in δ^{18}O are among the highest worldwide due to the large difference in δ^{18}O between various ice facies and snowmelt (Yde and Knudsen, 2004; Bhatia et al., 2011). At large-scale GrIS catchments such as at Watson River, temporal variations in δ^{18}O during the peak flow period are small and may be linked to episodic events, such as jökulhlaups or extreme ablation, or to long-term trends related to altitudinal increase of the snowline (Reeh and Thomsen, 1993).

5 Conclusions

In this study, we have examined the oxygen isotope hydrology in three of the most studied glacierized river catchments in Greenland to improve our understanding of the prevailing differences between contrasting glacial environments.

Diurnal oscillations in δ^{18}O were most conspicuous at the small-scale Mittivakkat Gletscher River catchment. This was due to the presence of an efficient subglacial drainage system and diurnal variation in the ablation rates of snow and ice that had distinguishable oxygen isotope compositions. Diversions from the prevailing diurnal pattern occurred due to episodic inputs of rainwater or minor changes within the subglacial drainage system, which caused storage and release of a specific water source component that may control the variability of the δ^{18}O composition for some days. A hydrograph separation revealed that diurnal oscillations in δ^{18}O lagged the diurnal oscillations in runoff by approximately three hours.

In contrast to the observations at Mittivakkat Gletscher River, no diurnal oscillations in δ^{18}O were observed at the medium-scale Kuannersuit Glacier River catchment in the years following a major glacier surge event. The most likely reason for this lack of diurnal oscillations was that meltwater was routed through a tortuous subglacial conduit network of linked cavities that was exposed to frequent damming by roof collapse. Five to six years after the surge event the subglacial drainage system had evolved into a more channelized system and stabilized enough to provide a weak isotopic signal of diurnal-scale changes in the proportional contributions between two components; most likely between a background signal from snowmelt on the upper part of the glacier and an ice melt signal from diurnal changes in ablation rates on the lower part of the glacier. It is also worth noting that the intense ablation on the newly formed glacier

tongue caused diurnal oscillations in runoff, solute export, and suspended sediment concentrations, but not in δ^{18}O.

At the large-scale Watson River catchment, which drains a sector of the GrIS, diurnal oscillations in δ^{18}O appeared in sub-catchment waters, however, a higher sampling frequency (> twice per day) and additional sampling sites are required to determine whether diurnal oscillations are obliterated after mixing of tributary river water.

On seasonal scale, snowmelt dominated in the early melt season at Mittivakkat Gletscher River, but as the snowline increased in altitude ice melt subsequently became the dominant water source. At Watson River, the climate is dry and meltwater in the early melt season primarily derived from melting of near-marginal basal ice, Pleistocene ice and early Holocene ice with relatively low δ^{18}O values. During the peak flow period, ice melt dominated at all three locations.

Spatial variability in δ^{18}O was observed along a proglacial river transect in the Watson River system. Hydrograph separation based on spot sampling on 23 July 2009 indicated that on this particular date approximately two-thirds of the water in Watson River derived from the Leverett sub-catchment of the Akuliarusiarsuup Kuua tributary and one-fourth from the Qinnguata Kuussua tributary. This is contrast to spot sampling in the early melt season, which indicates that the majority of water derives from Qinnguata Kuussua tributary, and encourages further research on the water flow dynamics of the river system. This study also revealed a systematic variability in δ^{18}O along a transverse transect on the tongue of Kuannersuit Glacier that calls for more attention.

This study has showed that environmental and physical contrasts in glacier river catchments influence the spatio-temporal variability of the δ^{18}O compositions. In GrIS waters (between −29.9 and −23.2 ‰) and water from large Greenland ice caps (between −23.0 and −17.8 ‰), the δ^{18}O compositions differ markedly from the δ^{18}O compositions in water draining small local glaciers in Greenland (between −17.4 and −13.7 ‰) and valley glaciers worldwide.

The results of this study reinforce that analysis of stable water isotopes is a useful tool to discriminate between temporal variations in meltwater production from snowmelt and ice melt in glacier river water emanating from small glaciers. It is therefore likely that snowmelt and ice melt estimates based on isotope hydrology have the potential to validate modelled snowmelt and ice melt estimates. However, this study finds that for large catchments along the margin of the GrIS it is more useful to apply δ^{18}O to estimate the proportional contributions from sub-catchments, which may be linked to large-scale runoff and mass balance modelling.

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References

Ahlstrøm, A. P., Bøggild, C. E., Olesen, O. B., Petersen, D., and Mohr, J. J.: Mass balance of the Amitsulôq ice cap, West Greenland, IAHS-AISH P., 318, 107–115, 2007.

Andreasen, J.-O.: Ilt-isotop undersøgelse ved Kidtlessuaq, Vestgrønland, PhD dissertation, University of Aarhus, Aarhus, p. 33, 1984.

Bárcena, T. G., Yde, J. C., and Finster, K. W.: Methane flux and high-affinity methanotrophic diversity along the chronosequence of a receding glacier in Greenland, Ann. Glaciol., 51, 23–31, 2010.

Bárcena, T. G., Finster, K. W., and Yde, J. C.: Spatial patterns of soil development, methane oxidation, and methanotrophic diversity along a receding glacier forefield, southeast Greenland, Arct., Antarct. Alp. Res., 43, 178–188, 2011.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M. A., and Sole, A.: Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier, Nat. Geosci., 3, 408–411, 2010.

Behrens, H., Bergmann, H., Moser, H., Rauert, W., Stichler, W., Ambach, W., Eisner, H., and Pessl, K.: Study of the discharge of Alpine glaciers by means of environmental isotpes and dye tracers, Z. Gletscherk. Glazialgeol., 7, 79–102, 1971.

Behrens, H., Moser, H., Oerter, H., Rauert, W., and Stichler, W.: Models for the runoff from a glaciated catchment area using measurements of environmental isotope contents, in: Proceedings of the International Symposium on Isotope Hydrology, International Atomic Energy Agency, Vienna, 829–846, 1978.

Bellas, C. M., Anesio, A. M., Telling, J., Stibal, M., Tranter, M., and Davis, S.: Viral impacts on bacterial communities in Arctic cryoconite, Environ. Res. Lett., 8, 045021, doi:10.1088/1748-9326/8/4/045021, 2013.

Bhatia, M. P., Das, S. B., Kujawinski, E. B., Henderson, P., Burke, A., and Charette, M. A.: Seasonal evolution of water contributions to discharge from a Greenland outlet glacier: insight from a new isotope-mixing model, J. Glaciol., 57, 929–941, 2011.

Blaen, P. J., Hannah, D. M., Brown, L. E., and Milner, A. M.: Water source dynamics of high Arctic river basins, Hydrol. Process., 28, 3521–3538, 2014.

Bøggild, C. E., Brandt, R. E., Brown, K. J., and Warren, S. G.: The ablation zone in Northeast Greenland: ice types, albedos and impurities, J. Glaciol., 56, 101–113, 2010.

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, The Cryosphere, 6, 821–839, doi:10.5194/tc-6-821-2012, 2012.

