Dear Kenny,

Thank you for the time you have spent on a thorough review of our manuscript. We have attempted to address the points and concerns and have revised the manuscript quite a lot. Please find the specific responses in *italics* to your comments below.

Best wishes
The Authors

Editor Decision: Publish subject to minor revisions (review by editor) (22 Jul 2020) by Kenichi Matsuoka
Comments to the Author:
Dear authors,

Thanks for submitting the response letter together with two versions of the manuscript for further consideration. The main difference between these two versions is whether the feature is referred as “active subglacial channel” or “subglacial river”. The authors made a point that “subglacial river” is an accepted glaciological term in the response letter so I evaluated the latter version for the further consideration.
I made a careful review for the final judgement and found a large number of points that need to be considered before the acceptance of this work in its final form. Please consider following suggestions and address questions in the next revision, and provide a marked manuscript and response letter as well. Page/line numbers refer those in the marked “200615_final_V2” manuscript.

General comments:
- Title: as I said above, the authors convinced me to keep using subglacial river. However, I don’t think that the current title captures the main point of this study. The possibility of subglacial river largely depends on a continuous topographic valley, which is hypothesized in this study. My suggestion is “Possible impacts of a 1000-km-long hypothetical subglacial valley towards Petermann Glacier in northern Greenland”.

- *Thanks for the suggested title change, it has been changed with one addition being “subglacial river valley” is used instead of “subglacial valley”. The motivation of this study was to investigate the possibility of a long subglacial river and if we remove “subglacial river” from the title then it does not represent the manuscript’s focus as well. However if this is not acceptable “river” can be removed without further objection.*

I am open for other alternatives, but please be careful to clarify that this is a sort of thought experiments and assessments of a hypothetical subglacial valley which does not appear in the recent bed topography dataset but cannot be denied because of the inadequate data coverage. Also, geographical scope/interest of this study is somewhat unclear at the beginning but gets clearer in Results. Please clarify the geographical scope of this study somewhere in Introduction so that it is clear for the readers from the beginning.

- *P2L3: Added to first paragraph: “The valley extends from 74.18 ◦ N, 42.54 ◦ W in the Greenland interior to 80.21 ◦ N, 56.46 ◦ W under Petermann Glacier. As described in (Bamber et al., 2013), the valley may extend further southward but a sparcity of radar passes makes this harder to determine.*

Also I found both Petermann Glacier and Petermann Ice Stream in this manuscript. I am not a Greenland specialist, but I think Petermann Glacier is more common than Petermann Ice Stream. In any case, use only one of them consistently throughout the manuscript.

- *Removed all references to "Petermann Ice Stream". Replaced with upper Petermann Glacier where needed.*
- *Have added "Upper Petermann Glacier" labels to Figs 1 and 6 to clarify.*
- *Referring to upper Petermann Glacier as the section of the glacier above where the valley enters to Petermann Glacier.*

- Another general suggestion is to re-organize Introduction, Section 2.3 and Appendix A so that the motivation of this work and bed modifications can be better presented as a single information package. The current manuscript presents this point at three different locations, and each of them is neither comprehensive nor standalone. A possible solution is to make Introduction shorter, and change Section 2.3 to a new Section 2 "Limited knowledge of bed topography" or "Bed topography: current knowledge and hypothesis" (I'm open for other section titles) before new Section 3 "Model and methods". In this way, the bed topography is explained before the current Section 2.2 "basal sliding and hydrology".

- *P2L17: Created new section 2 "Limited knowledge of bed topography"*
- *Combined introduction bedrock section, Appendix A and section 2.3 into section 2*
- *Figures have been re-arranged to account for these changes.*

- I cannot accept the majority of Discussion for the publication, because they are relevant to the main results only to a small degree, or they are speculative based on thought experiments. Please revise Discussion largely; shortening this section does not reduce the value of this paper. Rather it helps readers to get the main points of your paper and stay focused.

- *The discussion has been changed following the comments below.*

Line-by-line suggestions and questions:
P1L1: Re-organize the beginning of the abstract so that it does not start with a question. For general readers, it is hard to immediately understand thoughts behind this question. It is better to explain the current status of our understanding of bed topography (including its limit), and potential impact of the hypothetical valley on ice flow and mass balance of the ice sheet. After stating these points, this question can be better understood.

- *P1L1: The question is removed and the bed topography issue is introduced first.*
- *Removed references to "sediment flow" from introduction and throughout manuscript.*

P1L2: This is only one place you say Petermann Glacier, and you say Petermann Ice Stream at other locations. Please sort it out.

- *"Petermann Ice Stream" has been removed from the manuscript.*

P1L13: Is "present day active long subglacial water river" observed? I cannot catch what you mean exactly.

- *It is not observed but rather we are attempting to determine if it is possible that a currently active subglacial river is possible along the valley.*
- *"active" has been removed from manuscript.*

P1L20: “mirror like” radar reflectors are expected only when there is a subglacial lake. Subglacial water channels with a smaller spatial extent do not necessarily make “mirror like” reflectors.

- *The finding of Ekholm et al. we belive is written correctly here and the reference is to “not mirror like” returns that they found.*

P2L6-: Mention the fractional length of the mass-conservation-derived BedMachine topography to the entire hypothetical valley. E.g. “The mass conservation method was applied to the lowest one sixth of main flowline towards the Petermann Glacier, so the majority of the bed topography in this region is derived by Kriging so that its error largely depends on the location of radar data.”

- *P2L19: Thank you, this sentence has been added.*

P2L31: change to “a possible continuous subglacial valley”¨

- *P2L13: Change made.*

P3L3: at the beginning of this paragraph, add the spatial resolution of the model (5 km). You said “as detailed above” at P5L7 but you didn’t show it actually.

- *P3L7: The spatial resolution is stated in the second paragraph. We have now added it also to the beginning of the first paragraph as requested.*

P3L4: geographical model domain is uncertain. Is it better to say “….the state of the entire Greenland Ice Sheet”? (or is the simulation made only for the northern Greenland? Anyway, please clarify).

- *P4L5: Added “entire”.*

P3L7: change “final” to “last”

- *Change made.*

P3L10: Do not cite a manuscript in preparation in a way like (Greve et al. 2020). As a rule of thumb, manuscripts in preparation cannot be cited.

- *Sorry about this mistake. This manuscript is now published online but was not at the time of this review. The reference is corrected*
- *P4L10: Goezler et al. 2020 has now been accepted for publication and we have changed it to “in press”*

P3L11: change to “computed ice topography”

- *P4L11: Change made.*

P3L34: local depressions are not necessarily related to subglacial lakes. If the authors refer only to subglacial lakes, then this filling can be made only if the flat part is larger than a certain extent (i.e. lake extent). I assume that the authors rather refer to any type of small, local depressions in the bed topography.

