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Dear Dr. Markus Hrachowitz,
Hydrology and Earth System Sciences

We hereby submit the revisions of our manuscript hess-2015-154 “Stable oxygen isotope variability in two contrasting glacier river catchments in Greenland” (new title). First of all, we will like to express our gratitude to the three reviewers for their thorough, competent and constructive criticisms. The reviewers’ comments and suggestions have improved the manuscript significantly. Based on the reviewers’ recommendations we have made two major changes to the manuscript: (1) we have reorganized the manuscript by separating the Results and Discussion sections; and (2) we have removed the data from the Watson River system (as suggested by Reviewer #2). We have also clarified the inherent interest and importance of the manuscript.

Thank you for your help. If we can be of any assistance, please feel free to contact me.

With best regards

Jacob Clement Yde

Reply to Reviewer #1

We thank Reviewer #1 for the thorough and constructive review of our paper.

Reviewer #1

Yde et al. describe δ18O composition for three river catchments in Greenland, characterized by differing environmental settings, and ranging in size from 13.6 to 9743 km3. These catchments include Watson River in western Greenland which drains a section of the ice sheet, Mittivakkat Gletscher River in southeast Greenland which drains a glacier on Ammassalik Island, and Kuannersuit Glacier River in west Greenland which drains an outlet glacier of the Sermersuaq Ice Cap on Qeqertarsuaq (Disko) Island. The δ18O compositions of each catchment are found to vary widely, and are proposed to be influenced by a range of factors, including subglacial hydrology, climate and the age of melting ice.

1) I found it very difficult to draw any important conclusions from this study.

AUTHORS: We have clarified the Abstract and Conclusions sections to make it easier for readers to identify the novelty and conclusions. The following bullet points can summarize the novelty and significance:

- Besides a rather inaccessible PhD dissertation by Andreasen (1984), this is the first study on $\delta^{18}O$ dynamics in rivers draining glacierized catchments adjacent to the Greenland Ice Sheet. We report that the $\delta^{18}O$ composition in Mittivakkat Gletscher River is much higher than previously reported from Greenlandic rivers.
- We show that diurnal oscillations in $\delta^{18}O$ occur in meltwater from Mittivakkat Gletscher and use hydrograph separation to estimate that the ice melt component constitutes about 82 ± 5 % of the total runoff during the peak flow season. As Reviewer #2 points out, Mittivakkat Gletscher is a key location for studying glacier hydrology and glacier mass balance changes in Greenland. For instance, our results are important to modellers, who use the long mass balance record from Mittivakkat Gletscher and local meteorological data to test runoff models based on climatic forcings.
- We present the first study on $\delta^{18}O$ dynamics from a river draining a catchment containing a surging glacier, Kuannersuit Glacier. In contrast to Mittivakkat Gletscher River, we found that at Kuannersuit Glacier River there were no distinct diurnal oscillations in the years following the surge event. We conclude that this is a consequence of the formation of a subglacial linked-cavity drainage network formed during the surge event. We show, for the first time, that $\delta^{18}O$ analysis is a useful tool to evaluate structural changes in subglacial drainage systems beneath surging glaciers.
- We provide an up-to-date compilation of $\delta^{18}O$ data from glacier rivers.

Note that we have decided to remove the study of Watson River from the manuscript (see reply to Reviewer #2).

2) In the introduction you elude to the importance of identifying water sources and dynamics at catchment scale to better understand sea level contribution, future hydrological changes and water management issues, but you don't go on to explain how your results make a solid contribution to this.

AUTHORS: This is taken out of context. In the Introduction, we provide a background for studying water source dynamics in Greenland. We write that "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". Our results from Mittivakkat Gletscher River show that 82 ± 5 % of the total runoff derived from ice melt. This estimate is useful to validate the output of models that project past and future runoff from Mittivakkat Gletscher, as these models (e.g., SnowModel/HydroFlow; Liston and Mernild, Journal of Climate, 25, 5997-6014, 2012) estimate the amounts of snowmelt and ice melt per time step. The purpose of this study is to present new knowledge on catchment-scale water sources.

3) The three catchments you have studied are so different in their physical settings and processes that all you can really say is that very different catchments in Greenland have very different δ18O signatures.

AUTHORS: Yes, this study was designed to examine glacierized catchments with different physical settings. This approach provides much more new knowledge than a study of very similar glaciers. It is certainly incorrect to claim that "all you can really say is that very different catchments in Greenland have very different δ18O signatures". We present detailed analyses of the $\delta^{18}O$ dynamics of two catchments. For instance, we show that very different catchments such as Kuannersuit Glacier River and Killersuaq have similar $\delta^{18}O$ signatures but in the former case it is related to glacier surging and in the latter case it is due to snow-cover throughout the entire ablation season.

4) A more interesting study might have been how the oxygen isotope characteristics of three catchments of land-terminating sectors of the Greenland Ice Sheet compare; instead, the three catchments in question were chosen because they have been previously studied by the authors, as described in numerous papers.

AUTHORS: It is not clear to us why the reviewer thinks that a study of the $\delta^{18}O$ characteristics in rivers draining three GrIS sector catchments is more interesting. There are already published $\delta^{18}O$ data from three GrIS catchments (Yde and Knudsen, 2004; Bhatia et al., 2011; Hindshaw et al., 2014).

The reviewer accuses us for choosing the three catchments "because they have been previously studied by the authors". The reviewer is wrong! The catchments were chosen based on several criteria: (1) contrasting glacier settings, (2) connection to runoff measurements, (3) sites of interest to other researchers, and (4) logistic and financial constrains.

- Kuannersuit Glacier River was chosen because we hypothesized that $\delta^{18}O$ could be a useful tool to obtain knowledge about the post-surge configuration of the subglacial drainage network. It would also be the first study of the $\delta^{18}O$ dynamics in a river draining a surge-type glacier. The $\delta^{18}O$ sampling was initiated during our first visit to the site in 2000 (hence, there had not been any previous studies as the reviewer claims). A hydrometric station was established at the site in 2001, but it was destroyed in the spring 2002.
- Mittivakkat Gletscher River was chosen because it is key location to study glacier hydrology in Greenland. The site has the longest history of hydrological studies and the longest glacier mass balance record in Greenland. The University of Copenhagen has conducted runoff measurements in the river for decades. It is correct that we, among others, have studied this site since 1972, but note that our sampling began in 2003 before many other published studies were conducted.
- Watson River was meant to be our GrIS site. It was chosen do to the relative easy logistics and because it is the catchment in Greenland, where most glacial hydrology and hydrochemistry research is conducted, making our fingerprinting of the spatial runoff contributions from different parts of the river system relevant to many colleagues. The $\delta^{18}O$ sampling was also connected to a research grant for the establishment of a hydrometric station at the bridge in Kangerlussuaq. Again, the reviewer fails to note that the $\delta^{18}O$ sampling started in 2005.

We believe that we had chosen the three best catchments in Greenland. We also think that it is a benefit to the study that a lot of research activity is happening in the same catchments, but the motivation for choosing these sites was not that the sites had been previously studied by us.

5) In the context of the current structure of the manuscript and discussion of the data, the material presented is not enough to warrant a standalone paper, and would perhaps be better suited as supporting data within broader individual studies of the hydrology of these three catchments. With a more considered approach to how the manuscript is structured and in relating the three data sets to one another, a better paper could be produced; as it stands, it reads like three unrelated mini studies.

AUTHORS: We note that the other two reviewers disagree with the opinion of Reviewer #1. We have followed the advice of Reviewer #2 to remove the part on Watson River from the manuscript. Following the advices of all three reviewers, we have also changed the structure of the manuscript to better relate the data sets to each other.

Specific comments:

6) In the introduction (page 5846, lines 16-18) you say “Then, we compare our findings with previous investigations to characterize the oxygen isotope composition in Greenlandic glacier rivers.”, but in section 4.4 you compare against very few Greenland-specific studies, and also make comparisons with various valley and outlet glaciers in other regions. I would argue that you do not then characterize the oxygen isotope composition in Greenlandic glacier rivers.

AUTHORS: We agree that the current number of investigations of the oxygen isotope composition in Greenlandic glacier rivers is limited. To our knowledge we compare our results to all available datasets on oxygen isotope compositions in Greenlandic glacier rivers (including two previously unpublished datasets). With our new results we are able to provide a better qualitative characterization of the oxygen isotope composition in Greenlandic glacier rivers because the compiled data now includes $\delta^{18}O$ values from two peripheral glaciers: a temperate glacier and a surge-type outlet glacier from an ice cap. It is correct that we do not aim for presenting a quantitative characterization of representative oxygen isotope composition in Greenlandic glacier rivers. That will be an almost impossible task to accomplish. In order to avoid misunderstandings we have amended the text to clarify this.

7) The manuscript lacks a proper methods section, within which the sampling strategy for each glacier should have been described. Instead this is included in the combined results and discussion section, which is very busy. I’d recommend revising the structure of the manuscript to a standard methods-results-discussion structure, where a separate discussion section which might then describe the key differences between your three sites, and comparisons with other glacier catchments.

The manuscript would benefit from also including a) a description of your hydrograph separation technique, b) a better discussion of uncertainty with regards to instrumental precision, sampling, and the spatial and temporal variations in the new and old water components, and c) an expanded description of runoff measurement in each catchment.

AUTHORS: We have restructured the manuscript as recommended. Following the Reviewer’s advice, the Discussion section is now separated into section 5.1 “Differences in $\delta^{18}O$ between Mittivakkat Gletscher River and Kuannersuit Glacier River”, section 5.2 “$\delta^{18}O$ compositions in glacier rivers” and section 5.3 “Uncertainties in $\delta^{18}O$ hydrograph separation models”.

The Methods section now includes a description of the sampling strategy for each glacier in section 3.1 “Sampling protocol and isotope analyses”.

a) The general description of the hydrograph separation technique is presented in the Introduction section. We have structured the Results section so that it should be easier for readers to follow our construction of the hydrograph separation. The first three sub-sections in the Results section now address “$\delta^{18}O$ end-member components”, “$\delta^{18}O$ characteristics” and “Hydrograph separation”.

b) The uncertainties of the instrumental precision, sampling and runoff measurements are now presented together in the Methods section. The spatial and temporal variations in the snowmelt and ice melt components are parts of the results and presented in the Results section (section 4.1 “δ^{18}O end-member components” and section 4.4 “Longitudinal and transverse δ^{18}O transects”).
c) We have expanded the description of the runoff measurements in section 3.3.

8) In section 4.1 you state that “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 on δ18O 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.” (line 24, page 5850 – line 3, page 5851). Can you highlight which ongoing studies you are referring to?

AUTHORS: We have removed these two sentences, as the runoff modelling study we refer to is not finished.

9) On page 5852 (lines 18-21) you talk about an assumed channelized subglacial network. Do you have further evidence for channelization? If so, state what it is. It would also be interesting to hear if there is additional evidence for the roof collapse you mention on pages 5853 and 5854. “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).” (5854, lines 4-8). This description is not entirely convincing. Is there more evidence to support this?

AUTHORS: With regards to the subglacial channelization at Mittivakkat Gletscher, there is evidence from dye tracing experiments. We have inserted a reference to Mernild (2006), who found evidence of channelization on the lower part of Mittivakkat Gletscher.

We think that temporary damming of a part of the subglacial drainage system on 11 August best explains the sudden release of meltwater on 12 August. It is impossible to obtain direct evidence of a damming within the inaccessible subglacial drainage network, unless it is a really spectacular event causing a sudden lowering or collapse of the glacier surface. Such an event is unlikely to occur at Mittivakkat Gletscher, except for at the near-marginal area above the portal. A jökulhlaup event will not explain the disturbances of the runoff observed on 11 August and none of the ice-marginal lakes were observed to have drained during this period. No rainfall events occurred during the period.