Boye, B.: En undersøgelse af variationer i δ^{18}O-indholdet i prøver indsamlet på Mittivakkat gletscheren i Østgrønland, Ms thesis, Aarhus University, Aarhus, p. 101, 1999.

Cappelen, J.: Weather observations from Greenland 1958–2012, Danish Meteorological Institute Technical Report 13-11, Danish Meteorological Institute, Copenhagen, p. 23, 2013.

Carrivick, J. L., Turner, A. G. D., Russell, A. J., Ingeman-Nielsen, T., and Yde, J. C.: Outburst flood evolution at Russell Glacier, western Greenland: effects of a bedrock channel cascade with intermediary lakes, Quaternary Sci. Rev., 67, 39–58, 2013.

Česnulevičius, A., Šeirenė, V., Kazakauskas, V., Baltrūnas, V., Šinkūnas, P., and Karmaza, B.: Morphology and sediments of ice-dammed lake after its outburst, West Greenland, Geologija, 51, 42–52, 2009.

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Chandler, D. M., Wadham, J. L., Lis, G. P., Cowton, T., Sole, A., Bartholomew, I., Telling, J., Nienow, P., Bagshaw, E. B., Mair, D., Vinen, S., and Hubbard, A.: Evolution of the subglacial drainage system beneath the Greenland Ice Sheet revealed by tracers, Nat. Geosci., 6, 195–198, 2013.

Christiansen, H. H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J., Holmlund, P., Sannel, A. B. K., Sigsgaard, C., Åkerman, H. J., Foged, N., Blikra, L. H., Pernosky, M. A., and Ødegård, R. S.: The thermal state of permafrost in the Nordic area during the International Polar Year 2007–2009, Permafrost Periglac., 21, 156–181, 2010.

Clason, C. C., Mair, D. W. F., Nienow, P. W., Bartholomew, I. D., Sole, A., Palmer, S., and Schwanghart, W.: Modelling the transfer of supraglacial meltwater to the bed of Leverett Glacier, Southwest Greenland, The Cryosphere, 9, 123–138, doi:10.5194/tc-9-123-2015, 2015.

Cook, J. M., Hodson, A. J., Anesio, A. M., Hanna, E., Yallop, M., Stibal, M., Telling, J., and Huybrechts, P.: An improved estimate of microbially mediated carbon fluxes from the Greenland ice sheet, J. Glaciol., 58, 1098–1108, 2012.

Coplen, T. B.: New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data, Geochim. Cosmochim. Acta, 60, 3359–3360, 1996.

Cowton, T., Nienow, P., Bartholomew, I., Sole, A., and Mair, D.: Rapid erosion beneath the Greenland ice sheet, Geology, 40, 343–346, 2012.

Craig, H.: Isotopic variations in meteoric waters, Science, 133, 1702–1703, 1961.

Dahlke, H. E., Lyom, S. W., Jansson, P., Karlin, T., and Rosquist, G.: Isotopic investigation of runoff generation in a glacierized catchment in northern Sweden, Hydrol. Process., 28, 1383–1398, 2014.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–468, 1964.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., and Gundestrup, N.: Stable isotope glaciology, Meddelelser om Grønland, 197, 1–53, 1973.

Dieser, M., Broemsen, E. L. J. E., Cameron, K. A., King, G. M., Achberger, A., Choquette, K., Hagedorn, B., Sletten, R., Junge, K., and Christner, B. C.: Molecular and biogeochemical evidence for methane cycling beneath the western margin of the Greenland Ice Sheet, ISME J., 8, 2305–2316, 2014.

Dinçer, T., Payne, B. R., Florkowski, T., Martinec, J., and Tongiorgi, E.: Snowmelt runoff from measurements of tritium and oxygen-18, Water Resour. Res., 6, 110–124, 1970.

Dissing, L.: Studier af kemiske forhold i sne aflejret på og ved Mittivakkat-gletscheren i Østgrønland, Ms thesis, Aarhus University, Aarhus, p. 102, 2000.

Fairchild, I. J., Killawee, J. A., Sharp, M. J., Spiro, B., Hubbard, B., Lorrain, R., and Tison, J.-L.: Solute generation and transfer from a chemically reactive Alpine glacial-proglacial system, Earth Surf. Proc. Land., 24, 1189–1211, 1999.

Gat, J. R. and Gonfiantini, R.: Stable isotope hydrology. Deuterium and oxygen-18 in the water cycle, Technical Report Series, 210, International Atomic Energy Agency, Vienna, p. 334, 1981.

Graly, J. A., Humphrey, N. F., Landowski, C. M., and Harper, J. T.: Chemical weathering under the Greenland Ice Sheet, Geology, 42, 551–554, 2014.

Haldorsen, S., Riise, G., Swensen, B., and Sletten, R. S.: Environmental isotopes as tracers in catchments, in: Geochemical Processes, Weathering and Groundwater Recharge in Catchments, edited by: Saether, O. M. and de Caritat, P., Balkema, Rotterdam, 185–210, 1997.

Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K., and Stephens, A.: Runoff and mass balance of the Greenland ice sheet: 1958–2003, J. Geophys. Res., 110, D13108, doi:10.1029/2004JD005641, 2005.

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M.: Increased runoff from melt from the Greenland ice sheet: a response to global warming, J. Climate, 21, 331–341, 2008.

Hanna, E., Mernild, S. H., Cappelen, J., and Steffen, K.: Recent warming in Greenland in a long-term instrumental (1881–2012) climatic context. Part 1: Evaluation of surface air temperature records, Environ. Res. Lett., 7, 045404, doi:10.1088/1748-9326/7/4/045404, 2012.

Hanna, E., Jones, J. M., Cappelen, J., Mernild, S. H., Wood, L., Steffen, K., and Huybrechts, P.: Discerning the influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2012 Greenland summer climate and melt, Int. J. Climatol., 33, 862–888, 2013.

Hasholt, B. and Mernild, S. H.: Glacial erosion and sediment transport in the Mittivakkat Glacier catchment, Ammassalik Island, southeast Greenland, 2005, IAHS-AISH P., 306, 45–55, 2006.

Hasholt, B., Mikkelsen, A. B., Nielsen, M. H., and Larsen, M. A. D.: Observations of runoff and sediment and dissolved loads from the Greenland Ice Sheet at Kangerlussuaq, West Greenland, 2007 to 2010, Z. Geomorphol., 57, 3–27, 2013.

Hawkings, J. R., Wadham, J. L., Tranter, M., Raiswell, R., Benning, L. G., Statham, P. J., Tedstone, A., Nienow, P., Lee, K., and Telling, J.: Ice sheets as a significant source of highly reactive nanoparticulate iron to the oceans, Nat. Comm., 5, 3929, doi:10.1038/ncomms4929, 2014.

Hindshaw, R. S., Rickli, J., Leuthold, J., Wadham, J., and Bourdon, B.: Identifying weathering sources and processes in an outlet glacier of the Greenland Ice Sheet using Ca and Sr isotope ratios, Geochim. Cosmochim. Acta, 145, 50–71, 2014.