- *P4L30: Removed “to account for subglacial lakes”*

P4L3: spell out RMSD and I think modeled and observed surface flow speeds are compared both in the logarithmic scale (rather than only observed speed in the logarithmic scale).

- *P5L1: Changed to root-mean-square deviation. Added comma to clarify sentence.*

P4L4: Remove a citation to a manuscript in preparation.

- *Updated as above.*

P4L9: typo? "Petermann in at an average…"

- *Corrected.*

P4L10: It is said that the modification is made to make the average elevation around -400 m. However, it is unclear for me why the presented procedure gives this average depth. Probably, the authors aimed to say that the derived hypothetical bed topography gives the valley floor at about -400 m. However, as far as I can see in Fig. 2a, BedMachine gives slightly shallower valley floor (it is represented as yellow/brown, instead of distinct green for your hypothesized valley). So, I doubt that this procedure gives the bed elevation of -400 m. Did you make any other adjustments and if so why is this floor depth of -400 m chosen? Overall, I would like to see Section 2.3 improved significantly to present the bed topography modifications more clearly. Some suggestions follow.

- *We have removed the reference to -400 m, it was a rough guide but through the process used it did end up varying quite a bit along the route as you state.*
- *P3L9 This paragraph has been updated following the suggestions below*

P4L10: Does "standard topography" refer BedMachine topography? If so, please say so explicitly rather than make a new term.

- *P3L6: Changed to "unaltered BedMachine topography down-scaled to the 5 km grid ".*

P4L12: Change to "consequences of the modified bed topography".

- *P3L8: Changed*

P4L14-16: Show the size of the valley polygon (how wide is the polygon from the valley center line? Might be 5 km, the resolution of the model??). Later at line 17, this polygon is converted to the center line. In principle, polygon (with a certain areal extent) cannot be converted to a flowline. Development of the modified bed topography is subjective by nature, which I can accept, but please be careful to explain the process as clear as possible.

- *P3L11: Changed "a polygon of the rough location" > "a polyline of the rough location"*
- *The "polygon" changed to "drawn polyline localizing" the valley is converted to a "smooth" centerline ", and then described through a spline" changed to "though spline interpolation". Data points situated within the valley "polygon" changed to "buffer" are converted from their Cartesian coordinates (x;y) towards this flow-oriented coordinate (s;n) system.*

P4L16: What is "a new BedMachine"? Do you refer a modified bed topography, i.e. "Valley"? Please clarify.

- *P3L12: Changed to "used to interpolate a new modified bed topography to be used in the "Valley" simulation"*

P4L16: If I understand correctly, the authors also used kriging (i.e. same procedure and parameters of BedMachine), which the authors criticized in Introduction. Is it correct? Then except for the saddle removing step, what do the procedures presented in the second paragraph bring in this study? Why do you need the steps, instead of simply removing rises from BedMachine?

- *Outside of the domain of the buffer we used the same Kriging parameters as BedMachine. Inside the buffer we used anistropic kriging, as knowledge of the thalweg is included through a morphed coordinate system.*
- *P3L19: Sentence added:*
- *“Moreover, outside of the domain of the buffer we use the same Kriging parameters as BedMachine, whereas inside the buffer we use anistropic kriging, as knowledge of the thalweg is included through a morphed coordinate system.”*

P4L28: Re-consider the title of Section 2.4. I cannot see why it is “idealized”. This section can be probably named as “Sensitivity tests on geothermal flux” or “Possible melt water supply from NEGIS”.

- *Removed idealized.*
- *P5L5: Changed to “Sensitivity tests on geothermal flux”*

P4L29: probably “whether” instead of “where” (you compare only two experiments), and add “… is routed to this valley.” Do both Control and Valley bed topography route the subglacial water to this valley? Or do you enforce such water flow in the model?

- *P5L6: Changed to “whether basal water melted near the source of NEGIS is routed down the valley.”*
- *We do not enforce the water flow, we just insert the spot of enhanced geothermal heat flux.*

P4L33: Fig. 7b cited here, though only Figs. 1 and 2 are cited to this point. All figures need to be named in the order of citation in the paper.

- *Figures have now been reordered.*

P5L1: Does Fahnestock et al. infer 1.5 W/m2 at the hot spot? If so, please say so and if not please explain why it is set to 1.5W/m2.

- *Ours is a bit higher peak heat flux, we explain:*
- *P5L10: To do this a bell-shaped geothermal heat flux anomaly centred at 74 ◦ N, 40 ◦ W is introduced with a 1-sigma radius of 50 km and peak heat flux of 1.5 W m −2 which creates a broader region with a comparable value to the regional heat flux of 0.97 W m −2 estimated byFahnestock et al. (2001).*

P5L5: this section shows (1) Control, (2) ControlIS, (3) Valley, (4) ValleyIS sensitivity tests. However, at P5L32, sensitivity tests are mentioned again and cites Appendix B. Appendix B presents four more sensitivity tests, not 1-4 above, which is very confusing. Please re-organize this section and mention additional four sensitivity tests in this section. And more fundamentally, do you really need additional sensitivity tests presented in Appendix B?

- *The sensitivity to valley depth tests were requested during peer review and required extra work so we would rather not remove them. We believe they present useful results on how sensitive the routing is to what we set the depth of the valley to.*

- *The wording is changed to more clearly distinquish these tests from the geothermal heat flux tests.*
- *P6L13: "Four additional sensitivity tests have been used to investigate the robustness of these responses by altering the valley depth (Appendix A). These additional results indicate that the location and magnitude of this water flux out of the valley is sensitive to the valley depth due to its consequent effect on the steepness of the valley sides.*

P5L7: you didn't say the resolution of the model (5 km), though you say "as detailed above" here.

- Addressed earlier.

P5L9: I think it clearer if you say "basal water thickness"

- *Changed to "basal water thickness" throughout article.*

P5L10: Is it better to say "the simulated basal water depth is affected by the Valley bed topography not only in the Petermann catchment but also the North Greenland in general." I think most readers understand that this paper primarily focuses on the Petermann catchment, and it is suddenly said North Greenland here.

- Changed to:
- P5L21: "For the Petermann catchment and northern Greenland in general"

P5L11: better to say "separated" instead of "independent", and change "deeper basal water" to "thicker basal water". I already pointed out above, but also change "basal water depth" to "basal water thickness", and "deeper and uninterrupted" to "thicker and uninterrupted". I don't point out this "deeper vs. thicker" issues below but the same suggestion is applied for all locations.