10) Page 5857, lines 27-21: It would be better to show the solutes and suspended sediment time series in figure 8 rather than have to look them up elsewhere, and to state clearly why they correlate with runoff but not δ18O.

AUTHORS: As the variations in solutes and suspended sediments are controlled by runoff (Yde et al., 2005a; Knudsen et al., 2007), we think that it is best to keep the focus on the correlation between runoff and $\delta^{18}O$. However, it is relevant in this context to mention that the correlations between runoff and the two other variables deviate from the correlation between runoff and $\delta^{18}O$.

11) Page 5858, lines 25-28: Are there any recommendations you can make to help tackle this issue?

AUTHORS: This part on Watson River has been removed.

12) Page 5860, lines 15-26: There are a lot of assumptions made here. How much error would you attribute to these assumptions given the temporal variability in δ18O?

AUTHORS: This part on Watson River has been removed.

13) Section 4.4 is really more a loose comparison of the three study sites than a discussion of δ18O variability in (Greenlandic) rivers. As suggested above, I would prefer to see this section rebranded as a discussion, with sub-sections on comparing the three catchments, comparison with other catchments, and possibly a section on sources of error and recommendations for future sampling.

AUTHORS: Following the advice of the Reviewer, we have restructured the manuscript so that the new Discussion section consists of the three suggested sub-sections.

14) Page 5862, lines 14-21: I don’t see the value in this comparison given the entirely different environmental conditions.

AUTHORS: The environmental conditions are not that different. In both cases the meltwater derives from large ice caps located in West Greenland, but the glaciological conditions (surging vs. non-surging glacier) deviate from each other. The main value of the comparison is the observations of lack of diurnal oscillations in $\delta^{18}O$ at both sites. Such observations are rare and the comparison shows that they can be caused by different processes. Where the lack of diurnal oscillations at Killersuaq is related to snow-covered conditions during the ablation season, the lack of diurnal oscillations at Kuannersuit Glacier is a consequence of glacier surging.

15) You make concluding remarks (also in the abstract) about how there are large differences in δ18O composition between Greenlandic ice sheet water, ice cap water, and glacier water. In reality, the sample of Greenlandic rivers studies from which you have drawn these conclusions is very limited, and comparison between the surging Kuannersuit Glacier and Killersuaq Glacier is particularly tenuous. I'd perhaps be careful in concluding that large ice caps have a distinctly different δ18O signature than either the ice sheet or local glaciers, given that you have a sample of two.

AUTHORS: The Reviewer makes a valid point that the number of Greenlandic river studies is too limited to draw conclusions about a link between glacier type (glacier size) and $\delta^{18}O$ composition. We have now moderated the text in the Conclusions section and Abstract to say that the $\delta^{18}O$ composition in rivers draining glaciers and ice caps differs from rivers draining the GrIS.

16) Table 7: Within the "Greenland" section it might not be obvious to someone who doesn't study Greenland glaciology which sites are on the ice sheet proper and which drain from ice caps or local glaciers. I'd recommend that you make this distinction within the table in order to better illustrate the differences in δ18O composition between glaciers, ice caps and the ice sheet.

AUTHORS: We agree with the Reviewer and now include the glacier type of the Greenlandic glaciers in the table (now Table 3).

Technical corrections:

17) Page 5846, line 12: Is 20 years ago recent?

AUTHORS: Deleted "recently".

18) Page 5846, line 25: I think 'emanates' would be better replaced with something like 'flows'.

AUTHORS: Changed as suggested.

19) Pages 5846, line 26 - Page 5847, line 2: This sentence makes it sound like the sampling site defines the hydrological catchment. It would be better to start a new sentence with "The hydrological catchment has an area of. . .".

AUTHORS: Changed as suggested.

20) Page 5847, line 14: Does ‘type location’ mean ‘representative location’?

AUTHORS: Changed to “representative”.

21) Page 5848, line 1: Again, the use of ‘emanates’ sounds strange here. Perhaps change to ‘originates’.

AUTHORS: Changed to “originates”.

22) Page 5848, line 10: MAAT needs to be defined.

AUTHORS: The abbreviation MAAT is now defined in section 2.1.

23) Page 5848, line 15: Should read “. . . estimated the catchment area to be. . .”

AUTHORS: The text on Watson River has been removed.

24) Page 5848, lines 18-20: Perhaps it would be better to say “. . . comprises two of the most well-examined. . .”?

AUTHORS: The text on Watson River has been removed.

25) Page 5848, line 26: There is an ‘a’ missing from ‘downstream’.

AUTHORS: The text on Watson River has been removed.

26) Page 5850, line 1: ‘water’ is missing an ‘a’.

AUTHORS: Typo fixed.

27) Page 5852, lines 27-29: ". . .the runoff suddenly remained constant. . .". This doesn't make sense as it's currently written. Change to something like "the diurnal trend in runoff was interrupted, remaining at a constant level until. . ."

AUTHORS: The sentence has been rephrased.

28) Page 5853, line 4: change to ". . . before returning to a diurnal oscillation of runoff".

AUTHORS: The sentence has been amended as suggested.

29) Page 5853, lines 20-21: It might be more appropriate to say ". . . subglacial drainage likely occurs within a channelized network. . .".

AUTHORS: We have inserted a reference to Mernild (2006) to support the statement that "… subglacial drainage mainly occurs within a channelized network …"

30) Page 5853, lines 25-26: again, perhaps change to ". . . the possible existence of an inefficient. . .".

AUTHORS: Changed the text as suggested.

31) Page 5854, line 3: ". . .is derived from a. . .".

AUTHORS: Changed the text as suggested.

32) Page 5854, lines 19-21: Consider changing the wording to "As a consequence of the surge event, the glacier front advanced from c. 500 m a.s.l. down to 100 m a.s.l. . . .".

AUTHORS: The sentence now reads: "During the surge event of Kuannersuit Glacier, the glacier front advanced from c. 500 m a.s.l. down to 100 m a.s.l., while …"

33) Page 5855, line 13: "related to".

AUTHORS: Typo fixed.

34) Page 5855, lines 24-29: This sentence is too long. Consider splitting into one sentence describing the presence of naled and another describing what it is.

AUTHORS: The sentence has been split into two as suggested.

35) Page 5856, line 1: “an outlier”.

AUTHORS: Typo fixed.

36) Page 5856, line 22: ‘possibly’ rather than ‘probably’?

AUTHORS: Changed as suggested.

37) Page 5857, line 7: “transforms”.

AUTHORS: Typo fixed.

38) Page 5857, lines 10-13: Consider rewording to something like “. . .frequent loud noises interpreted as drainage system roof collapses were observed, in addition to flushing out of ice blocks from a marginal hydrological portal, suggesting ongoing changes to the internal drainage system.”

AUTHORS: The sentence now reads: “… frequent loud noises interpreted as drainage system roof collapses were observed, in addition to episodic export of ice blocks from the portal, suggesting ongoing changes to the englacial and subglacial drainage system”.

39) Page 5857, line 16: Perhaps change “are seen as” to “appear as”

AUTHORS: Changed as suggested.

40) Page 5857, lines 23-24: This sounds like sampling was done in May, June and July in 2005, 2007, 2008 and 2009. Rephrase to something like “sampling was conducted during the melt season in 2005. . .”.

AUTHORS: This text on Watson River has been removed.

41) Page 5857, line 24 – Page 5858, line 5: The information in these lines is confusing. Rephrase to better pull out the point(s) you're trying to make here.

AUTHORS: This text on Watson River has been removed.

42) Page 5859, line 14: ". . .captured due to the sampling period".

AUTHORS: This text on Watson River has been removed.

43) Page 5861, line 27 – page 5862, line 2: Needs to be rephrased. I suggest something like "In the quiescent phase following the 1995-1998 surge of Kuannersuit Glacier no diurnal oscillations in δ18O were observed. However, the most recent result from 2005 indicate. . .".

AUTHORS: As we agree with Reviewer #2 that more data from 2005 were needed to conclude that diurnal oscillations were starting to appear, we have changed the text accordingly.

44) Page 5852, line 12: ". . .large glaciers with lateral tributaries.".

AUTHORS: This sentence has been removed due to the restructuring of the manuscript.

45) Page 5852, line 14: Perhaps say something like "ice cap outlet glaciers" since Leverett or Russell could be described as large outlet glaciers.

AUTHORS: This sentence has been removed due to the restructuring of the manuscript.

46) Page 5864, line 7: "At the seasonal scale. . ."

AUTHORS: This sentence has been removed due to the rewriting and shortening of the Conclusions section.

47) Page 5864, line 8: Remove 'subsequently'.

AUTHORS: This sentence has been removed due to the rewriting and shortening of the Conclusions section.

48) Page 5864, line 17: “This is in contrast to. . .”.

AUTHORS: This sentence has been removed due to the rewriting and shortening of the Conclusions section.

49) Figure 2: I can’t see any details or read the text on these three images; the layout of this figure should be changed to optimize page space and image size.

AUTHORS: We are sorry about the poor quality of Figure 2. The figure was intended as a high quality figure covering two pages. We have changed the figure to a new Figure 1.

50) Figure 3: The x-axis labels on these two charts should be edited to better describe the independent variable, i.e. “Date”.

AUTHORS: “Date” has been added to the x-axis label.

51) Figure 4: As for figure 3.

AUTHORS: “Date” has been added to the x-axis label.

52) Figure 5: As for figure 3.

AUTHORS: “Date” has been added to the x-axis label.

53) Figure 7: The x-axis has no label here.

AUTHORS: “Time” has been added to the x-axis label.

54) Figure 8: As for figure 3.

AUTHORS: “Date” has been added to the x-axis label.

55) Figure 9: All of the text on this figure is too small.

AUTHORS: This figure showing data from Watson River has been removed.

Reply to Reviewer #2

We thank Wilfred Theakstone for the insightful review of our paper.

Wilfred Theakstone

In this paper, Yde et al. report an attempt “to attain knowledge on the diversity of spatio-temporal δ18O variations in glacier rivers” by studies at three glacierized catchments in Greenland. The observations at Mittivakkat supplement studies undertaken there since the mid-1990s and are a useful addition to knowledge of the glacier. Most of the data from this site was collected during annual studies between 2003 and 2009. Kuannersuit Glacier is of interest because of its recent surge history: it has been in a quiescent phase since 1998/99. Data were obtained annually from 2000 to 2005, during which the nature of the glacier tongue underwent major changes. The Watson River drains a sector of the Greenland ice sheet. Sampling glacier river water for oxygen isotope analysis was more sporadic there than at the two other sites and it is only for 2008, when 42 samples were collected in a 45 day period, that the studies can be described as detailed.

1) The paper cites a large number of papers. It is useful to have these included in one place, but the citations hinder easy reading. Thus, partway through the paragraph beginning at line 18, page 5845, 17 papers are cited. It is not possible to check these citations in the References section without losing track of the text around them. Are all the cited papers relevant to the reported studies or are they included in order to provide a comprehensive list of papers dealing with oxygen isotopes?

AUTHORS: We think that it is important to show that end-member isotope-mixing studies are timely and widely used in glacierized catchments. Thus it seems relevant to refer to both pioneering studies (by Behrens, Fairchild, Theakstone, Mark), studies from different regions (the Andes, Himalaya, Scandinavia, the Arctic) and the many recent studies (seven studies published in 2014). As the reviewer mentions, it is also convenient to have citations to these studies together in one place. We hope that readers will see this as a resource rather than a hindering in easy reading. We have kept the citations, but if the editor wants us to reduce the number of citations, we are of course willing to do so.

2) The structure of the paper could be improved. I would have preferred to see separate ‘Results’ and ‘Discussion’ sections.