Hodson, A., Bøggild, C., Hanna, E., Huybrechts, P., Langford, H., Cameron, K., and Houldsworth, A.: The cryoconite ecosystem on the Greenland ice sheet, Ann. Glaciol., 51, 123–129, 2010.

Hooper, R. P. and Shoemaker, C. A.: A comparison of chemical and isotopic hydrograph separation, Water Resour. Res., 106, 233–244, 1986.

Humlum, O.: Late-Holocene climate in central West Greenland: meteorological data and rock-glacier isotope evidence, Holocene, 9, 581–594, 1999.

Johnsen, S. J., Dansgaard, W., and White, J. W. C.: The origin of Arctic precipitation under present and glacial conditions, Tellus B, 41, 452–468, 1989.

Kamb, B.: Glacier surge mechanism based on linked cavity configuration of the basal water conduit system, J. Geophys. Res., 92, 9083–9100, 1987.

Kamb, B., Raymond, C. F., Harrison, W. D., Engelhardt, H., Echelmeyer, K. A., Humphrey, N., Brugman, M. M., and Pfeffer, T.: Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska, Science, 227, 469–479, 1985.

Keegan, K. M., Albert, M. R., McConnell, J. R., and Baker, I.: Climate change and forest fires synergistically drive widespread melt events of the Greenland Ice Sheet, P. Natl. Acad. Sci. USA, 111, 7964–7967, 2014.

Kendall, C. and Doctor, D. H.: Stable isotope applications in hydrological studies, in: Surface and Ground Water, Weathering, and Soils, Treatise on Geochemistry, 5, chapt. 11, edited by: Drever, J. I., Elsevier, Amsterdam, 319–364, 2004.

Knight, P. G.: Observations at the edge of the Greenland ice sheet: boundary condition implications for modellers, IAHS-AISH P., 170, 359–366, 1987.

Knight, P. G.: Stacking of basal debris layers without bulk freezing-on: isotopic evidence from West Greenland, J. Glaciol., 35, 214–216, 1989.

Knight, P. G., Waller, R. I., Patterson, C. J., Jones, A. P., and Robinson, Z. P.: Glacier advance, ice-marginal lakes and routing of meltwater and sediment: Russell Glacier, Greenland, J. Glaciol., 46, 423–426, 2000.

Knudsen, N. T., Yde, J. C., and Gasser, G.: Suspended sediment transport in glacial meltwater during the initial quiescent phase after a major surge event at Kuannersuit Glacier, Greenland, Geogr. Tidsskr., 107, 1–7, 2007.

Knudsen, N. T., Nørnberg, P., Yde, J. C., Hasholt, B., and Heinemeier, J.: Recent marginal changes of the Mittivakkat Glacier, southeast Greenland and the discovery of remains of reindeer (*Rangifer tarandus*), polar bear (*Ursus maritimus*) and peaty material, Geogr. Tidsskr., 108, 137–142, 2008.

Kong, Y. and Pang, Z.: Evaluating the sensitivity of glacier rivers to climate change based on hydrograph separation of discharge, J. Hydrol., 434–435, 121–129, 2012.

Kristiansen, S. M., Yde, J. C., Bárcena, T. G., Jakobsen, B. H., Olsen, J., and Knudsen, N. T.: Geochemistry of groundwater in front of a warm-based glacier in southeast Greenland, Geogr. Ann. A, 95, 97–108, 2013.

Larsen, N. K., Kronborg, C., Yde, J. C., and Knudsen, N. T.: Debris entrainment by basal freeze-on and thrusting during the 1995–1998 surge of Kuannersuit Glacier on Disko Island, West Greenland, Earth Surf. Proc. Land., 35, 561–574, 2010.

Lawson, E. C., Wadham, J. L., Tranter, M., Stibal, M., Lis, G. P., Butler, C. E. H., Laybourn-Parry, J., Nienow, P., Chandler, D., and Dewsbury, P.: Greenland Ice Sheet exports labile organic carbon to the Arctic oceans, Biogeosciences, 11, 4015–4028, doi:10.5194/bg-11-4015-2014, 2014.

Lutz, S., Anesio, A. M., Villar, S. E. J., and Benning, L. G.: Variations of algal communities cause darkening of a Greenland glacier, FEMS Microbiol. Ecol., 89, 402–414, 2014.

Lyon, S. W., Desilets, S. L. E., and Troch, P. A.: A tale of two isotopes: differences in hydrograph separation for a runoff event when using δD versus δ^{18}O, Hydrol. Process., 23, 2095–2101, 2009.

Mark, B. G. and Seltzer, G. O.: Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Peru, J. Glaciol., 49, 271–281, 2003.

Mark, B. G. and McKenzie, J. M.: Tracing increasing tropical Andean glacier melt with stable isotopes in water, Environ. Sci. Technol., 41, 6955–6960, 2007.

Meierbachtol, T., Harper, J., and Humphrey, N.: Basal drainage system response to increasing surface melt on the Greenland Ice Sheet, Science, 341, 777–779, 2013.

Meng, Y., Liu, G., and Zhang, L.: A comparative study on stable isotopic composition in waters of the glacial and nonglacial rivers in Mount Gongga, China, Water Environ. J., 28, 212–221, 2014.

Mernild, S. H. and Hasholt, B.: Observed runoff, jökulhlaups and suspended sediment load from the Greenland ice sheet at Kangerlussuaq, West Greenland, 2007 and 2008, J. Glaciol., 55, 855–858, 2009.
Mernild, S. H. and Liston, G. E.: The influence of air temperature inversions on snowmelt and glacier mass balance simulations, Ammassalik Island, southeast Greenland, J. Appl. Meteorol. Clim., 49, 47–67, 2010.
Mernild, S. H., Hasholt, B., Jakobsen, B. H., and Hansen, B. U.: Meteorological observations 2006 and ground temperature variations over 12-year at the Sermilik Station, Ammassalik Island, southeast Greenland, Geogr. Tidsskr., 108, 153–161, 2008a.
Mernild, S. H., Liston, G. E., and Hasholt, B.: East Greenland freshwater runoff to the Greenland–Iceland–Norwegian Seas 1999–2004 and 2071–2100, Hydrol. Process., 22, 4571–4586, 2008b.
Mernild, S. H., Liston, G. E., Steffen, K., van den Broeke, M., and Hasholt, B.: Runoff and mass-balance simulations from the Greenland Ice Sheet at Kangerlussuaq (Søndre Strømfjord) in a 30-year perspective, 1979–2008, The Cryosphere, 4, 231–242, doi:10.5194/tc-4-231-2010, 2010.
Mernild, S. H., Knudsen, N. T., Lipscomb, W. H., Yde, J. C., Malmros, J. K., Hasholt, B., and Jakobsen, B. H.: Increasing mass loss from Greenland's Mittivakkat Gletscher, The Cryosphere, 5, 341–348, doi:10.5194/tc-5-341-2011, 2011a.
Mernild, S. H., Liston, G. E., Hiemstra, C. A., Christensen, J. H., Stendel, M., and Hasholt, B.: Surface mass balance and runoff modelling using HIRHAM4 RCM at Kangerlussuaq (Søndre Strømfjord), West Greenland, 1950–2080, J. Climate, 24, 609–623, 2011b.
Mernild, S. H., Malmros, J. K., Yde, J. C., and Knudsen, N. T.: Multi-decadal marine- and land-terminating glacier recession in the Ammassalik region, southeast Greenland, The Cryosphere, 6, 625–639, doi:10.5194/tc-6-625-2012, 2012a.
Mernild, S. H., Liston, G. E., and van den Broeke, M.: Simulated internal storage buildup, release, and runoff from Greenland Ice Sheet at Kangerlussuaq, West Greenland, Arct. Antarct. Alp. Res., 44, 83–94, 2012b.
Mernild, S. H., Pelto, M., Malmros, J. K., Yde, J. C., Knudsen, N. T., and Hanna, E.: Identification of snow ablation rate, ELA, AAR and net mass balance using transient snowline variations on two Arctic glaciers, J. Glaciol., 59, 649–659, 2013a.