- *Changes made and throughout article:*
- *Basal water "depth" changed to "thickness" and "Deeper" changed to "thicker"*
- *Changed label on Fig. 7.*

P5L14: I don't call a water body of 10 cm thick as subglacial lakes. It is very unclear to show the thickness as "larger than" (even 100 m is larger than > 0.01 m!). It is much clearer if you say something like "thicker water bodies of about 10-15 cm were found at 6 locations along the valley". (Obviously I made up 15 cm and 6 locations!).

- *"subglacial lakes: removed.*
- *Changed sentence to:*
- *P5L25: "The thickest water (> 0.01 m) along the valley route occurs at 7 locations where the Priority Flood algorithm has been activated to a maximum thickness of 10 m."*

P5L15: do you mean no difference between Control and Valley experiments by "no change"? The word "change" often refers temporal changes, so please describe it in a more explicit way.

- *Changed to:*
- *P5L26: "In most interior areas away from the valley there is little or no difference in the basal water thickness between Control and Valley."*

P5L20ff: It seems to me that the location of thicker water shifted eastward at 74-75N as the bed topography is modified. Is it directly associated with the shift of valley position? I think it is better to mention this in the text. What features are directly related to the hypothetical topography and what features are more “wow, it’s unexpected”?

- *The valley position is not shifted but rather opened along route. More water is pirated by the valley hence the reduction seen to the west at 74-75 N.*
- *P5L32: Have added “an indication of water piracy by the valley.”*

P5L26-27: I cannot read “stuck” features from Fig. 4.

- *Have removed this part of the sentence, it is a little difficult to see unless the figure is made very large.*

P5L29ff: It is very hard to follow these statements. I think that the authors are trying to mention the feature of a “blue-red” pair blowing from the valley to northwest in Fig. 3d. Do I understand correctly? Then why don’t you explain it when you discuss Fig. 3 a few lines above?

- *It is mentioned when we discuss now Fig. 6. as quoted below (includes additional upper Petermann Glacier definiton now):*
- *P6L2: “The one region of increased basal water outside of the valley is a region that extends towards upper Petermann Glacier from NEEM zone in Figure 6d. NEEM zone is defined as the area of the valley to the southeast of the NEEM ice core drilling site as indicated on Figure 1. The effect of these changes is to redistribute the basal water under upper Petermann Glacier into a narrower and thicker plume that can also be seen in Figure 6b.*

P6L2: Is 1.6 m3/s a simple conversion of 10,000 m2/a (check the unit)? Also why do you convert it? Are you trying to tie this water flux to some observations at NEEM?

- *Here we attempt an estimate of the discharge using units typically used for river discharge.*
- *No, unfortunately there are no observations for discharge within the valley to compare with near NEEM.*

P6L5ff: What is the point of Fig. 5? Fig. 4 shows water flow directions, which are calculated based on the subglacial hydraulic potential I believe. Then why do you want to show ice and bed topography (i.e. more indirect way to show the water flow direction) here? If you argue that Fig. 5 is necessary in addition to Fig. 4 and others, consider presenting it in a smaller size. Also, is the bed topography presented here Control or Valley? Clarify it in caption.

- *The purpose of now Fig. 8 is to show how the path of the valley is related to the ice surface topography, how it roughly follows the northward ridge, is continually downslope. This figure allows the reader to see the broader picture of how the valley is related to the ice sheet shape.*
- *We are very keen to keep this figure if possible. It is important that the figure stretches north to south from Petermann to Basin. The resolution can be reduced but otherwise do not really want to reduce the geographical scope of the figure.*
- *Have added “BedMachine” to the caption.*
- *Reduced size, now it’s about half the size.*

P6L9-L14: I cannot follow the argument here. Why can’t you conclude that the bed is sloping or flat simply from the bed topography? In what context is post glacial adjustment discussed here?

- *P6L25: Post glacial adjustment sentences have been removed from here.*

-

P6L15ff: I am puzzled. Fig. 2 shows no topographic modification in the Steensby Glacier area (forgive me if I call it wrongly, but I want to point a glacier east of Petermann). No topo modification and no increase of water thickness in Fig. 3c are consistent, but the significant increase of surface flow speed (Fig. 6) is inconsistent with the other two. Please explain. It seems that this point is discussed and concluded negligible (P6LL23-24), which is incomplete and not convincing. Also, as the bed topography is modified, ice thickness is modified. Then the difference in surface flow speed is a combined effect of increased (thicker) ice deformation and basal sliding. Is it more straightforward to examine ice velocity of the deepest modeled ice layer?

- *P6L27: Have altered this paragraph based on this comment. We do not at this point know the reason for the sliding increase around Steensby and Ryder Glacier.*
- *P6L31: "These increases are consistent with the redistribution of basal water seen in Figure 6 and could also be related to the ice thickness change due to the modification of the bedrock."*
- *"Sliding changes also occur at certain outlet glaciers along the west coast as well as on the north coast around Steensby and Ryder Glacier to the east of Petermann. These changes, away from the valley and Petermann, are inconsistent across different model setups and do not show an obvious relationship to the changes in basal water distribution. They may be related to knock-on effects from the redistributions of ice mass due to the inserted valley. Considering other uncertainties and inaccuracies, the differences are too small to allow assessing which case is better compared to observed surface velocities."*

P6L27ff: I am afraid that Figure 7 needs to be revised to present these points clearer (or the authors read Fig. 7 too much). The most obvious thing is that basal melt rate along the valley increases only if the Valley topography is used. And regardless of the topography, the additional NEGIS hotspot increases basal melt rates towards the NEGIS and towards the west. I cannot immediately see the differential amount of basal melt towards NEGIS and west, when Control and Valley topography results are compared. Maybe the authors found this west-east contrast by examining the modeled results, but Fig. 7 is in any case inadequate to make this point. Also, this and following paragraphs in this section include discussion in addition to results. Please distinguish discussion and results more clearly and move statements to discussion as appropriately.

- *There may be a misunderstanding here.*
- *The basal melt rate is shown in the left panels and the basal water thickness differences are in the right two panels. So in the left panels there is no increase in basal melt rate along the valley shown in this figure.*
- *The most important point to be made here is in the right panel. This shows the difference in basal water thickness between two simulations with the same topography, but with one having the increased basal melting only in the region of the hot spot. So it shows that water thickens all along the valley which indicates that water flow from the hot spot down the entire valley is occuring. This is a key result demonstrating this fact and the potential for water flow all the way down the open valley.*

P6L35: Please carefully check the statements in this paragraph, and its evidence presented in the figures. I cannot agree with this statement about the region north of 80N.

- *In Figure 7d in the region north of 80 N the only region that has a significant regional change in water thickness is in the Petermann region.*

P7L1-3: You discuss the water flux here, while you have discussed basal melt rate in this paragraph. Reorganize.