AUTHORS: We have restructured the manuscript as suggested. It now contains separate Results and Discussion sections.

3) The results do not always emerge clearly. For example, the authors start section 4.1 by stating that “information on δ18O is valuable for validating the proportional contributions of snowmelt and ice melt to dynamic glacier models” without further elaboration, and follow this immediately by reference to three snow pits excavated at Mittivakkat Glacier in 1999. Glacier ice data then are given, followed by speculation about the “reasons for an absence of a δ18O lapse rate”. The authors suggest (line 18 page 5851) that “it is evident that end-member snowmelt has a relatively low δ18O compared to end-member ice melt and that these two water course components can be separated.” It is difficult to find the data on which this conclusion is based. The data from the three snow pits at different altitudes are not provided – only a mean of -16.5±0.6‰ is given. Did the pits reveal isotopic stratification related to variations of winter storm activity? If so, how far did individual samples deviate from the mean value? How representative of all the samples is the mean?

AUTHORS: We recognize that the results were not clearly presented. We have now separated the Results from the Discussion and amended the text. The data from the three snow pits belong to Dissing (2000), but we do have access to the data. Information about altitudes of snow pits, number of samples, sampling frequency and range of individual samples have been added to the text. The pits show some isotopic stratification, but the variations have not been linked to air mass trajectories or storm activity as the Reviewer did at Tustervatn (Theakstone, 2008).

4) Sampling glacier ice at 10 m increments along profiles totalling 2.95 km in length is summarised by a range (-15.0 to -13.3‰ and a mean value (14.1‰. Did the sample δ18O values have a normal distribution around the arithmetic mean?

AUTHORS: Unfortunately, we do not have access to the data sets collected by Boye (1999), so we are unable to test whether the data has a normal distribution around the arithmetic mean. Boye (1999) did not test this.

5) The authors state (line 23 page 5851) that “the mean annual δ18O value was -14.68±0.18‰´’ and that “the uncertainty of δ18O is given by the standard deviation”. A better indication of the homogeneity/heterogeneity of the sample values would be provided by the Coefficient of Variation (standard deviation divided by the mean): two groups of samples, one more homogeneous than the other, may have different mean values but identical standard deviations.

AUTHORS: The reviewer suggests that we apply coefficient of variation rather than standard deviation to express uncertainties. However, coefficient of variation is only meaningful on a ratio scale (e.g., such as length, mass etc.). As $\delta^{18}O$ is given by an interval scale (having an arbitrary zero value), it is meaningless to apply coefficient of variation on $\delta^{18}O$ data. Thus uncertainties are given by the standard deviation.

6) The suggestion (line 3 page 5852) that δ18O values ranging from -15.16 to -14.35‰ in late May and mid-June respectively indicate that ice melt had started before sampling was undertaken requires elaboration. It is not clear why an increase of 0.04‰ per day is equal to an increase of 1.7 in the snow melt: ice melt ratio.

AUTHORS: We have rewritten these sentences to clarify that the similarity in $\delta^{18}O$ between the early melt season and peak flow period indicates that ice melt had started before sampling in May 2005 commenced. We agree that the sentence about the trend in $\delta^{18}O$ was not clear and we have decided to remove it.

7) What are the assumed "end-member δ18O compositions of snow melt and ice melt"? (In the introduction, it is noted (line 29 page 4845) that it may be necessary to divide ice melt into several components.)

AUTHORS: This is now clarified in the sub-section 4.1 "$\delta^{18}O$ end-member components".

8) Is the assumption of a standard value for snow melt justified? Does the composition of the water leaving the melting snow pack change as the melt season proceeds? This should be considered in relation to the hydrograph shown in Fig. 5.

AUTHORS: We take into consideration the Reviewer's point that a seasonal change in the isotopic composition of the bulk water leaving the melting snowpack will influence the value of the end-member snowmelt component. We do not have data to estimate a seasonal effect on the water leaving the melting snowpack. A study by the Reviewer (Raben and Theakstone, 1998) showed that the isotopic composition in snow pits on Austre Okstindbreen, Norway, remained unchanged in the early melt season but increased between May/June and August. However, a seasonal effect on the isotopic composition of the water leaving the melting snow pack was not estimated. In order to answer this question in detail, a combination of field sampling of snowmelt, local meteorological data and ablation modelling is required and this is beyond the scope of our study. We have added a short discussion of the uncertainties involved in using end-member estimates in hydrograph separation models (section 5.3).

9) At Kuannersuit Glacier, longitudinal and transverse sampling at the post-surge glacier

surface revealed large δ18O fluctuations. On the transverse transect, relatively high values were observed at the glacier margins. The authors suggest (line 11 p 5855) that there are no comparable studies of transverse variations. In fact, Hambrey (1974 Geogr.Ann. 56 147-158) studied such variations on a small Norwegian glacier and suggested that marginal ice there was older and originated at a higher level than ice in the centre of the glacier. The contrast might be worth exploring.

AUTHORS: Thank you for making us aware of the study by Hambrey (1974). We have now made a separate sub-section 4.4 “Longitudinal and transverse $\delta^{18}O$ transects”, where we present the results of our transects and compare them with the findings from Charles Rabots Bre by Hambrey (1974) and Saskatchewan Glacier by Epstein and Sharp (1959).

10) 180 samples of glacier river water were collected at Kuannersuit Glacier during six summer periods. A mean value of -19.58‰ is noted (line 18 page 5854), but this is the mean of the five individual yearly means of Table 4. If an overall mean is needed (it probably is not), it should be calculated from weighted annual values, as the number of samples ranged from 2 (2005) to 109 (2001).

AUTHORS: We now apply a sample-weighted mean annual $\delta^{18}O$ as recommended.

11) After a discussion of glacier ice sampling, the paper continues with an examination of glacier river water sampled on one day in each of four successive summers. This reveals a marked difference in the last year (Fig. 7). (It is hard to discern the ‘tendency’ in 2002 (line 13 page 5856). Indicating the individual values would be better than the line plot.). However, one day’s sampling surely is insufficient to define a “trend in diurnal variability” or to indicate that, in 2003, “the glacier runoff was not well-mixed” (line 23 page 5856) or to indicate “the presence of a well-mixed drainage network” (line 2 page 5857).

AUTHORS: The reviewer is correct. We have moderated or deleted the interpretations. We tested the reviewer’s suggestion to plot the data in Figure 7 as individual values but it did not improve the clarity – in our opinion the line plot makes the best visual presentation of the diurnal $\delta^{18}O$ variations. We think that it is important to show a figure of the diurnal variability of these four July days without rainfall, in combination with the long time-series from 2001, in order to visualize the lack of diurnal oscillations in the years following the surge event.

12) Section 4.2 is somewhat confusing; results and discussion should have been separated.

AUTHORS: The Results and Discussion sections are now separated as suggested.

13) The Watson River sampling programme was sporadic, rather than systematic. A reasonable body of bulk water data was obtained only in 2008 (Table 3). It is difficult to identify the basis for the conclusion (line 6 page 5860) that "the dominating meltwater provenance was near-marginal melting of basal ice". Samples taken at different times of day on four days in 2005, one day in 2007, 5 days in 2008 and 2 days in 2009 (Table 5) or along the river on a single day in 2007 and 2009 (Table 6) are hardly a strong basis for a discussion of spatiotemporal variability of oxygen isotope composition in the Watson River catchment.

AUTHORS: We have taken the Reviewer's point into consideration and decided to remove all Watson River data from the manuscript.

14) Study of this section of the paper (4.3) is hindered by the poor quality of Figure 2.

AUTHORS: We are sorry about the poor quality of the former Figure 2. It was intended as a high quality figure covering two pages, but it came out wrong in the preprint.

15) In summary, I consider that the oxygen isotope data from the Watson River catchment is not adequate for either a stand-alone paper or a comparative one. The Mittivakkat and Kuannersuit Glacier studies are of interest, the former as part of long-term observations, the latter because there is no body of oxygen isotope data from a recently-surged glacier.

AUTHORS: The manuscript now focuses on the two sites of interest: Mittivakkat Gletscher River and Kuannersuit Glacier River.

16) Any revised paper(s) should have more clearly presented data, separate from a discussion of the results. Concentration on a two-component mixing model (ice melt/snow melt) should be avoided unless a discrete value for each component can be identified.

AUTHORS: We have taken the Reviewer's recommendations on board and separated the Results and Discussion. We believe that this has improved the clarity of the presentation of data. We have focused the paper on the isotopic differences between a surging glacier and non-surging glacier river catchment peripheral to the GrIS. We acknowledge the limitations of end-member hydrograph separation models (isotopic or hydrochemical), well knowing that a discrete value for each component cannot be identified and possibly does not exist over time. However, by using best-estimates of each component as end-member values we get information about the relative proportion of the components that is otherwise difficult to obtain. We believe that the use of isotopic hydrograph separation is legitimate in glacierized catchments, where the estimated values of each component are sufficiently different from each other (such as in Mittivakkat Gletscher River), but should be avoided in other glacierized catchments, where each component has not been identified within the catchment area (such as in Kuannersuit Glacier River). To address the limitations of the hydrograph separation technique, we have added a new sub-section (section 5.3) on uncertainties in $\delta^{18}O$ hydrograph separation models.

Reply to Reviewer #3

We appreciate the helpful comments and suggestions by Reviewer #3.

Reviewer #3

The manuscript presents a diverse water isotope ($\delta 18O$) data set from three different glacierized catchments in Greenland. Streamwater isotopic composition from samples collected between 2000 and 2009 are analyzed using isotopic hydrograph separation and isotope data collected from snow and ice samples. The paper is overall well written (although a few minor typos still need to be corrected). The study provides a nice compilation of different isotope data sets and the combined results section provide an interesting discussion of potential mechanisms responsible for the observed diurnal or spatiotemporal differences in the isotopic signals. The authors provided an excellent literature review and did a very good job supporting data interpretations and discussion of results with previous studies.

AUTHORS: Thank you.

1) My main recommendation to the authors that the manuscript needs a clearer structure and a more information in the methods section that make it easier for the reader to understand what calculations were done to estimate the different hydrograph components and how uncertain these estimates are. It is understandable that due to the challenging research environment many samples have been collected in an opportunistic way (e.g., one time stream sample). Nevertheless the work that is presented would gain value if sources of uncertainty were discussed and presented in the methods and result section. In the results section the actual results of the hydrograph separation get a little lost because there is no clear distinction between the description of the site characteristics, the end-members (e.g. snow or ice isotopic composition) and the interpretation of results. Perhaps instead of grouping the results section into the three watersheds the authors should rather consider structuring the results section into first a presentation of the input data (e.g. end-member composition across sites), the hydrograph separation results, discussion of uncertainties, comparison of hypothesized processes across sites and a separate discussion that is focusing on the comparison of findings with previous investigations as defined in the objectives.

AUTHORS: Thank you for your helpful recommendations. We have restructured the manuscript as suggested. The Methods section has been amended to improve the clarity. The results of the multi-sampling tests have been moved to the Methods section, so that the instrumental uncertainty, the sampling uncertainty and the uncertainty of the runoff measurements are presented in the same section. We have followed your suggested structure of the Results and Discussion sections; with the exception that we have places the discussion of uncertainties in the Discussion section.

Specific comments

2) Abstract Line 10: "specific water component" is not very specific. Could this be narrowed down to a list of the actual water sources that were discussed in the results section?

AUTHORS: We have rewritten the Abstract to avoid this poor phrasing.

3) Page 5849, last paragraph: Melting snow samples at room temperature causes a much stronger fractionation and concentration of lighter isotopes in the headspace than melting the snow slowly in a fridge. In addition, depending on the ratio of snow sample to bottle volume the resulting headspace in the melting process can be of variable volume for each sample again causing variable fractionation between melted snow samples. This effect needs to be determined (e.g. comparison of the isotopic value of two snow samples collected from the same location/layer, one melted at room temperature, the other melted in the fridge) and the uncertainty associated with this effect considered in the isotopic hydrograph separation.