Mernild, S. H., Knudsen, N. T., Hoffman, M. J., Yde, J. C., Hanna, E., Lipscomb, W. H., Malmros, J. K., and Fausto, R. S.: Volume and velocity changes at Mittivakkat Gletscher, southeast Greenland, J. Glaciol., 59, 660–670, 2013b.
Mernild, S. H., Hanna, E., Yde, J. C., Cappelen, J., and Malmros, J. K.: Coastal Greenland air temperature extremes and trends 1890–2010: annual and monthly analysis, Int. J. Climatol., 34, 1472–1487, 2014.
Mernild, S. H., Hanna, E., McConnell, J. R., Sigl, M., Beckerman, A. P., Yde, J. C., Cappelen, J., Malmros, J. K., and Steffen, K.: Greenland precipitation trends in a long-term instrumental climate context (1890–2012): evaluation of coastal and ice core records, Int. J. Climatol., 35, 303–320, 2015a.
Mernild, S. H., Malmros, J. K., Yde, J. C., Wilson, R., Knudsen, N. T., Hanna, E., Fausto, R. S., and van As, D.: Albedo decline on Greenland's Mittivakkat Gletscher in a warming climate, Int. J. Climatol., doi:10.1002/joc.4128, in press, 2015b.
Mikkelsen, A. B., Hasholt, B., Knudsen, N. T., and Nielsen, M. H.: Jökulhlaups and sediment transport in Watson River, Kangerlussuaq, West Greenland, Hydrol. Res., 44, 58–67, 2013.
Milner, A. M., Brown, L. E., and Hannah, D. M.: Hydroecological response of river systems to shrinking glaciers, Hydrol. Process., 23, 62–77, 2009.
Moser, H. and Stichler, W.: Environmental isotopes in ice and snow, in: Handbook of Environmental Isotope Geochemistry, Volume 1, The terrestrial environment, A, edited by: Fritz, P. and Fontes, J. C., Elsevier, Amsterdam, 141–178, 1980.
Nghiem, S. V., Hall, D. K., Mote, T. L., Tedesco, M., Albert, M. R., Keegan, K., Shuman, C. A., DiGirolamo, N. E., and Neumann, G.: The extreme melt across the Greenland Ice Sheet in 2012, Geophys. Res. Lett., 39, L20502, doi:10.1029/2012GL053611, 2012.
Ohlanders, N., Rodriguez, M., and McPhee, J.: Stable water isotope variation in a Central Andean watershed dominated by glacier and snowmelt, Hydrol. Earth Syst. Sci., 17, 1035–1050, doi:10.5194/hess-17-1035-2013, 2013.
Penna, D., Engel, M., Mao, L., Dell'Agnese, A., Bertoldi, G., and Comiti, F.: Tracer-based analysis of spatial and temporal variations of water sources in a glacierized catchment, Hydrol. Earth Syst. Sci., 18, 5271–5288, doi:10.5194/hess-18-5271-2014, 2014.
Reeh, N. and Thomsen, H. H.: Model for simulering af ilt-isotop variationen i smeltevandsafstrømningen fra Indlandsisens rand ved Pâkitsup Akuliarusersua, Jakobshavn, Grønlands Geologiske Undersøgelse Gletscher-Hydrologiske Meddelelser, 86, 1–34, 1986.

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Reeh, N. and Thomsen, H. H.: Using stable isotopes as natural tracers to delineate hydrological drainage basins on the Greenland Ice-Sheet margin, Chem. Geol., 109, 281–291, 1993.
Reeh, N., Oerter, H., and Thomsen, H. H.: Comparison between Greenland ice-margin and ice-core oxygen-18 records, Ann. Glaciol., 35, 136–144, 2002.
Rennermalm, A. K., Smith, L. C., Chu, V. W., Forster, R. R., Box, J. E., and Hagedorn, B.: Proglacial river stage, discharge, and temperature datasets from the Akuliarusiarsuup Kuua River northern tributary, Southwest Greenland, 2008–2011, Earth Syst. Sci. Data, 4, 1–12, doi:10.5194/essd-4-1-2012, 2012.
Rennermalm, A. K., Smith, L. C., Chu, V. W., Box, J. E., Forster, R. R., Van den Broeke, M. R., Van As, D., and Moustafa, S. E.: Evidence of meltwater retention within the Greenland ice sheet, The Cryosphere, 7, 1433–1445, doi:10.5194/tc-7-1433-2013, 2013.
Roberts, D. H., Yde, J. C., Knudsen, N. T., Long, A. J., and Lloyd, J. M.: Ice marginal dynamics and sediment delivery mechanisms during surge activity, Kuannersuit Glacier, Disko Island, West Greenland, Quaternary Sci. Rev., 28, 209–222, 2009.
Rodriguez, M., Ohlanders, N., and McPhee, J.: Estimating glacier and snowmelt contributions to stream flow in a Central Andes catchment in Chile using natural tracers, Hydrol. Earth Syst. Sci. Discuss., 11, 8949–8994, doi:10.5194/hessd-11-8949-2014, 2014.
Russell, A. J.: A comparison of two recent jökulhlaups from an ice-dammed lake, Søndre Strømfjord West Greenland, J. Glaciol., 35, 157–162, 1989.
Russell, A. J.: Extraordinary meltwater run-off near Søndre Strømfjord, West Greenland, J. Glaciol., 36, 353, 1990.
Russell, A. J.: Obstacle marks produced by flow around stranded ice blocks during a glacier outburst flood (jökulhlaup) in West Greenland, Sedimentology, 40, 1091–1111, 1993a.
Russell, A. J.: Supraglacial lake drainage near Søndre Strømfjord, Greenland, J. Glaciol., 39, 431–433, 1993b.
Russell, A. J.: Controls on the sedimentology of an ice-contact jökulhlaup-dominated delta, Kangerlussuaq, West Greenland, Sediment. Geol., 193, 131–148, 2007.
Russell, A. J.: Jökulhlaup (ice-dammed lake outburst flood) impact within a valley-confined sandur subject to backwater conditions, Kangerlussuaq, West Greenland, Sediment. Geol., 215, 33–49, 2009.
Russell, A. J. and de Jong, C.: Lake drainage mechanisms for the ice-dammed Oberer Russellsee, Søndre Strømfjord, West Greenland, Z. Gletscherk. Glazialgeol., 24, 143–147, 1988.