- *The paragraph discusses basal water thickness primarily.*

P7L4ff: The majority of the discussion here is irrelevant or at least not significantly connected to the results presented here. In particular the first few paragraphs explain general knowledge, which is not necessary for this paper in my opinion. I suggest to delete the first 1-3 paragraphs and the 5th and 6th paragraphs because of inadequate relevance to the results. The 4th paragraph is somewhat relevant, but it is not directly linked to specific results in the current manuscript. If you retain this paragraph in the new version, please deepen the discussion and clearly connect the discussion to the results you obtained.

- *Deleted the first 1-6 paragraphs of the discussion.*

P8L16ff: I am not yet convinced that this discussion and Fig. 8 are necessary in the final form of this paper. I see the importance to examine boundaries of surface/ice and subglacial/water drainage basins. The current Fig. 8 shows the subglacial/water boundary for the Valley topography (I assume so, but it is not clear in the caption). If the authors have important discussion points on this issue, please present both boundaries of surface/ice and subglacial/water drainage basins for (1) Control topography and (2) Valley topography in two panels next to each other, and discuss how (2) is different from (1). Keep it in your mind that topography modification is hypothetical and the main aim of your work is to draw an attention to improve the bed topography of northern Greenland. You don’t need to examine all small features.

- *A colour bar has been added and the topography has been removed from the plot to make it clearer.*
- *The last reviewer said that figure 8 was helpful so we would prefer to retain it, hopefully now it is a bit more clear with the topography removed.*
- *The caption states “basal water flux from the sensitivity simulation that has a valley with fixed depth of −100 m (valley removal described in Appendix B)”*

P9L4ff: I think that the discussion about the link between the NEGIS hotspot and Petermann Ice Stream is valid. However, this paragraph starts with the discsussion about R-channels and so on. Please re-consider this paragraph and make sure that the discussion is directly pointed to the most important issues.

- *Removed “The current simulations do not include subglacial channelized water flow, such as within R-channels, in the hydrology module. Channelized water flow could funnel different amounts of water away from, and to, particular locations leading to focused areas of suppressed and enhanced sliding. This may effect the sliding model results that should be seen as a view of the potential for change in different regions rather than a prediction for the valley's influence on sliding speed.”*

P9L17ff: I don’t really think that discussion in this and following paragraphs are directly relevant to the hypothetical subglacial valley. Nonetheless, if you really want to point out these issues, limit the topics which are directly relevant and highly important for the ice-sheet dynamics. I really think that the 4-page-long discussion in the current form can be dramatically shortened to 1 page or so. It actually helps the authors to address the most important issues directly related to the results.

- *P8L21: This paragraph has been shortened to 2 sentences.*

P11L6ff: Please update this section according to your revisions in Discussion. The link to the NEGIS hotspot can be mentioned here, but the statements to this point (P11L16) can be shortened. I didn't point out at other locations, but the authors occasionally call the feature as "active" subglacial river, though the word "active" was removed from the title. I don't clearly see meaning added with this word, so suggest the authors to carefully consider what it really means. Also, the statements about wet sediment flow system and paleo-fluvial rivers are too weak to be concluded/presented here. My take-home message from this paper is that more radar surveys are necessary to examine the absence of these "removed" rises. If this is the case, please clarify this point both in Abstract and conclusions, and possibly in Introduction.

- *P9L25 we think has been addressed earlier regarding the significance of the result that water melted in the deep interior can pass the whole way along the valley if it is opened.*
- *remove "active" in relation to subglacial river throughout the manuscript.*
- *P10L5: The paleo-river is referring to terminology used by Bamber et al. (2013) so we are making the point that a subglacial river requires a different understanding and form to a river that flowed when there was little or not ice because they are such different systems.*
- *Referall to wet sediment flows have been removed.*

P11L9: change "are not real" to "may not be real". The lack of evidence does not means that there are no rises.

- *P9L3: Changed to may not be real.*

P12L3ff: Overall revisions are necessary to the two paragraphs for Appendix B. For example, it is unclear what "linear" and "idealized" mean (L5), why 26 valleys are used for 4 additional experiments (L5), what "grid point values" of "along-valley rectangle" mean (L6), what "short SICOPOLIS simulation" (L7) and "standard SICOPOLIS topography" (L9) mean, and what "4th test" refers (L9). There are just examples to show why I require overall revisions to Appendix B. I expect concise, but adequate descriptions in Appendix. Also, above all, do you really need Appendix B?

- *P10L9 onwards:*
- *We have changed the wording and added some additional sentences, specifically:*
- *Changed "linear" to "straight"*
- *Changed "valleys" to "channels"*
- *Changed "grid point values" to "bedrock elevation grid point values"*
- *"short SICOPOLIS simulation" is removed.*
- *"The first three of the four tests insert 26 straight 10 km wide channels to form an uninterrupted valley from Interior to Petermann. The channels are created using the Matlab function "inpolygon" that sets bedrock elevation grid point values within a rectangle that is aligned along the path valley. This method is used as it creates a flatter base than the method used in simulations Control and Valley. Consequently it is more suitable for testing the sensitivity to a particular valley base elevation."*
- *Changed "standard SICOPOLIS topography" to "unmodified BedMachine topography"*
- *We have added additional explanation about the "first three of the four tests" to clarify about the "fourth test"*
- *Appendix B is now Appendix A and was introduced to address earlier reviewer comments. It is useful for showing the sensitivity of the basal water distribution to the valley depth given that the form of the valley is uncertain so we would rather keep it.*

P.17 Figure 1: the legend says Petermann surface catchment, but I think it is a buffer of 200 km used to modify the bed topography, rather than defined from the surface topography. Also, the label shows Petermann Glacier but the text mostly refers as Petermann Ice Stream.

- *The Petermann surface catchment is correctly labeled.*
- *"Petermann ice stream" is removed and replaced with "upper Petermann Glacier" in the manuscript.*

P.19: Figure 3: change the unit for Fig. 3a/b colorbar from meters to millimeters. Also the caption does not need to say "from SICOPOLIS simulations for the year 1990". Also explain the label "NEEM zone" in the text. If you meant the NEEN ice core site, show the core site using a small symbol and explain it in the caption.

- *Changed the labels to mm here and on other figures.*
- *Removed "from SICOPOLIS…"*
- *Added a definition of NEEM zone as "NEEM zone is defined as area of the valley to the southeast of the NEEM ice core drilling site as indicated on Figure 1."*
- *Added a label for the NEEM ice core onto Figure 1b.*
- *Added "key locations and ice core sites" to the key of Figure 1.*

P.19 Figure 3c and 3d: consider adjusting the colorbar. The current figure does not support a statement in the main text about larger amount of water in the NEEM zone. The entire valley looks similarly red.

