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 "$\delta^{18}O$ end-member components" and section 4.4 "Longitudinal and transverse $\delta^{18}O$ 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.