Russell, A. J., Aitken, J. F., and de Jong, C.: Observations on the drainage of an ice-dammed lake in West Greenland, J. Glaciol., 36, 72–74, 1990.
Russell, A. J., van Tatenhove, F. G. M., and van de Wal, R. S. W.: Effects of ice-front collapse and flood generation on a proglacial river channel near Kangerlussuaq (Søndre Strømfjord) West Greenland, Hydrol. Process., 9, 213–226, 1995.
Russell, A. J., Carrivick, J. L., Ingeman-Nielsen, T., Yde, J. C., and Williams, M.: A new cycle of jökulhlaups at Russell Glacier, Kangerlussuaq, West Greenland, J. Glaciol., 57, 238–246, 2011.
Ryo, J.-S. and Jacobson, A. D.: CO_2 evasion from the Greenland Ice Sheet: a new carbon-climate feedback, Chem. Geol., 320–321, 80–95, 2012.
Stibal, M., Bælum, J., Holben, W. E., Sørensen, S. R., Jensen, A., and Jacobsen, C. S.: Microbial degradation of 2,4-dichlorophenoxyacetic acid on the Greenland Ice Sheet, Appl. Environ. Microbiol., 78, 5070–5076, 2012a.
Stibal, M., Hasan, F., Wadham, J. L., Sharp, M. J., and Anesio, A. M.: Prokaryotic diversity in sediments beneath two polar glaciers with contrasting organic carbon substrates, Extremophiles, 16, 255–265, 2012b.
Stibal, M., Telling, J., Cook, J., Mak, K. M., Hodson, A., and Anesio, A. M.: Environmental controls on microbial abundance and activity on the Greenland Ice Sheet: a multivariate analysis approach, Microb. Ecol., 63, 74–84, 2012c.
Stibal, M., Wadham, J. L., Lis, G. P., Telling, J., Pancost, R. D., Dubnick, A., Sharp, M. J., Lawson, E. C., Butler, C. E. H., Hasan, F., Tranter, M., and Anesio, A. M.: Methanogenic potential of Arctic and Antarctic subglacial environments with contrasting organic carbon sources, Global Change Biol., 18, 3332–3345, 2012d.
Sugden, D. E., Clapperton, C. M., and Knight, P. G.: A jökulhlaup near Søndre Strømfjord, West Greenland, and some effects on the ice-sheet margin, J. Glaciol., 31, 366–368, 1985.
Tedesco, M., Serreze, M., and Fettweis, X.: Diagnosing the extreme surface melt event over southwestern Greenland in 2007, The Cryosphere, 2, 159–166, doi:10.5194/tc-2-159-2008, 2008.
Tedesco, M., Fettweis, X., van den Broeke, M. R., van de Wal, R. S. W., Smeets, C. J. P. P., van de Berg, W. J., Serreze, M. C., and Box, J. E.: The role of albedo and accumulation in the 2010 melting record in Greenland, Environ. Res. Lett., 6, 014005, doi:10.1088/1748-9326/6/1/014005, 2011.

Telling, J., Stibal, M., Anesio, A. M., Tranter, M., Nias, I., Cook, J., Bellas, C., Lis, G., Wadham, J. L., Sole, A., Nienow, P., and Hodson, A.: Microbial nitrogen cycling on the Greenland Ice Sheet, Biogeosciences, 9, 2431–2442, doi:10.5194/bg-9-2431-2012, 2012.

Theakstone, W. H.: Temporal variations of isotopic composition of glacier-river water during summer: observations at Austre Okstindbreen, Okstindan, Norway, J. Glaciol., 34, 309–317, 1988.

Theakstone, W. H.: Oxygen isotopes in glacier-river water, Austre Okstindbreen, Okstidan, Norway, J. Glaciol., 49, 282–298, 2003.

Theakstone, W. H. and Knudsen, N. T.: Temporal changes of glacier hydrological systems indicated by isotopic and related observations at Austre Okstindbreen, Okstindan, Norway, 1976–87, Ann. Glaciol., 13, 252–256, 1989.

Theakstone, W. H. and Knudsen, N. T.: Isotopic and ionic variations in glacier river water during three contrasting ablation seasons, Hydrol. Process., 10, 523–539, 1996a.

Theakstone, W. H. and Knudsen, N. T.: Oxygen isotope and ionic concentrations in glacier river water: multi-year observations in the Austre Okstindbreen basin, Norway, Nord. Hydrol., 27, 101–116, 1996b.

van As, D., Hubbard, A. L., Hasholt, B., Mikkelsen, A. B., van den Broeke, M. R., and Fausto, R. S.: Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations, The Cryosphere, 6, 199–209, doi:10.5194/tc-6-199-2012, 2012.

van den Broeke, M., Smeets, P., and Ettema, J.: Surface layer climate and turbulent exchange in the ablation zone of the West Greenland ice sheet, Int. J. Climatol., 29, 2309–2323, 2009.

van de Wal, R. S. W. and Russell, A. J.: A comparison of energy balance calculations, measured ablation and meltwater runoff near Søndre Strømfjord, West Greenland, Global Planet. Change, 9, 29–38, 1994.

van Tatenhove, F. G. M.: Changes in morphology at the margin of the Greenland Ice Sheet (Leverett Glacier), in the period 1943–1992: a quantitative analysis, Earth Surf. Proc. Land., 21, 797–816, 1996.

van Tatenhove, F. G. M. and Olesen, O. B.: Ground temperature and related permafrost characteristics in West Greenland, Permafrost Periglac., 5, 199–215, 1994.

Weidick, A. and Morris, E.: Local glaciers surrounding the continental ice sheets, in: Into the Second Century of World Glacier Monitoring – Prospects and Strategies, edited by: Haeberli, W., Hoelzle, M., and Suter, S., UNESCO Studies and Reports in Hydrology, 56, 167–176, 1998.

Wimpenny, J., James, R. H., Burton, K. W., Gannoun, A., Mokadem, F., and Gíslason, S. R.: Glacial effects on weathering processes: new insights from the elemental and lithium isotopic composition of West Greenland rivers, Earth Planet. Sc. Lett., 290, 427–437, 2010.

Wimpenny, J., Burton, K. W., James, R. H., Gannoun, A., Mokadem, F., and Gíslason, S. R.: The behaviour of magnesium and its isotopes during glacial weathering in an ancient shield terrain in West Greenland, Earth Planet. Sc. Lett., 304, 260–269, 2011.

Yallop, M. L., Anesio, A. M., Perkins, R. G., Cook, J., Telling, J., Fagan, D., MacFarlene, J., Stibal, M., Barker, G., Bellas, C., Hodson, A., Tranter, M., Wadham, J., and Roberts, N. W.: Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland Ice Sheet, ISME J., 6, 2302–2313, 2012.

Yde, J. C. and Knudsen, N. T.: The importance of oxygen isotope provenance in relation to solute content of bulk meltwaters at Imersuaq Glacier, West Greenland, Hydrol. Process., 18, 125–139, 2004.