- *These figures show the basal water thickness difference so anywhere where it is yellow or red is where the water is thicker between the simulations.*

P.20 Figure 4: The labels of NEEM Zone for Figs. 3 and 4 point to different locations at a glance; adjust them so that both labels point to the right regions. Maybe adding arrows to Fig. 3 helps. Add the descriptions to the lower two panels (please clarify that these are zoom up of panels a and b). I understand that the authors chose the logarithmic scale because of the largely variable range of water flux shown here. But the river locations are shown in Fig. 3 already. Then is it actually better to show the water flux in the linear scale or at least adjust the colorbar so that the water flux increasing along the river can be better seen? I any case, clarify in the caption that the water flux colorbar is in the logarithmic scale if you stick with the logarithmic scale.

- *NEEM zone circles have been added to both figures to clarify the location.*
- *Added better NEEM zone labels to now Figure 7 (formerly Fig 4)*
- *Add c) and d) to the caption and stated that they are zoomed regions.*
- *Added "colours in a non-linear scale chosen to best demonstrate the distribution" to Fig 7.*
- *The water flux is not increasing along the river but is rather fairly constant.*

P.21 Figure 5: see the comment at P6L5ff.

- *Addressed earlier.*

P.22 Figure 6: Is it possible to show the extent of Petermann Ice Stream? The text says that the basal sliding increases significantly in the valley (> 10 m/a) but only little in the ice stream (< 0.5 m/a). It is hard to see the latter point in this figure. Maybe you can add the grounding line, or use non-white background color so that we can see near-zero difference (white) more clearly.

- *Added "Upper Petermann Glacier" label.*

P.23 Figure 7: see my comments above. And revise the unit for the basal water thickness colorbar from meters to millimeters.

- *changed scale to mm,*

P.24 Figure 8: Re-consider about this figure as suggested above (see my comments to p.8). If you retain Fig. 8 nearly as is, add colorbar, and the legend for blue/orange polygons. It is not easy to distinguish this orange polygon as the lower bed is shown with similar color. In any case, I expect that you modify Fig. 8 largely or delete it from the paper.

- *A colour bar has been added and the topography has been removed from the plot to make it clearer.*

Non-public comments to the Author:
Dear Chris, Ralf and others, I apologize that the review of this manuscirpt takes so long time. Also, I am afraid that you would be disappointed by seeing this large amount of revisions I am requesting in this stage. However, frankly speaking, the current manuscript is very hard to read and I think your messages can be much better presented if these points are considered. I hope to see your revision soon. Warmest regards, Kenny

- *Thanks again for the time you have spent reviewing this, we hope we have provided enough changes to progress forward and are happy to make further modifications accordingly.*
- *Best regards, the Authors.*

~~On the possibility~~ Possible impacts of a 1000 km long hypothetical subglacial river ~~under the north~~ valley towards Petermann Glacier in northern Greenland~~ice sheet~~

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Abstract. ~~Does an active subglacial river, or wet sediment flow, contained within a ~1000 km long valley, with a source at a known area of basal melting deep in the interior of the Greenland ice sheet, reach the sea at the Petermann Glacier grounding line? Basal~~ Greenland basal topographic data shows a segmented valley extending from Petermann Fjord into the centre of Greenland, however the locations of radar scan lines, used to create the bedrock topography data, indicate that valley ~~discontinuity~~ segmentation is due to data interpolation. Therefore, as a thought experiment, simulations where the valley is opened are used to investigate its effects on basal water movement and distribution. The simulations indicate that the opening of this valley can result in an uninterrupted water pathway from the interior to Petermann Fjord. Along its length, the path of the valley progresses gradually down an ice surface slope causing a lowering of ice overburden pressure that could enable water ~~and sediment~~ flow along its path. The fact that the valley base appears to be relatively flat and follows a path near the interior ice divide that roughly intersects the east and west basal hydrological basins, is presented as evidence that its present day form may have developed in conjunction with an overlying ice sheet. Experiments where basal melting is increased solely within the deep interior near the known large area of basal melting, result in an increase in the flux of water northwards along the entire valley. The results are consistent with a ~~present day active~~ long subglacial river, however considerable uncertainty remains over aspects such as whether adequate water is available at the bed, whether water escapes from the valley or is refrozen, and over what form a hydrological ~~or wet sediment~~ conduit could take along the valley base.

1 Introduction

The surface of the Greenland ice sheet holds visual clues to the topography of the bedrock, which in the interior can be below 2 to over 3 km of ice. Ekholm et al. (1998) found two, roughly 75 km long, elongated depressions in the surface of the ice that were connected by a “more than 100 km long, gently curving trench”. Ice penetrating radar returns from the depressions were not “mirrorlike”, which was considered a possible indication that subglacial water was being transported in the trench northward through a basal hydrological system. With improved topographic data Bamber et al. (2013) identified a “paleofluvial mega-canyon” that extends from central Greenland all the way to Petermann Fjord (Figure 1). The Ekholm et al. features are interior sections of this “canyon”. While the feature was referred to as paleofluvial, Bamber et al. (2013) also suggested that the valley could have water flowing through sections of it today. Specifically they demonstrated water was routed along independent sections of the valley but not along the whole length. In situ observations of water in the valley have not been obtained to date, nor are there current plans to acquire them. Since this “trench” (Ekholm et al., 1998), “subglacial valley” (van der Veen et al., 2007) or “canyon” (Bamber et al., 2013) takes a variety of cross-sectional forms along its length, in this article we will simply refer to it in the broadest term as a subglacial “valley”. The valley extends from 74.18°N, 42.54°W in the Greenland interior to 80.21°N, 56.46°W under Petermann Glacier. As described in Bamber et al. (2013), the valley may extend further southward but a sparcity of radar passes makes this harder to determine.

The term "subglacial river" has been previously used (Mooers, 1989; Clayton et al., 1999; Remy and Legresy, 2004; Popov and Masolov , to describe under ice sheet subglacial hydrological drainage within a valley and we follow this terminology. Therefore "subglacial river" is used to cover a variety of possible non-film subglacial hydrological conduit forms such as within R-channels, (Röthlisberger, 1972; Shreve, 1972), or Nye channels (Nye, 1973). In addition, a subglacial river may incorporate storage within reservoirs along route that release water only over certain periods, and can flow uphill in certain situations. A subglacial river beneath an ice sheet is therefore considered to have quite different properties from those of a terrestrial river.

The goal of our research is to investigate the impact of a possible continuous subglacial valley on the flow of basal water as a thought experiment, using a state-of-the-art ice sheet model. In addition, the effects on ice sheet sliding are explored as well as the impact of focussed interior basal melt on water flow along the valley. This is done in the framework of investigating whether a subglacial river along the valley base is possible.