AUTHORS: Kinetic effects during the melting of samples have absolutely no influence on the uncertainty beyond the instrumental uncertainty. The reason is that the amount of water molecules in the liquid phase is several orders of magnitude higher than the amount of water molecules in the headspace. Hence, it does not matter whether the melting was conducted at 5C or 20C.

This can be exemplified by the following rough calculations: Assume that we have 20 ml water equivalent snow in a 40 ml bottle (a 1:1 volume ratio between air and water), then melting at 5C and 20C will have water vapor pressures of 10 HPa and 20 HPa, respectively. Hence, in the bottle there will be 0.02 l (*c.* 1 mol) of liquid water and 0.02 l * 20 HPa/1013 HPa = 0.0004 l water vapor at 20C. 0.0004 l water vapor is equal to 0.0004 l/24l/mol = 1.6 e-5 mol. Thus, in the bottle the molar ratio between water and water vapor is 60000:1 at 20C. At 5C, the ratio is 120000:1.

4) Page 5850, line 1: Correct "wter isotope".

AUTHORS: Typo fixed.

5) Page 5851, line 3: I find it strange to use the German word for glacier in as glacier name (e.g. Mittivakkat Gletscher).

AUTHORS: “Gletscher” is also the former Danish word for glacier, and the name “Mittivakkat Gletscher” is widely used by the local population and in international scientific literature. We have chosen not to use the new name “Mittivakkat Gletsjer”, as the word “Gletsjer” has not yet been implemented in scientific literature. This may change in the future. A manuscript by Bjørk et al. containing the official names of Greenlandic glaciers is currently under review for The Cryosphere. Here, Mittivakkat Gletscher is used as an example of a widely used informal name.

6) Page 5851, line 11: Here it would make sense to restate the elevation range of the catchment or glacier in parentheses.

AUTHORS: Following the Reviewer’s advice, we now restate the elevation range of Mittivakkat Gletscher.

7) Page 5852, line 10: Replace “where” in “30 May 2008 where a rainfall event” with “when”.

AUTHORS: The sentence has been amended to “… 30 May 2008 when a rainfall event …”

8) Page 5852, line 28: Awkward phrasing. “. . .the runoff suddenly remained constant, coinciding with an air temperature increase and a change in 18O from decreasing to. . .”.

AUTHORS: The sentence has been rephrased.

9) Page 5853, line 12 ff.: I would find it interesting if the snowmelt/ice melt dynamics would be explored more in depth using the diurnal variation of the isotope signal. Could it be that as snowmelt is increasing over the day, subsequently the snowmelt volume passing through the glacier is increasing as well causing melting of the englacial conduits due to

the heat of fusion introduced with the snowmelt. It would be interesting to see of rates of conduit enlargement could be correlated to observed increases in ice meltwater contributions.

AUTHORS: We agree with the Reviewer that a study coupling snowmelt and ice melt dynamics, energy balance components, glacier hydrology and isotope dynamics will be interesting. While a theoretical model study is possible, it will be difficult to validate the model output. For instance, it will be difficult to estimate the amount of englacial melting of conduits caused by heat of fusion from snowmelt and separate this contribution to runoff from contributions to runoff caused by other ice melting processes. However, as the application of advanced runoff modelling is beyond the scope of this study, we focus our interpretation of diurnal variations on (1) the proportional contributions of snowmelt, ice melt and rainwater, and (2) the use of $\delta^{18}O$ variation to gain insights into the configuration of the subglacial drainage system.

10) Page 5857, line 25: You mention the interannual mean δ18O was -24.17±0.20‰ while at the same time you provide information that this value was only calculated over the July-Aug. period. I would say "interannual" is the wrong term here since clearly you didn't take samples every month over one year. This needs to be corrected. In addition, I would suggest adding information throughout the manuscript on how many samples these mean values are based (e.g. n=7).

AUTHORS: This part on Watson River has been removed from the manuscript (see our reply to Reviewer #2 point 13).

11) Page 5858, line 19: Insert "was" before ". . .derived from mixed proglacial snowmelt and ice-marginal ice melt.".

AUTHORS: This part on Watson River has been removed from the manuscript.

12) Page 5861, line 24: "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." This sentence is not clear.

AUTHORS: The sentence has been rephrased and now reads: "An alternative explanation may be that snowmelt only constituted so small a proportion of the total runoff in the late melt season that discrimination between snowmelt and ice melt was impossible."

13) Page 5862, line 12: Plural! “. . .phenomenon on large glacier with lateral tributary. . .”.

AUTHORS: The sentence has been rephrased and now reads: “Hence, it therefore remains unknown whether a high spatial variability in $\delta^{18}O$ is a common phenomenon or related to specific circumstances such as surge activity or presence of tributary glaciers.

14) Figure 2: This figure is hard to read. I would suggest using a topographic depiction instead of a Lands

AUTHORS: We are sorry about the poor quality of Figure 2. The figure was intended as a high quality figure covering two pages. The figure has been amended.

Stable oxygen isotope variability in two contrasting glacier river catchments in Greenland

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Abstract. Analysis of stable oxygen isotope ($\delta^{18}O$) characteristics is a useful tool to investigate water provenance in glacier river systems. In order to attain knowledge on the diversity of $\delta^{18}O$ variations in Greenlandic rivers, we examined two contrasting glacierized catchments disconnected to the Greenland Ice Sheet (GrIS). At Mittivakkat Gletscher River, a small river draining a local temperate glacier in Southeast Greenland, diurnal oscillations in $\delta^{18}O$ occurred with a three-hour time lag to the diurnal oscillations in runoff. The mean annual $\delta^{18}O$ was -14.68 ± 0.18 ‰ during the peak flow period. A hydrograph separation analysis revealed that the ice melt component constituted 82 ± 5 % of the total runoff and dominated the observed variations in total runoff. The snowmelt component peaked between 10:00 and 13:00 hours, reflecting the long travel time and an inefficient distributed subglacial drainage network in the upper part of the glacier. At Kuannersuit Glacier River on the island Qeqertarsuaq in West Greenland, the $\delta^{18}O$ characteristics were examined after the major 1995-1998 glacier surge event. The mean annual $\delta^{18}O$ was -19.47 ± 0.55 ‰. Despite large spatial variations in the $\delta^{18}O$ 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. This is likely a consequence of a tortuous subglacial drainage system consisting of linked-cavities, which formed during the surge event. Overall, a comparison of the $\delta^{18}O$ compositions from glacial river water in Greenland shows distinct differences between water draining local glaciers and ice caps (between -23.0 ‰ and -13.7 ‰) and the GrIS (between -29.9 ‰ and -23.2 ‰).

1 Introduction

There is an urgent need for improving our understanding of the controls on water sources and flow paths 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 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 our knowledge of the potential consequences of future hydrological changes in Greenlandic river catchments.

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Slettet: Throughout the peak flow season the $\delta^{18}O$ 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.
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Slettet: In 2002 there were indications of diurnal oscillations, and in 2003 there were large diurnal fluctuations in $\delta^{18}O$. At Watson River, a large catchment at the western margin of the Greenland Ice Sheet, the spatial distribution of $\delta^{18}O$ 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 ... [1]
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Analysis of stable oxygen isotopes ia a very useful technique to investigate water provenance in glacial river systems. 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).

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 stable oxygen isotope composition in two Greenlandic glacier river systems, namely Mittivakkat Gletscher River (13.6 km^2) which drains a local non-surging glacier in Southeast Greenland and Kuannersuit Glacier River (258 km^2) which drains a local glacier on the island Qeqertarsuaq, West Greenland. The latter experienced a

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Slettet: , which are selected for this study because they are draining very different glaciological environments (Figure 1):

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major glacier surge event in 1995-1998. Our aim is to gain insights into the variability and controls of the oxygen isotope composition in contrasting glacierized river catchments located peripheral to the GrIS (i.e. the river systems do not drain meltwater from the GrIS). Besides a study by Andreasen (1984) at the glacier Killersuaq in West Greenland, this is the first study of oxygen isotope dynamics in rivers draining glacierized catchments peripheral to the GrIS.

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 (Figure 1). The entire glacier covers an area of 26.2 km^2 (in 2011; Mernild et al., 2012) 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 flows into the Sermilik Fjord. The sampling site is located at a hydrometric station 1.3 km down-valley from the main subglacial meltwater portal. The hydrological catchment has an 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 (MAAT) 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., 2011). In recent decades the recession has accelerated and the glacier has lost approximately 29% of its volume between 1994 and 2012 (Yde et al., 2014), 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., 2012, 2013b) and serves as a representative 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 (Figure 1). 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 per day (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

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down-valley and approximately 3 km^3 of ice were moved to form a new glacier tongue (Larsen et al., 2010).

Kuannersuit Glacier River originates 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 has an altitude range of 100-1650 m a.s.l. and covers 258 km^2 of which Kuannersuit Glacier constitutes 103 km^2 of the total glacierized area of 168 km^2 (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 °C and -1.7 °C in 2011 and 2012, respectively (Cappelen, 2013).

3 Methods

3.1 Sampling protocol and isotope analyses

In total, 287 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 relatively high runoff). The most intensively sampled period was from 8 August to 22 August 2004, where sampling was conducted with a 4-hour frequency supplemented by short periods of higher frequency sampling. 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. An additional 40 river samples were collected for multi-sampling tests.

During five field seasons in July 2000, 2001, 2002, 2003 and 2005, a total of 180 oxygen isotope samples were collected from Kuannersuit Glacier River (Table 2) and another 44 river samples were collected for multi-sampling tests. In addition, 13 ice samples were obtained along a longitudinal transect at the centreline of the newly formed glacier tongue with 500 m sampling increments in July 2001, and 23 ice samples were collected along a transverse transect with 50 m sampling increments in July 2003. The transverse transect crossed the longitudinal transect at a distance of 3250 m from the glacier front. Seven samples of rainwater were collected in a Hellmann rain gauge located in the vicinity of the glacier terminus in July 2002.

All water samples were collected manually in 20 ml vials. Ice samples were collected in 250 ml polypropylene bottles or plastic bags before being slowly melted and decanted to 20 ml vials. A potential kinetic fractionation effect may occur due to the air temperature during the melting of samples, but the importance of the effect has not been quantified. The vials were stored in cold (~5 °C) and dark conditions to avoid fractionation related to biological activity.

Jacob Clement Yde 9/11/2015 18.00
Slettet: emanat

Jacob Clement Yde 12/11/2015 14.58
Slettet: with an altitude range of 100-1650 m a.s.l.

Jacob Yde 21/9/2015 15.29
Slettet:
Sampling and analysis

Jacob Yde 21/9/2015 15.29
Slettet: Sampling and analysis

Jacob Yde 21/9/2015 15.46
Formateret: Ingen punkttegn eller nummerering

Jacob Yde 2/11/2015 13.04
Flyttet (indsættelse) [4]

Jacob Yde 2/11/2015 13.13
Slettet: O

Jacob Clement Yde 13/11/2015 12.00
Flyttet (indsættelse) [16]

Jacob Clement Yde 13/11/2015 12.01
Slettet:

Jacob Yde 2/11/2015 13.05
Flyttet (indsættelse) [5]

Jacob Yde 2/11/2015 13.11
Flyttet (indsættelse) [6]

Jacob Yde 2/11/2015 13.11
Formateret: Indrykning: Første linje: 1,25 cm

Jacob Clement Yde 12/11/2015 15.02
Slettet: at

Jacob Clement Yde 12/11/2015 15.02
Slettet: during rainfall events

Jacob Yde 2/11/2015 13.22
Slettet: .