Yde, J. C. and Knudsen, N. T.: Glaciological features in the initial quiescent phase of Kuannersuit Glacier, Greenland, Geogr. Ann. A, 87, 473–485, 2005a.

Yde, J. C. and Knudsen, N. T.: Observations of debris-rich naled associated with a major glacier surge event, Disko Island, West Greenland, Permafrost Periglac., 16, 319–325, 2005b.

Yde, J. C. and Knudsen, N. T.: 20th-century glacier fluctuations on Disko Island (Qeqertarsuaq), Greenland, Ann. Glaciol., 46, 209–214, 2007.

Yde, J. C., Knudsen, N. T., and Nielsen, O. B.: Glacier hydrochemistry, solute provenance, and chemical denudation at a surge-type glacier in Kuannersuit Kuussuat, Disko Island, West Greenland, J. Hydrol., 300, 172–187, 2005a.

Yde, J. C., Knudsen, N. T., Larsen, N. K., Kronborg, C., Nielsen, O. B., Heinemeier, J., and Olsen, J.: The presence of thrust-block naled after a major surge event: Kuannersuit Glacier, West Greenland, Ann. Glaciol., 42, 145–150, 2005b.

Yde, J. C., Riger-Kusk, M., Christiansen, H. H., Knudsen, N. T., and Humlum, O.: Hydrochemical characteristics of bulk meltwater from an entire ablation season, Longyearbreen, Svalbard, J. Glaciol., 54, 259–272, 2008.

Yde, J. C., Hodson, A. J., Solovjanova, I., Steffensen, J. P., Nørnberg, P., Heinemeier, J., and Olsen, J.: Chemical and isotopic characteristics of a glacier-derived naled in front of Austre Grønfjordbreen, Svalbard, Polar Res., 31, 17628, doi:10.3402/polar.v31i0.17628, 2012.

Yde, J. C., Kusk Gillespie, M., Løland, R., Ruud, H., Mernild, S. H., de Villiers, S., Knudsen, N. T., and Malmros, J. K.: Volume measurements of Mittivakkat Gletscher, southeast Greenland, J. Glaciol., 60, 1199–1207, 2014a.

Yde, J. C., Knudsen, N. T., Hasholt, B., and Mikkelsen, A. B.: Meltwater chemistry and solute export from a Greenland Ice Sheet catchment, Watson River, West Greenland, J. Hydrol., 519, 2165–2179, 2014b.

Zhou, S., Wang, Z., and Joswiak, D. R.: From precipitation to runoff: stable isotopic fractionation effect of glacier melting on a catchment scale, Hydrol. Process., 28, 3341–3349, 2014.

Table 1. Summary of $\delta^{18}O$ (‰) mean and range in bulk water samples at Mittivakkat Gletscher River.

Year	Campaign period	n	$\delta^{18}O_{mean}$	$\delta^{18}O_{max}$	$\delta^{18}O_{min}$
2003	11–13 Aug	4	−14.42	−14.30	−14.65
2004	8–22 Aug	103	−14.55	−14.19	−14.91
2005	30 May–12 Jun	29	−14.71	−14.35	−15.16
	23–26 Jul	19	−14.10	−13.74	−14.41
	11–19 Aug	44	−14.73	−14.13	−16.43
2006	11–16 Aug	11	−14.85	−14.26	−15.42
2007	2–10 Aug	17	−14.69	−14.07	−15.11
2008	29 May–11 Jun*	28	−16.92	−15.92	−17.35
	10–16 Aug	15	−14.84	−14.47	−15.20
2009	8–16 Aug	17	−14.88	−14.56	−15.13

* Collected at a sampling site c. 500 m closer to the glacier front.

Table 2. Summary of $\delta^{18}O$ (‰) mean and range in bulk water samples at Kuannersuit Glacier River.

Year	Campaign period	n	$\delta^{18}O_{mean}$	$\delta^{18}O_{max}$	$\delta^{18}O_{min}$
2000	24–27 Jul	21	−19.80	−19.47	−19.97
2001	14–31 Jul	109	−19.25	−17.82	−19.55
2002	14–15 Jul	21	−19.01	−18.75	−19.39
2003	18–26 Jul	27	−20.43	−19.03	−21.88
2005	19–24 Jul	2	−19.42	−19.32	−19.51

Table 3. Summary of $\delta^{18}O$ (‰) mean and range in bulk water samples at Watson River.

Year	Campaign period	n	$\delta^{18}O_{mean}$	$\delta^{18}O_{max}$	$\delta^{18}O_{min}$
2005	12 Jul–24 Aug	8	−23.97	−23.54	−24.40
2007	28 Jul	1	−24.19		
2008	13 Jul–26 Aug	42	−24.20	−23.59	−24.76
2009	25–28 May	7	−26.79	−25.99	−27.17
	21–30 Jul	13	−24.35	−24.20	−24.54

Table 4. Relative contributions from the Akuliarusiarsuup Kuua (sampling site #7) and Qinnguata Kuussua (sampling site #8) tributaries to the total runoff of Watson River based on $\delta^{18}O$ measurements. For 28 July 2007 the percentages denote the relative contributions from the Russell Glacier and Leverett Glacier sub-catchments to the Akuliarusiarsuup Kuua tributary.

Date of sampling	Qinnguata Kuusua tributary	Akuliarusiarsuup Kuua tributary	Russell Glacier sub-catchment	Leverett Glacier sub-catchment
28 Jul 2007			24 %	76 %
26 May 2009	73 %	27 %		
28 May 2009	64 %	36 %		
23 Jul 2009	26 %		7 %	67 %

Table 5. $\delta^{18}O$ values in bulk water emanating from a glacier portal at Russell Glacier (sampling site #1) within the Watson River catchment.

Sampling time [LT = local time]	$\delta^{18}O$ [‰]
2 Aug 2005 11:00	−27.31
3 Aug 2005 15:00	−28.09
4 Aug 2005 16:00	−28.08
5 Aug 2005 16:00	−28.30
28 Jul 2007 15:35	−26.86
18 Jul 2008 11:40	−27.98
1 Aug 2008 15:10	−28.25
6 Aug 2008 11:30	−28.59
7 Aug 2008 17:40	−28.79
25 Aug 2008 15:30	−26.98
27 May 2009 10:05	−25.49
3 Aug 2009 09:30	−27.57

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Table 6. Transects of the spatial variations in $\delta^{18}O$ downstream along the river in Akuliarusiarsuup Kuua from the headwaters of the Russell Glacier sub-catchment to the main sampling site at the Watson River outlet into the fjord Kangerlussuaq.

Sampling site	Distance from headwater portal [km]	$\delta^{18}O$ (28 Jul 2007) [‰]	$\delta^{18}O$ (27 May 2009) [‰]
#1 Portal of Russell Glacier	0	−26.86	−25.49
#2 Upper bridge	2.1		−25.97
#3 Before Russell Glacier front	9.5	−27.06	−26.77
#4 After Russell Glacier front	11.3	−26.96	−26.89
#5 Outwash plain after junction with Leverett Glacier tributary	15.9	−24.65	−26.65
#6 Waterfall near mount Sugar Loaf	22.1	−24.28	
Watson River after junction with Qinnguata Kuussua tributary	32.4	−24.19	−26.98

Table 7. Maximum and minimum $\delta^{18}O$ in glacier rivers in Greenland. Sites outside Greenland are included for comparison.