2 Limited knowledge of bed topography

The BedMachine v3 basal topographic dataset (Morlighem et al., 2017) shows that the valley appears to be blocked by topographic rises at many points along its route (Figure 1b,c). ~~However, based~~ The mass conservation method was applied to the lowest one sixth of main flowline towards the Petermann Glacier, so the majority of the bed topography in this region is derived by Kriging such that its error largely depends on the location of radar data. The kriging algorithm is described in Morlighem et al. (2017) as “The variogram is modeled as a Gaussian function, with a sill of 100 m, a range of 8 km and a nugget effect of 50 m, to account for uncertainty in ice thickness measurements”. Based on the locations of the radar data lines that were used to generate this dataset and the limited extent of the valley bed elevation derived by mass conservation~~(two example regions are shown in Figure 1c,d)~~, it is clear that these rises occur only in regions where data was not obtained (two example regions are shown in Figure 1c,d). A map of error estimates from BedMachine v3 shows the variation in error across north Greenland (Figure 2). Errors range from 2 to $\sim$600 metres with a median of 158 metres along the valley. The results of Bamber et al. (2013) showed water routing along numerous independent sections of the valley, however they inferred that water was being routed away from the valley in these data sparse regions and so the valley was “likely to have influenced basal water flow from the ice sheet interior to the margin”. Since these rises are due to kriging interpolation, there is currently no evidence to suggest that this valley is filled~~(see Appendix A for further detail on BedMachine error estimates)~~. This poses the question; are these rises damming subglacial water flow along this conduit and negatively impacting ice sheet model simulations?

If it is assumed that the valley is open, then the elevation of the bottom of the valley can be roughly determined by the points along its route where data was obtained. In ~~(~~Figure 1b ~~) The~~ the gaps in the valley where the valley base elevation rises above $-100\,\mathrm{m}$ occur where no data has been obtained and interpolation has smoothed out the valley. In fact, after accounting for the smoothing effects of interpolation, a roughly level incised valley will only be resolved correctly exactly at the points where the data was obtained and everywhere else it will be shallower than it should be. Taking this into account a rough assessment is that the valley has a base that varies between $-250\,\mathrm{m}$ and $-500\,\mathrm{m}$ along its length from Interior to Petermann~~in Figure 1b~~.

In order to investigate the effect of removing the rises in the valley we alter the bedrock topographic data in a way to ensure that the valley is open from Interior to Petermann (Figure 3b). The case with the unaltered BedMachine topography down-scaled to the $5\,\mathrm{km}$ grid, is referred to as “Control” and the case with the altered open valley as “Valley”. The simulation initialisations are otherwise identical so that the results only show the consequences of the modified bed topography.

The ~~term "subglacial river" has been previously used (Mooers, 1989; Clayton et al., 1999; Remy and Legresy, 2004; Popov and Masolov , to describe under ice sheet subglacial hydrological drainage within a valley and we follow this terminology. Therefore "subglacial river" is used to cover a variety of possible non-film subglacial hydrological conduit forms such as within R-channels, canals, or Nye channels. These different forms are explained further in the discussion. In addition, a subglacial river may incorporate storage within reservoirs along route that release water only over certain periods, and can flow uphill in certain situations. A subglacial river beneath an ice sheet is therefore considered to have quite different properties from those of~~ topographic modification is done using a flow-oriented interpolation scheme and then taking the BedMachine and the flow-oriented scheme and extracting the lowest bedrock elevation at each grid point. Given the BedMachine topography and flight lines (Figure 1), a polyline of the rough location of the valley is drawn using a geographic information system (GIS). A buffer of 200 kilometres around this polyline is created and measurements falling into this buffer are used to interpolate a new modified bed topography to be used in the “Valley” simulation, with the same procedure and parameters as Morlighem et al. (2017). The drawn polyline localizing outlining the valley is converted to a ~~terrestrial river~~smooth centerline through spline interpolation. Data points situated within the valley buffer are converted from their Cartesian coordinates (x, y) towards this flow-oriented coordinate (s, n) system. This is a common reference frame, where s describes the distance of the thalweg and n is the normal in right-hand direction, and it outperforms ordinary kriging and other methods when used with an anistropic adjustment (Merwade et al., 2006). Here the anisotropic factor was 10, with a nugget of 20 metres, a sill of 30 metres, and a range of 300 metres. Moreover, outside of the domain of the buffer we use the same Kriging parameters as BedMachine, whereas inside the buffer we use anistropic kriging, as knowledge of the thalweg is included through a morphed coordinate system. Further details on the procedure of flow-oriented interpolation are detailed in Legleiter and Kyriakidis (2008).

For three regions, saddles are present along the valley. Bounding boxes over these saddlepoints are drawn that cover both the saddle and trenches within. Over these subsets a watershed algorithm called Maximally Stable Extremal Region (MSER; Donoser and Bischof, 2006) tracking is run to detect the trenches to be connected. Pixels between the trenches on either side of the saddle are found through connecting mathematical morphologic operations. These selected pixels are then adjusted by linear interpolation of the elevation information in the trenches to make a seamless passage.

The ~~goal of our research is to investigate the impact of a continuous subglacial valley on the flow of basal water as athought experiment,using a state-of-the-art ice sheet model. In addition,~~along valley profile (Figure 4g) indicates that our introduced valley is deeper in the interior than in the BedMachine data. The cross-sections along 3 flight lines across the valley (Figure 4a,b,c) indicate the valley sides have similar slope angles on the ~~effects on ice sheet sliding are explored as well as the impact of focussed interior basal melt on water flow along the valley. This is done in the framework of investigating whether a present-day active subglacial river along the valleybase is possible~~5 km grid to the observed. 3 more example cross-sections (Figure 4d,e,f) in regions of high BedMachine error (away from flight lines) show the consequent failure to resolve the valley.

3 Model and methods

3.1 Spin-up until 1990

We use the SImulation COde for POLythermal Ice Sheets (SICOPOLIS, www.sicopolis.net) version 5.1 (Greve and SICOPOLIS Developer Team, 2019), a polythermal ice sheet model originally created by Greve (1995, 1997) at 5 km horizontal resolution. To simulate the state of the entire Greenland ice sheet for our reference year 1990, we carry out a spin-up over the last glacial/interglacial cycle (134 ka). The main forcing is the surface temperature anomaly derived from the δ^{18}O record of the NGRIP ice core (Nielsen et al., 2018), modified by a surface temperature anomaly derived for the GISP2 site for the ~~final~~ last 4 ka (Kobashi et al., 2011). Except for the topographic and geothermal heat flux sensitivity tests described below, the set-up is identical to the one employed for the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), which, in turn, is based on the one used by Greve (2019). ~~It will be described in detail elsewhere (Goelzer et al., 2020; Greve et al., 2020b)~~ The ISMIP6 setup is described in Goelzer et al. (2020) and shall only be summarized here.