Jacob Clement Yde 10/11/2015 16.15
Slettet: Snow and i

Jacob Clement Yde 10/11/2015 17.36
Slettet: at room temperature

The relative deviations (δ) of water 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 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 uncertainty of $\delta^{18}O$ is given by the standard deviation.

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, 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.

In this text, the uncertainty of $\delta^{18}O$ is given by the standard deviation.

3.2 Multi-sample tests

In Mittivakkat Gletscher River, we conducted three multi-sample tests at 14:00 hours 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 Kuannersuit Glacier River, 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, possibly because different parts of the drainage system merged close to the glacier portal.

3.3 Runoff measurements

Stage-discharge relationships were used to determine runoff at each study site. The accuracy of individual runoff measurements is within ± 10-15 %. For details on runoff measurements we refer to Hasholt and Mernild (2006) for Mittivakkat Gletscher River and Yde et al. (2005a) for Kuannersuit Glacier River. In short, at Mittivakkat Gletscher River the runoff measurements were conducted at a hydrometric monitoring station located after the braided river system had changed into a single river channel about 500 m from the river outlet. The station was installed in August 2004 and recorded water stage every 10 minutes during the peak flow period. At Kuannersuit Glacier River the runoff measurements were obtained at a hydrometric monitoring station installed in July 2001 at a location where the river merges to a single channel. Water stage was recorded every hour during the peak flow period. The station was destroyed during the spring river break-up in 2002.

Jacob Yde 21/9/2015 15.30
Slettet: of all samples from Mittivakkat Glacier River and Kuannersuit River and most samples from Watson River

Jacob Clement Yde 12/11/2015 15.12
Slettet: In this text, t

Jacob Yde 21/9/2015 15.30
Slettet: The 1992 samples from Watson River were analyzed at the Alfred Wegener Institute in Bremerhaven, Germany.

Jacob Yde 21/9/2015 15.30
Slettet: such as in the Watson River catchment,

Jacob Yde 21/9/2015 16.49
Formateret: Mellemrum Efter: Automatisk

Jacob Yde 21/9/2015 16.47
Flyttet (indsættelse) [1]

Jacob Yde 21/9/2015 16.47
Slettet: W

Jacob Yde 2/11/2015 13.48
Formateret: Skrifttype:Kursiv

Jacob Yde 2/11/2015 13.48
Formateret: Skrifttype:Kursiv

Jacob Yde 2/11/2015 13.49
Formateret: Skrifttype:Kursiv

Jacob Yde 21/9/2015 16.49
Flyttet (indsættelse) [2]

Jacob Yde 21/9/2015 16.51
Formateret: Indrykning: Første linje: 1,25 cm, Mellemrum Efter: 10 pkt.

Jacob Yde 21/9/2015 16.50
Slettet: comparison

Jacob Clement Yde 9/11/2015 18.40
Slettet: robably

Jacob Yde 21/9/2015 16.51
Slettet:

Jacob Yde 21/9/2015 15.54
Formateret: Listeafsnit; Indrykning: Første linje: 0 cm

Jacob Yde 21/9/2015 15.54
Formateret: Skrifttype:Fed, Engelsk (Storbritannien)

Jacob Clement Yde 9/11/2015 14.22
Flyttet (indsættelse) [15]

Jacob Clement Yde 9/11/2015 14.22
Flyttet opad [15]: The accuracy of individual runoff measurements is within ± 10-15 %.

Jacob Yde 21/9/2015 16.34
Formateret: Engelsk (USA)

4 Results

4.1 $\delta^{18}O$ end-member components

On Mittivakkat Gletscher, three snow pits (0.1 m sampling increments) 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). The range of individual samples in each snow pit varied between -14.5 ‰ and -19.5 ‰ (269 m a.s.l.; n = 36), -13.8 ‰ and -21.2 ‰ (502 m a.s.l.; n = 21) and -11.9 ‰ and -21.6 ‰ (675 m a.s.l.; n = 26) (Dissing, 2000). Also, two ice-surface $\delta^{18}O$ records of 2.84 km 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 ‰ (Boye, 1999), 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 (160-880 m a.s.l.) of Mittivakkat Gletscher, but ice dynamics, ice age and meteorological conditions, such as frequent inversion (Mernild and Liston, 2010), may also have an impact. 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). 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. Contributions from rainwater will likely result in episodic increase in the $\delta^{18}O$ of bulk meltwater.

In the Kuannersuit Glacier River system, the glaciological setting differed from the Mittivakkat Gletscher River system. During the surge event of Kuannersuit Glacier, the glacier front advanced from ~500 m a.s.l. down 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. The mean $\delta^{18}O$ value of glacier ice collected along the longitudinal and transverse transects was -20.5 ± 1.0 ‰ (n = 36). This is consistent with $\delta^{18}O$ values of glacier ice located near the glacier front, showing mean $\delta^{18}O$ of -19.4 ± 0.9 ‰ (n = 20) in a section with debris layers formed by thrusting and -19.8 ± 1.1 ‰ (n = 37) in a section without debris layers (Larsen et al., 2010). In contrast to the setting at Mittivakkat Gletscher River, it was likely that other ice melt component in bulk runoff from Kuannersuit Glacier comprised water from several ice facies sub-component sources with various $\delta^{18}O$ values and spatial variability. 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

Jacob Yde 21/9/2015 17.41
Formateret: Skrifttype:Fed

Jacob Yde 21/9/2015 15.44
Slettet: and discussion

Jacob Yde 21/9/2015 16.58
Formateret: Indrykning: Venstre: 0 cm, Hængende: 0,5 cm, Tal og bogstaver + Niveau: 1 + Nummereringstypografi: 1, 2, 3, … + Begynd med: 2 + Justering: Venstre + Justeret: 0,63 cm + Indrykning: 1,27 cm

Jacob Yde 3/11/2015 11.05
Formateret: Skrifttype:Fed

Jacob Yde 21/9/2015 16.43
Slettet: Mittivakkat Gletscher River

Jacob Yde 21/9/2015 16.38
Slettet: 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 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.

Jacob Clement Yde 11/11/2015 17.54
Slettet: –

Jacob Clement Yde 11/11/2015 17.55
Slettet: –

Jacob Clement Yde 11/11/2015 17.55
Slettet: –

Jacob Yde 21/9/2015 16.55
Flyttet nedad [3]: 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.

Jacob Yde 21/9/2015 16.55
Flyttet (indsættelse) [3]

Jacob Yde 2/11/2015 14.03
Flyttet (indsættelse) [7]

Jacob Yde 2/11/2015 15.57
Slettet: A consequence of the surge event was that

Jacob Clement Yde 9/11/2015 18.26
Slettet: was relocated

Jacob Clement Yde 9/11/2015 18.26
Slettet: a position at an altitude of ~500 m a.s.l.

Jacob Clement Yde 9/11/2015 18.27
Slettet: during the surge event

Jacob Yde 2/11/2015 15.58
Slettet:

resulted in variations in the δ18O composition. The δ18O 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). Also, during the termination of the surge event in the winter 1998/1999 proglacial naled 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). Naled is an extrusive ice assemblage formed in front of the glacier by rapid freezing of winter runoff and/or proglacial upwelling water mixed with snow. A profile in a thrust-block naled section showed a δ18O of -20.1 ± 0.5 ‰ (n = 60; excluding an outlier polluted by rainwater; Yde and Knudsen, 2005b). With regards to the end-member compositions of snowmelt and rainwater at Kuannersuit Glacier River, it was not possible to access snow on the upper part of the glacier, so no δ18O values on snowmelt were measured. Rainwater was collected during rainfall events in July 2002, showing a wide range in δ18O between -18.78 ‰ and -6.57 ‰ and a median δ18O of -10.32 ± 4.49 ‰ (n = 7).

4.2 δ18O characteristics

At Mittivakkat Gletscher River, the early melt season is characterised by an increasing trend in δ18O. In 2005 the δ18O values in the early melt season were similar to the δ18O values during the peak flow period (Figure 2a; Table 1). This indicates that the onset of ice melt commenced before the early melt season sampling campaign. 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 when a rainfall event (19 mm in the nearby town of Tasiilaq located 10 km to the southeast of the Mittivakkat Gletscher River catchment; Cappelen, 2013) caused a positive peak in δ18O of ~1 ‰ (Figure 2b). Episodic effects on δ18O by precipitation seem common throughout the ablation season. For instance, another short-term change occurred on 14 – 15 August 2005 (Figure 2a), where a negative peak in δ18O of ~2 ‰ coincided with a snowfall event (14 mm in Tasiilaq; Cappelen, 2013) and subsequent elevated contribution from snowmelt.

During the peak flow period, the mean annual δ18O was -14.68 ± 0.18 ‰ (Table 1). We use the 2004 time-series 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 (Mernild, 2006). In Figure 3, the 2004 δ18O 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 δ18O composition, e.g. on 9-10 and 16-18 August 2004. However, the diurnal pattern was severely disturbed at around 03:00 hours on 11 August. The hydrograph shows that during the falling limb the diurnal trend in runoff was interrupted, coinciding with an air temperature increase and a change in δ18O from decreasing to slightly increasing values. The runoff stayed almost constant until a rapid 39 % increase in runoff occurred at 13:00 hours on 12 August, accompanied by an

Jacob Clement Yde 9/11/2015 18.35
Slettet: (an extrusive ice assemblage formed in front of the glacier by rapid freezing of winter runoff and/or proglacial upwelling water mixed with snow)
Jacob Yde 2/11/2015 14.22
Flyttet (indsættelse) [9]
Jacob Yde 2/11/2015 16.15
Slettet: I
Jacob Yde 2/11/2015 14.11
Flyttet (indsættelse) [8]
Jacob Yde 3/11/2015 11.04
Formateret: Skrifttype:Fed
Jacob Yde 3/11/2015 11.04
Formateret: Skrifttype:Fed
Jacob Yde 3/11/2015 11.23
Slettet: ... [5]
Jacob Yde 2/11/2015 13.04
Flyttet opad [4]: Oxygen isotope sa ... [6]
Jacob Yde 21/9/2015 16.47
Flyttet opad [1]: We conducted thr ... [7]
Jacob Yde 2/11/2015 13.05
Flyttet opad [5]: In the years 2005 ... [8]
Jacob Yde 3/11/2015 11.23
Slettet: In 2005,
Jacob Yde 3/11/2015 11.35
Slettet: the
Jacob Yde 3/11/2015 11.23
Formateret ... [4]
Jacob Yde 3/11/2015 11.23
Slettet: had
Jacob Clement Yde 10/11/2015 13.38
Slettet: , as reflected in δ18O ranging ... [9]
Jacob Yde 3/11/2015 11.24
Slettet: During this period δ18O incr ... [10]
Jacob Clement Yde 10/11/2015 18.42
Slettet: re
Jacob Clement Yde 11/11/2015 17.56
Slettet: 3
Jacob Clement Yde 13/11/2015 12.01
Slettet: -
Jacob Clement Yde 11/11/2015 17.56
Slettet: 3
Jacob Clement Yde 13/11/2015 12.00
Flyttet opad [16]: The most intens ... [11]
Jacob Clement Yde 13/11/2015 12.01
Slettet: se
Jacob Clement Yde 13/11/2015 12.01
Slettet: data
Jacob Clement Yde 11/11/2015 17.57
Slettet: 4
Jacob Clement Yde 9/11/2015 18.08
Slettet: suddenly remained constant,

increase in δ^{18}O and decrease in electrical conductivity. Thereafter, runoff remained at an elevated level for more than two days before returning to a diurnal oscillation of runoff. Hydrograph separation of water sources is a helpful tool to elucidate the details of this event (see section 4.3).