Site	Sampling period	Latitude	Longitude	Maximum [‰]	Minimum [‰]	Reference
Greenland						
Mittivakkat Gletscher	2003–2009	65°41′ N	37°50′ W	−13.7	−17.4	This paper
Hobbs Gletscher	2004	65°46′ N	38°11′ W	−14.7	−15.1	Yde, unpublished data
Kuannersuit Glacier	2000–2005	69°46′ N	53°15′ W	−17.8	−21.9	This paper
Killersuaq	1982–1983	66°07′ N	50°10′ W	−19.5	−23.0	Andreasen (1984)
Watson River	1992, 2005–2009	67°00′ N	50°41′ W	−23.5	−27.2	This paper
Leverett Glacier [a]	2009	67°04′ N	50°10′ W	−23.2	−24.2	Hindshaw et al. (2014)
"N" Glacier	2008	68°03′ N	50°16′ W	∼ −23.3	∼ −28.3	Bhatia et al. (2011)
Isunnguata Sermia	2008	67°11′ N	50°20′ W	−26.2 [b]		Yde, unpublished data
Imersuaq	2000	66°07′ N	49°54′ W	−24.3	−29.9	Yde and Knudsen (2004)
Scandinavia and Svalbard						
Austre Okstindbreen, Norway	1980–1995	66°00′ N	14°10′ E	−11.8	−14.4	Theakstone (2003)
Storglaciären, Sweden	2004 and 2011	67°54′ N	18°38′ E	−10.9	−15.9	Dahlke et al. (2014)
Austre Grønfjordbreen, Svalbard	2009	77°56′ N	14°19′ E	−11.2 [b]		Yde et al. (2012)
Longyearbreen, Svalbard	2004	78°11′ N	15°30′ E	−12.3	−16.7	Yde et al. (2008)
European Alps						
Glacier de Tsanfleuron, Switzerland	1994	46°20′ N	07°15′ E	∼ −7.8	−12.2	Fairchild et al. (1999)
Hintereisferner, Austria	1969–1970	46°49′ N	10°48′ E	∼ −13.8	∼ −19.4	Behrens et al. (1971)
Kesselwandferner, Austria	1969–1970	46°50′ N	10°48′ E	∼ −14.8	∼ −18.1	Behrens et al. (1971)
Andes						
Cordillera Blanca catchments, Peru	2004–2006	9–10° S	77–78° W	−13.3	−15.3	Mark and McKenzie (2007)
Juncal River, Chile	2011–2012	32°52′ S	70°10′ W	∼ −16.4	∼ −18.0	Ohlanders et al. (2013)
Asia						
Kumalak Glacier No. 72, China	2009	41°49′ N	79°51′ E	−9.8 [b]		Kong and Pang (2012)
Urumqi Glacier No. 1, China	2009	43°07′ N	86°48′ E	−8.7 [b]		Kong and Pang (2012)
Hailuogou Glacier River, China	2008–2009	29°34′ N	101°59′ E	−13.7	−17.6	Meng et al. (2014)

[a] Sub-catchment of Watson River.
[b] Single sample.

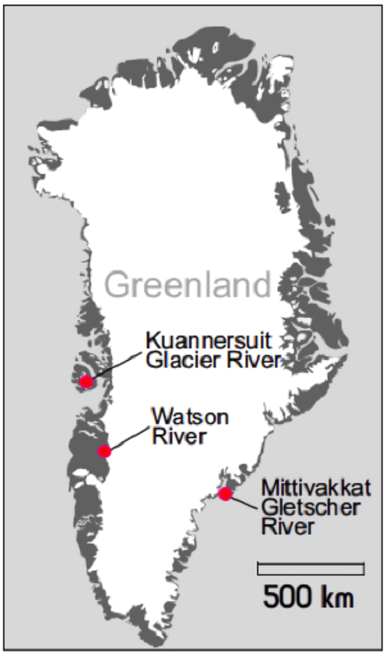

Figure 1. Location map of the three study sites in Greenland.

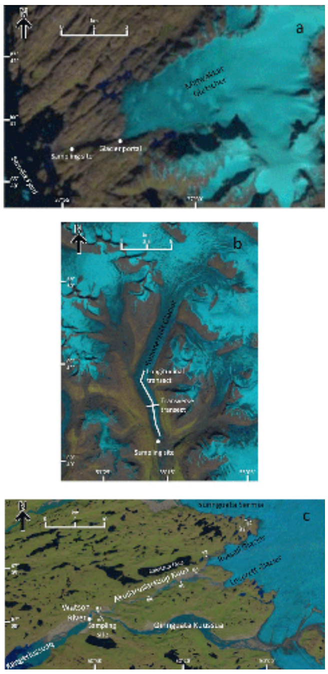

Figure 2. Location maps of the study areas **(a)** at Mittivakkat Gletscher River, southeast Greenland (image from Landsat 8 OLI on 3 September 2013); **(b)** at Kuannersuit Glacier River, West Greenland (image from Landsat 8 OLI on 8 July 2014); and **(c)** at Watson River, West Greenland. The numbers (#1–#8) show the secondary sampling sites along a river transect in the Akuliarusiarsuup Kuua tributary and at the outlet of the Qinnguata Kuussua tributary (image from Landsat 8 OLI on 12 July 2014).

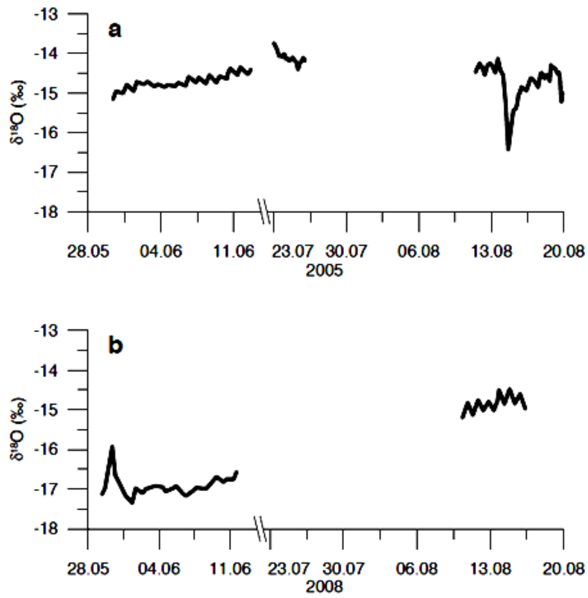

Figure 3. δ^{18}O time-series in bulk river water draining Mittivakkat Gletscher in **(a)** 2005 and **(b)** 2008.