During the last 9 ka, the horizontal resolution is 5 km, and the computed ice topography is continuously nudged towards the (slightly smoothed) observed present-day topography. Prior to 1 ka ago, this is done by the method described by Rückamp et al. (2019), and shallow-ice dynamics is employed. For the last 1 ka, nudging is achieved via the ‘implied SMB’ by Calov et al. (2018) with a relaxation time of 100 a, and hybrid shallow-ice–shelfy-stream dynamics is used (Bernales et al., 2017). Ice thermodynamics is treated by the one-layer melting-CTS enthalpy method (Greve and Blatter, 2016). The bed topography is BedMachine v3 (Morlighem et al., 2017), the geothermal heat flux is by Greve (2019), and glacial isostatic adjustment (GIA) is modelled by the local-lithosphere–relaxing-asthenosphere (LLRA) approach with a time lag of 3 ka (Le Meur and Huybrechts, 1996). For the ~~topographic and~~ geothermal heat flux sensitivity tests (~~Sects. ??,~~ Sect. 3.4), only the last 9 ka of the spin-up are re-computed.

3.2 Basal sliding and hydrology

Following the approach by Goelzer et al. (2020)~~and Greve et al. (2020b)~~, we use a basal sliding law that incorporates basal hydrology. The hydrology model is coupled to the ice dynamics using a modified Weertman-Budd-type sliding law proposed by Kleiner and Humbert (2014) with the parameters determined by Calov et al. (2018). The flux and storage of water in the subglacial hydrology model is governed by both the water pressure and the "elevation potential" which when considered together is known as the hydraulic potential (Shreve, 1972; Le Brocq et al., 2006). The basal melt rates from SICOPOLIS are used as the water input for the routing scheme and there is no basal water source from ice sheet surface melting. Water moves in a layer only a few mm thick as a distributed water film where the water pressure and ice overburden pressure are in equilibrium. As such there is no explicit subglacial channelized water flow in the current formulation and so the thin-film model is used as a guide for where subglacial water is moving and collecting under the ice sheet. Where the film is thickest along an uninterrupted path to an ocean entry is considered to be a sign of a basal environment with an increased likelihood of consisting of some form of ~~active~~ subglacial river. The flux-routing method requires that local sinks and flat areas ~~are~~ be removed, and this is done using a Priority-Flood algorithm which fills depressions and adds a small gradient, using the method of Barnes et al. (2014) to a ~~depth~~ basal water thickness of $10\,\mathrm{m}$~~to account for subglacial lakes~~.

The basal sliding coefficient is determined individually for 20 different regions, the 19 basins by Zwally et al. (2012) plus a separate region for the Northeast Greenland Ice Stream (NEGIS, defined by $\geq 50\,\mathrm{m\,a^{-1}}$ surface velocity). This is done iteratively for the last $1\,\mathrm{ka}$ of the spin-up sequence by minimizing the ~~RMSD~~ root-mean-square deviation between simulated and observed, logarithmic surface velocities. A detailed description of this procedure ~~will be given elsewhere (Greve et al., 2020b)~~ is given in Greve et al. (2020a). Note that we do not re-compute the optimization for the ~~topographic and~~ geothermal heat flux sensitivity tests (Sects. ~~??,~~ 3.4), rather, the coefficients determined by the standard bed topography (Morlighem et al., 2017) and geothermal heat flux (Greve, 2019) are used for all tests unchanged.

3.3 ~~Bedrock modifications~~Sensitivity tests on geothermal flux

~~The bedrock topographic data is altered in a way to ensure that the valley is open from Interior to Petermann in at an average depth of around $-400\,\mathrm{m}$ (Figure 2b). The case with the standard topography is referred to as "Control" and the case with the open valley as "Valley". The simulation initialisations are otherwise identical so that the results only show the consequences of the topographic change.~~

~~The topographic modification is done using a flow-oriented interpolation scheme. Given the BedMachine topography and flight lines (Figure 1), a polygon of the rough location of the valley is drawn using a geographic information system (GIS). A buffer of 200 kilometres around this polygon is created and measurements falling into this buffer, but not into the valley polygon, are used to interpolate a new BedMachine, with the same procedure and parameters as Morlighem et al. (2017). The polygon outlining the valley is converted to a centerline, and then described through a spline. Data points situated within the valley polygon are converted from their Cartesian coordinates (x,y) towards this flow-oriented coordinate (s,n) system. This is a common reference frame, where s describes the distance of the thalweg and n is the normal in right-hand direction,~~

~~and it outperforms ordinary kriging and others when used in with an anistropic adjustment (Merwade et al., 2006). Here the anisotropic factor was 10, with a nugget of 20 metres, a sill of 30 metres and a range of 300 metres. Further details on the procedure are detailed in Legleiter and Kyriakidis (2008).~~

~~For three regions, saddles are present along the valley. Bounding boxes over these saddlepoints are drawn that cover both the saddle and trenches within. Over these subsets a watershed algorithm called Maximally Stable Extremal Region (MSER; Donoser and Bischof, 2006) tracking is run to detect the trenches to be connected. Pixels between both trenches of the saddle are found through connecting mathematical morphologic operations. These selected pixels are then adjusted by linear interpolation of the elevation information in the trenches to make a seamless passage.~~

3.4 ~~Idealized interior basal melt sensitivity experiments~~

Two additional sensitivity tests are designed to assess ~~where~~ whether basal water melted near the source of NEGIS is routed down the valley. The tests are referred to as ControlS that uses the ~~standard~~ BedMachine topography as before, and ValleyS that uses the Valley topography. Whereas the geothermal heat flux distribution of Greve (2019) is used in Control and Valley, for ControlS and ValleyS the geothermal heat flux is increased locally to generate a basal melt rate of between 0.13 to $0.14\,\mathrm{m\,a^{-1}}$ near the source of NEGIS as shown in Figure ~~7~~5b. To do this a bell-shaped geothermal heat flux anomaly centred at 74°N, 40°W is introduced with a 1-sigma radius of $50\,\mathrm{km}$ and peak heat flux of $1.5\,\mathrm{W\,m^{-2}}$ which creates a broader region with a comparable value to the regional heat flux of 0.97 $\mathrm{W\,m^{-2}}$ estimated by Fahnestock et al. (2001). The anomaly is located over the region of enhanced basal melting at the source of NEGIS shown in Fahnestock et al. (2001, Figure 2). The intention here is not to produce a realistic melt rate distribution but rather to test the effect of increasing melting in the interior near the source of NEGIS. However, both the maximum melt rates, and the cross-sectional distribution are comparable to the cross section of derived basal melt rates of Fahnestock et al. (2001, Figure 3).