In the Kuannersuit Glacier River, the sample-weighted mean annual δ^{18}O was -19.47 ± 0.55 ‰ during the peak flow period (a sample-weighted value is applied because the number of samples per year deviated between 2 and 109). In Figure 4, the variations in δ^{18}O are presented together with runoff for the period 14 – 31 July 2001. The 2001 runoff measurements showed diurnal oscillations with minimums around 10:00 – 12:00 hours and maximums at 19:00 – 20:00 hours, correlating with reversed oscillations in solutes (Yde et al., 2005a) and poorly with suspended sediment concentrations (Knudsen et al., 2007). However, the variability of δ^{18}O did not correlate with runoff or any of these variables. While some of the episodic damming and meltwater release events appear as peaks on the runoff time-series, the peaks in the δ^{18}O time-series coincided with rainfall events (e.g. on the nights of 21 July and 29 July 2001). Besides these episodic peaks, a lack of diurnal fluctuations in δ^{18}O characterised the δ^{18}O time-series.

Figure 5 shows the diurnal δ^{18}O variations during four July days without rainfall in the years 2000-2003. There were no diurnal oscillations in 2000, 2001 and 2002. In 2003, the fluctuations were much larger than in the preceding years, but the highest δ^{18}O (-19.03 ‰) was measured at 21:00 hours and low δ^{18}O prevailed during the night (~-21.0 ‰). This diurnal variability was also reflected 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. Although these measurements from a single day each year are insufficient to represent the conditions for the entire peak flow period, they may indicate post-surge changes in the structure of subglacial hydrological system which are worth addressing in detail in future studies of the hydrological system of surging glaciers.

4.3 Hydrograph separation

The conditions for conducting hydrograph separation during the peak flow period were different for the two study catchments. At Mittivakkat Gletscher River it was possible to distinguish between the δ^{18}O values of end-member ice melt and snowmelt components, and there were diurnal oscillations in δ^{18}O. In contrast, the available data from Kuannersuit Glacier River did not allow hydrograph separation in the years following the surge event. Here, there were no diurnal oscillations in δ^{18}O, and the composition and importance of the snowmelt component were unknown. Hence, we will continue by using the 2004 time-series to construct the hydrograph separation for Mittivakkat Gletscher River.

First, 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 =

Jacob Clement Yde 9/11/2015 18.16
Slettet: retaining the diurnal oscillation pattern again

Jacob Yde 3/11/2015 12.52
Formateret: Indrykning: Første linje: 1,25 cm

Jacob Clement Yde 10/11/2015 14.26
Slettet: 58

Jacob Clement Yde 9/11/2015 14.40
Slettet: season

Jacob Yde 3/11/2015 11.39
Slettet: (the uncertainty is given by the standard deviation)

Jacob Clement Yde 11/11/2015 17.57
Slettet: 8

Jacob Clement Yde 13/11/2015 12.02
Slettet: -

Jacob Clement Yde 13/11/2015 12.02
Slettet: -

Jacob Clement Yde 9/11/2015 18.51
Slettet: are seen

Jacob Yde 3/11/2015 12.09
Flyttet (indsættelse) [10]

Jacob Yde 3/11/2015 12.30
Slettet: In Figure 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 hours and maximums at 19:00-20:00 hours, correlating with reversed oscillations in solutes (Yde et al., 2005a) and poorly with suspended sediment concentrations (Knudsen et al., 2007). However, the variability of δ^{18}O did not correlate with any of these variables.

Jacob Clement Yde 11/11/2015 17.58
Slettet: 7

Jacob Clement Yde 10/11/2015 14.36
Slettet: and

Jacob Clement Yde 10/11/2015 14.36
Slettet: , but in

Jacob Clement Yde 10/11/2015 14.37
Slettet: a low δ^{18}O (~-19.4 ‰) was measured between 09:00 hours and 15:00 hours while a high δ^{18}O (~-18.8 ‰) was measured in the evening (20:00 - 02:00 hours)

Jacob Yde 4/11/2015 09.48
Formateret: Indrykning: Første linje: 0 cm

Jacob Clement Yde 9/11/2015 14.40
Slettet: season

Jacob Yde 3/11/2015 11.38
Slettet:

Jacob Yde 3/11/2015 13.53
Slettet: W

0.58), indicating the combined effect of the two primary components, snowmelt and ice melt, on the $\delta^{18}O$ variations. The diurnal amplitude in $\delta^{18}O$ ranged between 0.11 ‰ (11 August 2004) and 0.49 ‰ (16 August 2004). However, there was no statistical relation between diurnal $\delta^{18}O$ 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 $\delta^{18}O$.

Based on the assumption that snowmelt and ice melt reflect their end-member $\delta^{18}O$ compositions (-16.5 ‰ and -14.1 ‰, respectively), a hydrograph showing contributions from snowmelt and ice melt is constructed for the 2004 sampling period (Figure 6). The ice melt component constituted 82 ± 5 % of the total runoff and dominated the observed variations in total runoff ($r^2 = 0.99$). This is expected late in the peak flow period, where the subglacial drainage mainly occurs in a channelized network in the lower part of the glacier (Mernild, 2006). The slightly decreasing trend in the daily snowmelt component was likely a consequence of the diminishing snow cover on the upper part of the glacier. The snowmelt component peaked around 10:00-13:00 hours each day, reflecting the long distance from the melting snowpack to the proglacial sampling site and the possible 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 hours later, is a roof collapse causing ice-block damming of a major subglacial channel. The hydrograph separation (Figure 6) shows that the proportion between ice melt and snowmelt remained almost constant after the event commenced, indicating that the bulk water derived from a well-mixed part of the drainage system, which was unaffected by the large diurnal variation in ice melt generation. This suggests that the functioning drainage network transported meltwater from the upper part of the glacier with limited connection to the drainage network on the lower part. Meanwhile, ice melt was stored in a dammed section of the subglacial network located in the lower part of the glacier, and suddenly released when the dam broke at 13:00 hours on 12 August (Figure 6). 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 (Figures 3 and 6).

4.4 Longitudinal and transverse $\delta^{18}O$ transects

Glacier ice samples were collected on the surface of Kuannersuit Glacier to gain insights into the spatial variability of $\delta^{18}O$ on the newly formed glacier tongue. Both the longitudinal and transverse transects showed large spatial fluctuations in $\delta^{18}O$ (Figure 7). 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-

Jacob Yde 4/11/2015 13.10
Slettet:

Jacob Clement Yde 11/11/2015 17.59
Slettet: 5…. The ice melt componen ... [12]

Jacob Clement Yde 11/11/2015 17.59
Slettet: 5… shows that the proportio ... [13]

Jacob Yde 4/11/2015 09.58
Slettet: ... [14]

Jacob Yde 4/11/2015 09.57
Formateret: Skrifttype:Fed

Jacob Yde 4/11/2015 09.57
Slettet: Kuannersuit Glacier River

Jacob Yde 2/11/2015 13.11
Flyttet opad [6]: During five field seasons in July 2000, 2001, 2002, 2003 and 2005, oxygen isotope samples were collected from Kuannersuit Glacier River (Table 2).

Jacob Yde 3/11/2015 12.04
Slettet: During five field seasons in July in July 2000, 2001, 2002, 2003 and 2005, oxygen isotope samples were collected from Kuannersuit Glacier River (Table 2). T ... [15]

Jacob Yde 2/11/2015 14.03
Flyttet opad [7]: A consequence of the surge event was that the glacier front was relocated from a position at an altitude of ~500 m a.s.l. 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.

Jacob Yde 4/11/2015 09.58
Slettet: However…he,…longitudina ... [16]

Jacob Clement Yde 11/11/2015 18.00
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glacier with 50 m increments, showed a more systematic trend where relatively high δ^{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 δ^{18}O between -22.69 ‰ and -20.08 ‰. The total range of measured δ^{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 δ^{18}O signal), whereas the glacier ice in the western central part mainly derived from high elevation areas of Sermersuaq ice cap (low δ^{18}O signal). At present, there are only few comparable studies on transverse variations in δ^{18}O across glacier tongues. Epstein and Sharp (1959) found a decrease in δ^{18}O towards the margins of Saskatchewan Glacier, Canada. Hambrey (1974) measured a similar decrease in δ^{18}O towards the margins of Charles Rabots Bre, Norway, in an upper transect, whereas a lower transect showed wide unsystematic variations in δ^{18}O. Hambrey (1974) concluded that in the upper transect the marginal ice derived from higher altitudes than ice in the centre, whereas in the lower transect the wide variations were related to structural complexity of the glacier. However, both of these studies are based on few samples. Hence, it therefore remains unknown whether a high spatial variability in δ^{18}O is a common phenomenon or related to specific circumstances such as surge activity or presence of tributary glaciers.

5 Discussion

5.1 Differences in δ^{18}O between Mittivakkat Gletscher River and Kuannersuit Glacier River

A significant difference between the δ^{18}O dynamics in Mittivakkat Gletscher River and Kuannersuit Glacier River is the marked diurnal oscillations in the former and the lack of a diurnal signal in the latter. At Mittivakkat Gletscher River, the hydrograph separation analysis showed a three-hour lag of δ^{18}O to runoff caused by the difference in travel time for ice melt and snowmelt. Meltwater in the early melt season was dominated by snowmelt with relatively high δ^{18}O, whereas diurnal oscillations with amplitudes between 0.11 ‰ and 0.49 ‰ existed 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). The largest diurnal amplitudes in δ^{18}O have been observed in small-scale GrIS catchments, such as at Imersuaq and "N Glacier", where large differences in δ^{18}O exist between various ice facies and snowmelt (Yde and Knudsen, 2004; Bhatia et al., 2011).

The lack of strong diurnal oscillations as observed in the post-surge years at Kuannersuit Glacier River indicates either a mono-source system, a well-mixed drainage network, or a multi-source system, where the primary components have similar δ^{18}O

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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 rainwater (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 transforms 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, frequent loud noises interpreted as drainage system roof collapses were observed, in addition to episodic export of ice blocks from the portal, suggesting ongoing changes to the englacial and subglacial drainage system. 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).

Lack of diurnal oscillations in $\delta^{18}O$ has previously been related to other causes at non-surging glaciers. At Glacier de Tsanfleuron, Switzerland, sampling in the late melt season (23-27 August 1994) showed no diurnal variations in $\delta^{18}O$, which was interpreted by Fairchild et al. (1999) 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 total runoff in the late melt season that discrimination between snowmelt and ice melt was impossible. At the glacier Killersuaq, an outlet glacier from the ice cap Amitsulooq in West Greenland, Andreasen (1984) found that diurnal oscillations in $\delta^{18}O$ were prominent during the relatively warm summer of 1982, whereas no diurnal $\delta^{18}O$ 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).

5.2 $\delta^{18}O$ compositions in glacier rivers

It is clear from the studies of Mittivakkat Gletscher River and Kuannersuit Glacier River that glacier rivers have different $\delta^{18}O$ compositions. The bulk meltwater from Mittivakkat Gletscher has a $\delta^{18}O$ 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 3). The $\delta^{18}O$ composition of Kuannersuit Glacier is lower and similar to the $\delta^{18}O$ composition of the glacier Killersuaq (Table 3). Currently, the lowest $\delta^{18}O$ compositions are found in bulk meltwater draining the GrIS in West Greenland (Table 3), but there is a lack of $\delta^{18}O$ data from Antarctic rivers. Estimations of $\delta^{18}O$ based on δD measurements suggest $\delta^{18}O$ values of -32.1 ‰, -34.4 ‰ and -41.9 ‰ in waters draining Wilson Piedmont Glacier, Rhone Glacier and Taylor Glacier, respectively (Henry et al., 1977).