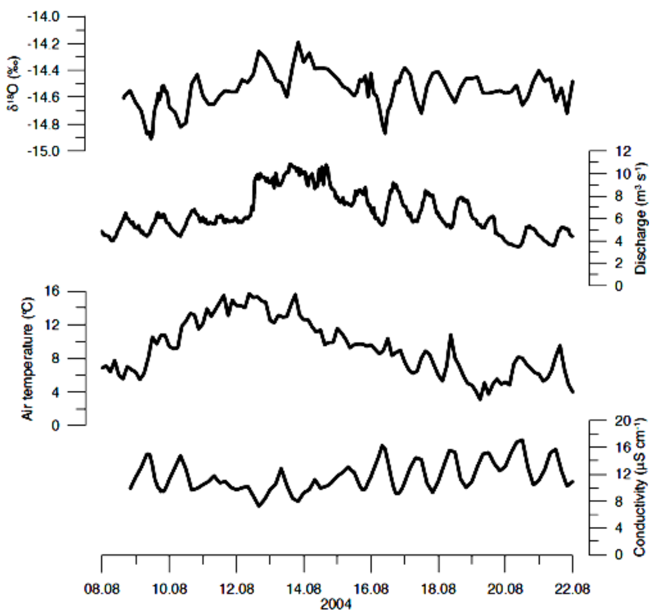

Figure 4. Time-series of δ^{18}O, discharge, air temperature and electric conductivity in bulk river water draining Mittivakkat Gletscher in 8–21 August 2004.

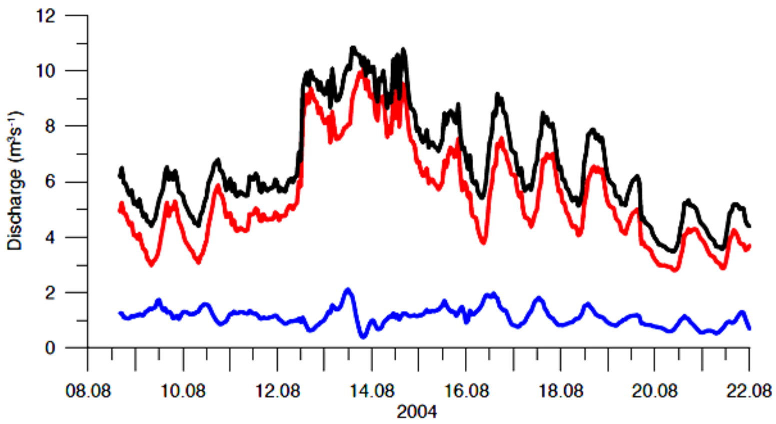

Figure 5. Hydrograph showing the separation of the discharge in Mittivakkat Gletscher River (black curve) into an ice melt component (red curve) and a snowmelt component (blue curve) during the period 8–21 August 2004.

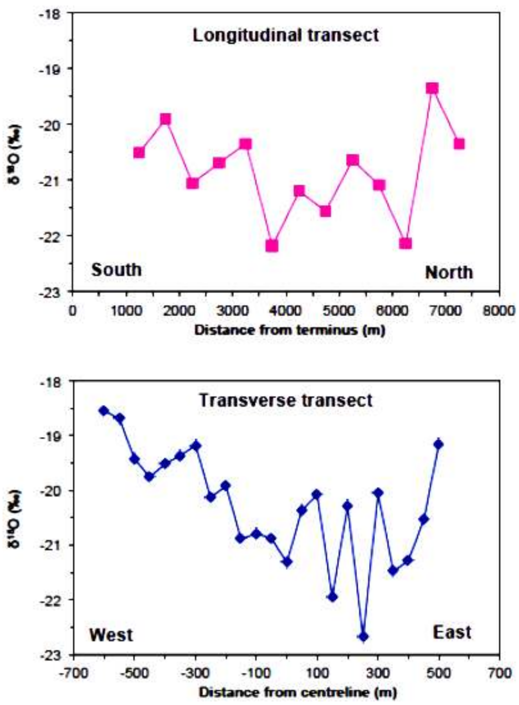

Figure 6. Variations in δ^{18}O of glacier ice along a longitudinal transect and a transverse transect on Kuannersuit Glacier. The transverse transect crosses the longitudinal transect at a distance of 3250 m from the glacier terminus.

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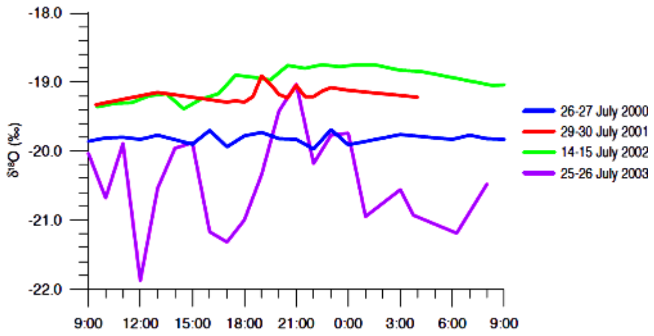

Figure 7. Diurnal δ^{18}O variations in Kuannersuit Glacier River on studied days in July in the post-surge years 2000–2003.

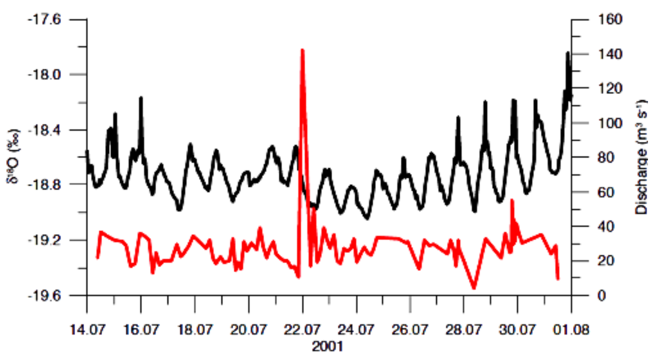

Figure 8. Time-series of δ^{18}O (red curve) and discharge (black curve) in Kuannersuit Glacier River during the period 14–31 July 2001.

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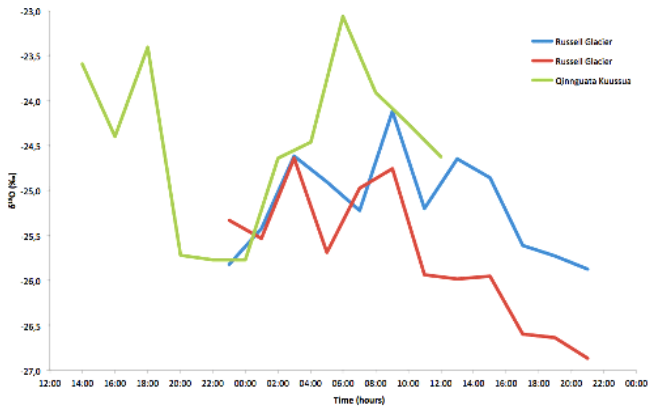

Figure 9. Diurnal δ^{18}O variations in sub-catchments of the Watson River system. Sampling was conducted in front of Russell Glacier (sampling site #4) on 22/23 July 1992 (red curve) and 30/31 July 1992 (blue curve), and from the Qinnguata Kuussua tributary (sampling site #8) on 15/16 July 1992 (green curve). Samples were collected with a two-hour frequency.