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5.3 Uncertainties in $\delta^{18}O$ hydrograph separation models

The accuracy of end-member hydrograph separation models is limited by the uncertainties of the estimated values of each end-member component and the uncertainty of $\delta^{18}O$ in the river. While the uncertainty of $\delta^{18}O$ in the river is likely to be relatively small, the uncertainties of each end-member component must be kept in mind. The assumption of discrete values of each end-member component is unlikely to reflect the spatial and temporal changes in bulk $\delta^{18}O$ of snowmelt, ice melt and rainwater. For instance, Raben and Theakstone (1998) found a seasonal increase in mean $\delta^{18}O$ in snow pits on Austre Okstindbreen, Norway, and episodic events such as passages of storms (e.g., McDonnell et al., 1990; Theakstone, 2008) or melting of fresh snow in the late ablation season may cause temporal changes in one component. It is also difficult to assess how representative snow pits and ice transects are for the bulk $\delta^{18}O$ value of each component. Spatial differences in $\delta^{18}O$ may exist within and between snow pits but the overall effect on the isotopic composition of the water leaving the melting snowpack at a given time is unknown. Future research based on field experiments and ablation modelling may help to improve the hydrograph separation technique by providing insights into the dynamics of $\delta^{18}O$ values of each component.

6 Conclusions

In this study, we have examined the oxygen isotope hydrology in two of the most studied glacierized river catchments in Greenland to improve our understanding of the prevailing differences between contrasting glacial environments. This study has provided insights into the variability and composition of $\delta^{18}O$ in river water draining glaciers and ice caps adjacent to the GrIS.

The following results were found:

- The Mittivakkat Gletscher River on Ammassalik Island, Southeast Greenland, has a mean annual $\delta^{18}O$ of -14.68 ± 0.18 ‰ during the peak flow period, which is similar to the $\delta^{18}O$ composition in glacier rivers in Scandinavia, Svalbard, European Alps, Andes and Asia. The Kuannersuit Glacier River on Disko Island, West Greenland, has a lower mean annual $\delta^{18}O$ of -19.47 ± 0.55 ‰, which is similar to the $\delta^{18}O$ composition in bulk meltwater draining an outlet glacier from the ice cap Amitsulooq but higher than the $\delta^{18}O$ composition in bulk meltwater draining the GrIS.
- In Mittivakkat Gletscher River the diurnal oscillations in $\delta^{18}O$ were conspicuous. This was due to the presence of an efficient subglacial drainage system and diurnal variations in the ablation rates of snow and ice that had distinguishable oxygen isotope compositions. The diurnal oscillations in $\delta^{18}O$ lagged the diurnal oscillations in runoff by approximately three hours. A hydrograph separation analysis revealed that the ice melt component constituted 82 ± 5 % of the total runoff and dominated the observed variations in total runoff during the peak flow period in 2004. The snowmelt

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component peaked between 10:00 and 13:00 hours, reflecting the long travel time and a possible inefficient distributed subglacial drainage network in the upper part of the glacier.

- In contrast to Mittivakkat Gletscher River, Kuannersuit Glacier River showed no diurnal oscillations in $\delta^{18}O$. This is likely a consequence of glacier surging. In the years following a major surge event, where Kuannersuit Glacier advanced 10.5 km, meltwater was routed through a tortuous subglacial conduit network of linked cavities, mixing the contributions from glacier ice, basal ice, snow and rainwater.

This study has showed that environmental and physical contrasts in glacier river catchments influence the spatio-temporal variability of the $\delta^{18}O$ compositions. In Greenlandic glacier rivers, the variability in $\delta^{18}O$ composition is much higher than previously known ranging from relatively high $\delta^{18}O$ values in small-scale coastal glacierized catchments to relatively low $\delta^{18}O$ values in GrIS catchments.

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In GrIS waters (between -29.9 ‰ and -23.2 and -23.2 ‰) and water from large Greenland ice caps (between -23.0 ‰ and -17.8 ‰ ... [37]

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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	$\delta^{18}O$ [‰]
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

Sampling site	Distance from headwater portal [km]	$\delta^{18}O$ (28 July 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	

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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.

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Watson River after junction with Qinnguata Kuussua tributary	32.4	-24.19	-26.98

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

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

Site	Sampling period	Latitude	Longitude	Maximum [‰]	Minimum [‰]	Reference
Greenland						
Mittivakkat Gletscher	2003-09	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	2000-05	69°46'N	53°15'W	-17.8	-21.9	This paper
Killersuaq	1982-83	66°07'N	50°10'W	-19.5	-23.0	Andreasen, 1984
Watson River	1992, 2005-09	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	1980-95	66°00'N	14°10'E	-11.8	-14.4	Theakstone, 2003
Storglaciären, Sweden	2004 & 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	1969-70	46°49'N	10°48'E	~ -13.8	~ -19.4	Behrens et al., 1971
Kesselwandferner, Austria	1969-70	46°50'N	10°48'E	~ -14.8	~ -18.1	Behrens et al., 1971
Andes						
Cordillera Blanca catchments, Peru	2004-06	9°-10°S	77°-78°W	-13.3	-15.3	Mark and McKenzie, 2007
Juncal River, Chile	2011-12	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	2008-09	29°34'N	101°59'E	-13.7	-17.6	Meng et al., 2014

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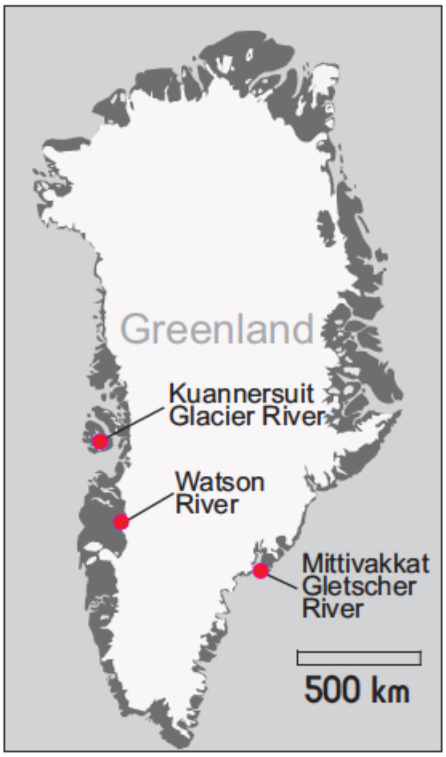

Fig. 1. Location map of the three study sites in Greenland.

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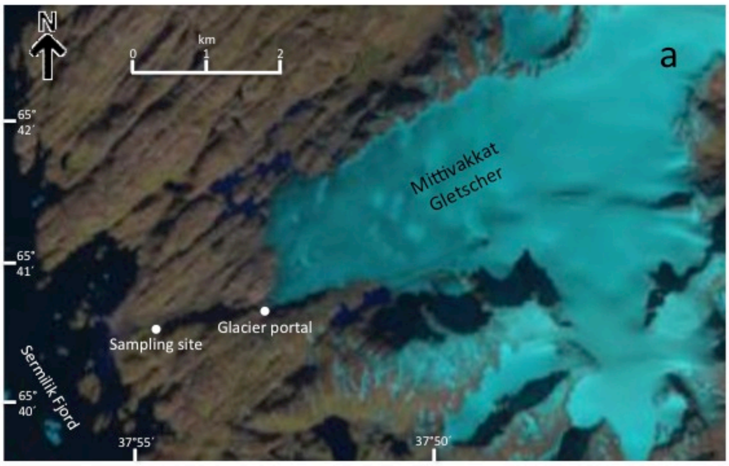
N
km
0
1
2
a
65° 42′
65° 41′
65° 40′
Mittivakkat Gletscher
Glacier portal
Sampling site
Sermilik Fjord
37°55′
37°50′

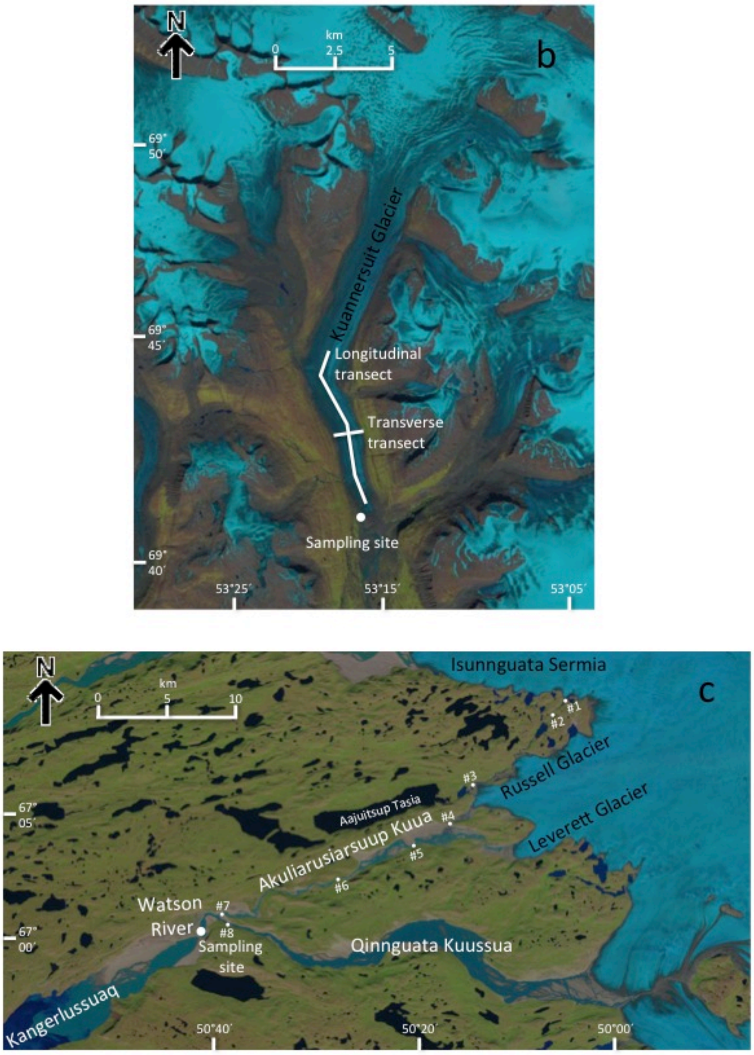

Fig. 2. Location maps of the study areas (a) at Mittivakkat Gletscher River, Southeast Greenland (image from Landsat 8 OLI on 3 September 2013); (b) at Kuannersuit Glacier River, West Greenland (image from Landsat 8 OLI on 8 July 2014); and (c) at Watson River, West Greenland. The numbers (#1-#8) show 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).

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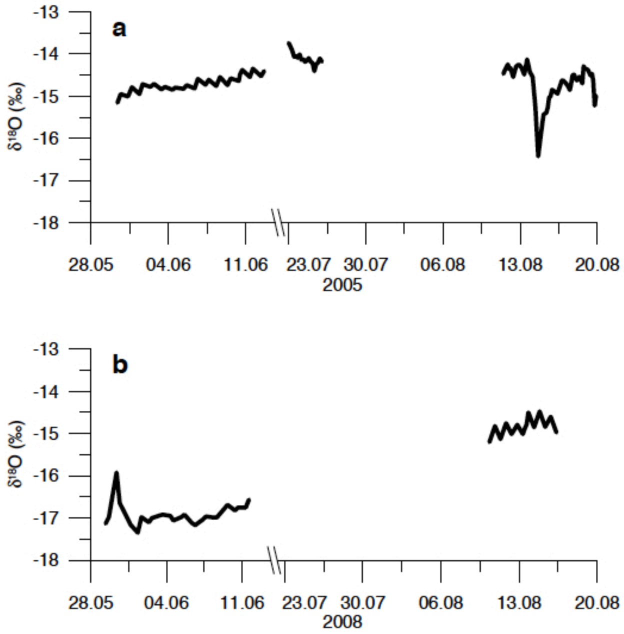

Fig. 3. $\delta^{18}O$ time-series in bulk river water draining Mittivakkat Gletscher in (a) 2005 and (b) 2008.

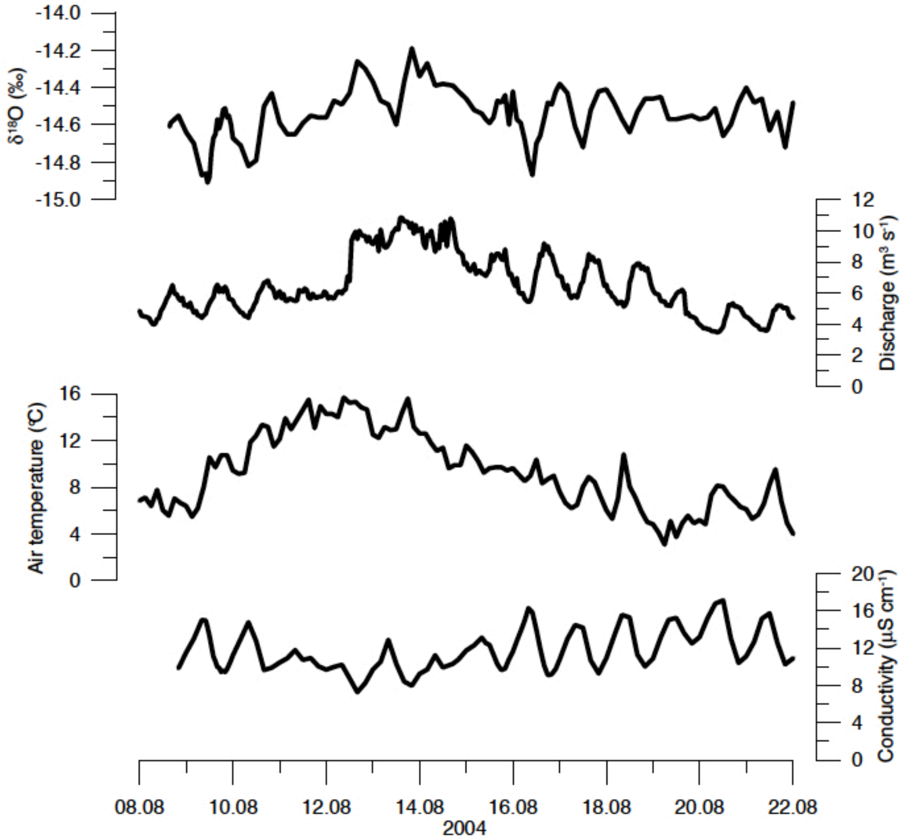

Fig. 4. Time-series of $\delta^{18}O$, discharge, air temperature and electric conductivity in bulk river water draining Mittivakkat Gletscher in 8-21 August 2004.

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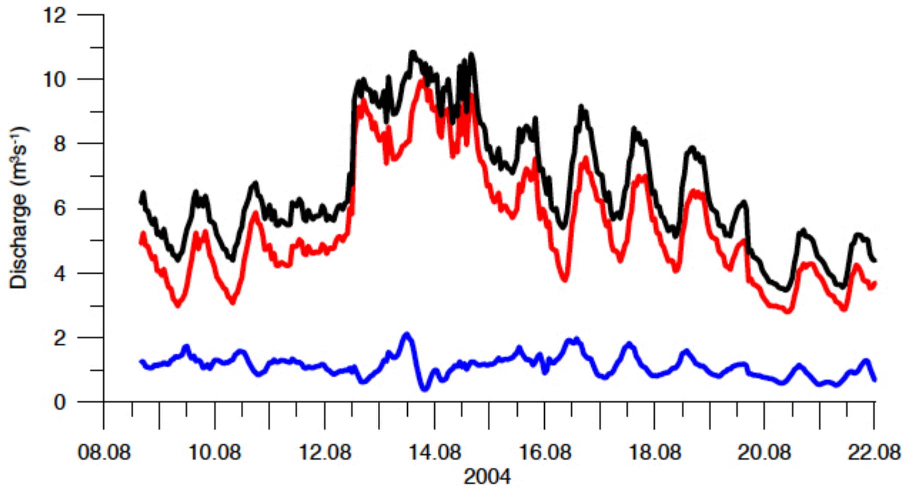

Fig. 5. Hydrograph showing the separation of the discharge in Mittivakkat Gletscher River (black curve) into an ice melt component (red curve) and a snowmelt component (blue curve) during the period 8-21 August 2004.

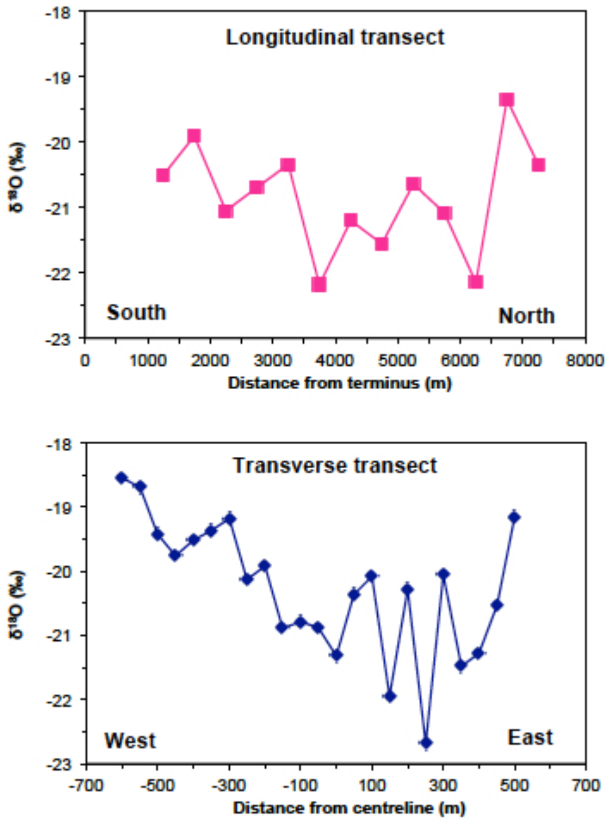

Fig. 6. Variations in $\delta^{18}O$ of glacier ice along a longitudinal transect and a transverse transect on Kuannersuit Glacier. The transverse transect crosses the longitudinal transect at a distance of 3250 m from the glacier terminus.

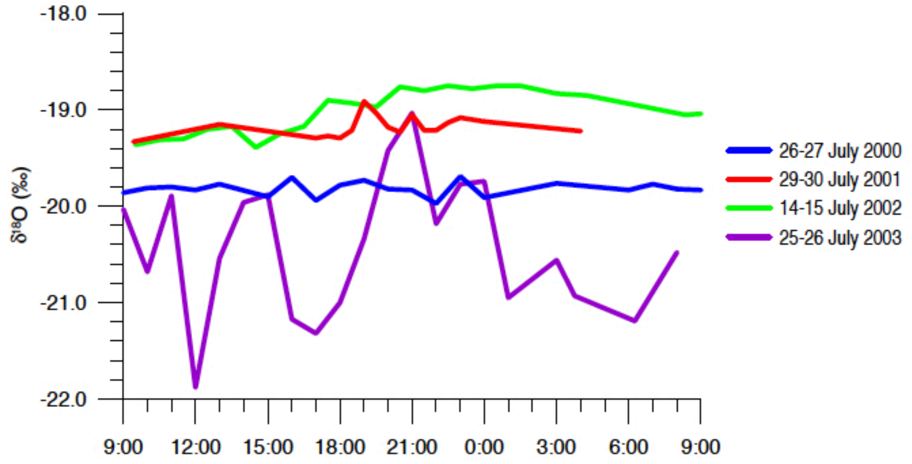

Fig. 7. Diurnal $\delta^{18}O$ variations in Kuannersuit Glacier River on studied days in July in the post-surge years 2000-2003.

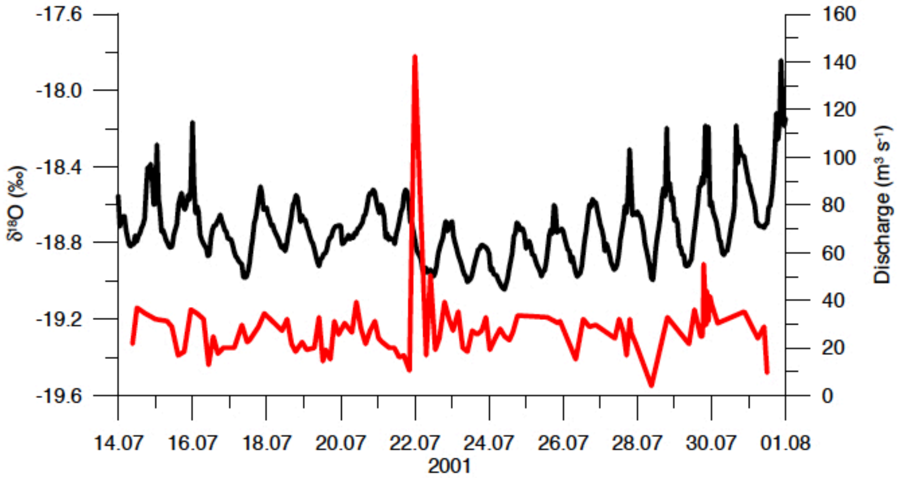

Fig. 8. Time-series of $\delta^{18}O$ (red curve) and discharge (black curve) in Kuannersuit Glacier River during the period 14-31 July 2001.

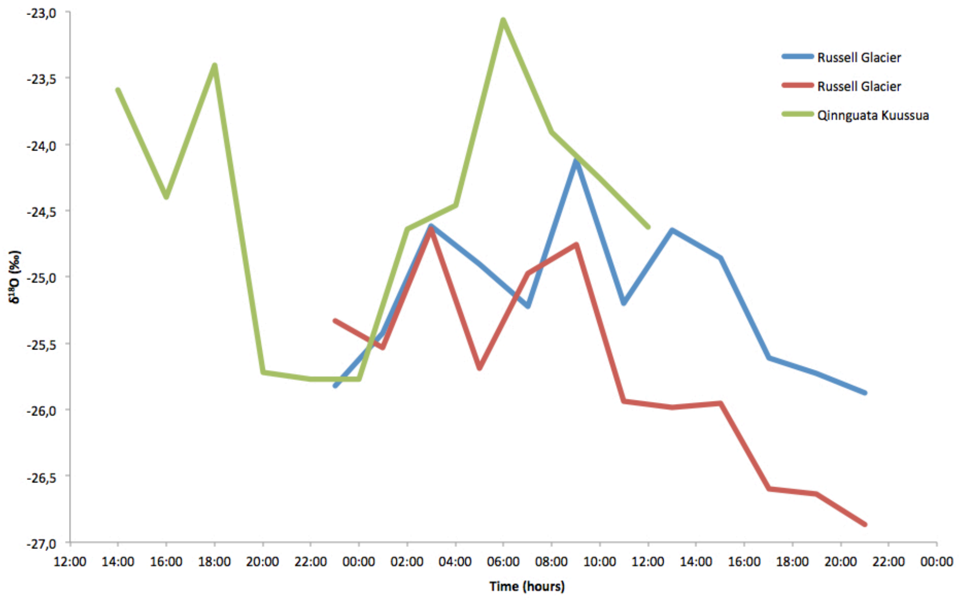

Fig. 9. Diurnal $\delta^{18}O$ variations in sub-catchments of the Watson River system. Sampling was conducted in front of Russell Glacier (sampling site #4) on 22/23 July 1992 (red curve) and 30/31 July 1992 (blue curve), and from the Qinnguata Kuussua tributary (sampling site #8) on 15/16 July 1992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