4 Results

All results presented here are from the SICOPOLIS simulation output for the year 1990 at $5\,\mathrm{km}$ horizontal resolution as detailed above. To examine the effect that the introduction of an uninterrupted valley has on the simulated ice sheet, an analysis of the basal water ~~depth~~thickness, basal water flux, and ice sheet velocity are presented.

For ~~north Greenland~~ the Petermann catchment and northern Greenland in general, the simulated basal water ~~depth~~ thickness is affected by the introduction of the valley in several ways. In Figure ~~3~~6a it can be seen that the standard topography produces ~~independent areas of deeper~~ separated areas of thicker basal water along the valley but there are clear gaps between these areas. In contrast, when a continuous valley is introduced (Figure ~~3~~6b) the basal water ~~depth is both deeper~~ thickness is both thicker and uninterrupted along the length of the valley all the way to Petermann Fjord. The thickest water ~~depth (>0.01~~(>10 mm) along the valley route occurs at 7 locations where the Priority Flood algorithm has been activated to ~~represent subglacial lakes~~a maximum thickness of 10 m. In most interior areas away from the valley there is little or no ~~change~~ difference in the basal water ~~depth~~thickness between Control and Valley. In particular, there is little to no effect on the basal water pathways associated with

NEGIS. The interior basal water changes are relatively small because the valley follows a path close to the boundary between the east and west basal water catchments and thus has less influence on them.

To obtain a clearer picture of the changes to the basal water due to the introduction of the valley, the difference in basal water between the cases (Valley – Control) is shown in Figure ~~3~~6c. Doing this reveals that the increased water within the valley is surrounded predominantly by a reduction in basal water adjacent to the valley, an indication of water piracy by the valley. Basal water reduction extends to some regions away from the valley, particularly to the west of the interior section. The one region of increased basal water outside of the valley is a region that extends towards ~~the Petermann Ice Stream at~~ upper Petermann Glacier from NEEM zone in Figure ~~3d.~~ 6d. NEEM zone is defined as the area of the valley to the southeast of the NEEM ice core drilling site as indicated on Figure 1. The effect of these changes ~~in the Petermann catchment~~ is to redistribute the basal water under upper Petermann Glacier into a narrower and ~~deeper~~ thicker plume that can also be seen in Figure ~~3~~6b.

To examine how the movement of basal water is altered by the introduction of the valley, the basal water flux is presented in Figure ~~4~~7. The valley causes a shift in basal water flux in its near vicinity, with increased flux within the valley base. Water flux streamlines give an indication that water flux is generally down-valley~~with streamlines getting “stuck” in the valley along certain sections~~. In the Petermann catchment region, the increase in water flux in the valley causes a shift downstream in the subglacial water distribution where the valley crosses a region of increased flux out of the interior (NEEM zone in Figure ~~4~~7). Along this section where the valley is oriented SSW to ENE the flux just NNW of the valley is reduced in the south and then increased to the north in the region upstream of ~~the interior part of the Petermann Ice Stream~~upper Petermann Glacier. This is consistent with the increase in basal water mentioned above. The simulated effect of the valley is therefore to focus maximum water flux into a narrower but more elongated region that is also shifted eastward. ~~Sensitivity tests (Appendix B)~~Four additional sensitivity tests have been used to investigate the robustness of these responses by altering the valley depth (Appendix A). These additional results indicate that the location and magnitude of this water flux out of the valley is sensitive to the valley depth due to its consequent effect on the steepness of the valley sides. Figure ~~4b (lower panel)~~ 7d indicates a basal water flux of 10,000 $\mathrm{m^2\,a^{-1}}$ in the valley across 5km grid boxes upstream of NEEM zone. This corresponds to a discharge of just 1.6 $\mathrm{m^3\,s^{-1}}$.

The rule of thumb helpful for understanding the relative roles on subglacial water flow of ice overburden pressure and basal topography, is that the topographic gradient needs to be 11 times greater than, and opposing, the ice surface slope for water flowing along the bed to start accumulating (e.g., Cuffey and Paterson, 2010). Figure ~~5~~ 8 indicates that the along-valley component of the ice surface gently slopes down-valley all the way to Petermann Fjord. This is an indication that the ice overburden pressure distribution does not oppose the flow of water towards the north and should generally reinforce it for the northern half of the introduced valley. As the ice sheet surface is very gently sloping in the interior, the basal topography and water fluxes will have a greater influence on subglacial water routing than around the edges of the ice sheet. In this situation the valley base topography could be either sloping downward towards the north, or flat, for water to flow northward. It appears it could be ~~closer to the latter, which is consistent with subglacial erosive and depositional water activity but does not prove it. The isostatic correction in Bamber et al. (2013, Figure S5) implies that for an ice-free Greenland the valley would~~

~~be 600 higher than present in the interior progressing to 200 metres higher near the coast. Today the valley base appears to be consistently between −250 and −500 metres with no clear trend along-valley~~the latter.

To demonstrate the influence of the valley on simulated ice sheet sliding, Figure ~~6~~ 9 shows the ice surface velocity difference between Valley and Control to highlight the locations where Valley increases or decreases sliding. The sliding changes are relatively modest and localized, with only small regions at certain outlet glaciers having a greater than $10\,\mathrm{m\,a^{-1}}$ change. Some sliding changes occur in the Petermann catchment (Figure ~~6~~9b) where sliding increases over the valley and very weakly ($\sim 0.5\,\mathrm{m\,a^{-1}}$) in the ~~Petermann Ice Stream~~upper Petermann Glacier. These increases are consistent with the redistribution of basal water seen in Figure ~~3~~6 and could also be related to the ice thickness change due to the modification of the bedrock. The sliding changes should be viewed as demonstrations of the potential for change due to the introduction of an open valley while considering that the simulated basal hydrology is limited by its reliance on a thin-film model. ~~Small sliding changes~~ Sliding changes also occur at certain outlet glaciers ~~such as Ryder Glacier and several~~ along the west coast as well as on the north coast around Steensby and Ryder Glacier to the east of Petermann. These changes, away from the valley and Petermann, are inconsistent across different model setups and do not show an obvious relationship to the changes in basal water distribution. They may be related to knock-on effects from the redistributions of ice mass due to the inserted valley. Considering other uncertainties and inaccuracies, the differences are too small to allow assessing which case is better compared to observed surface velocities.

To investigate whether water is transported down the length of the valley, two additional sensitivity simulations have been completed as described in section 3.4. The simulations compare scenarios with and without the open valley that also include an area of enhanced interior basal melting as shown in Figure ~~7~~5a,b. Figure ~~7~~5c shows the change in basal water ~~depth~~ thickness that occurs when ~~you introduce~~ the enhanced basal melting region is introduced into simulations with the ~~standard~~ BedMachine topography. The greater basal melting generates larger amounts of basal water that is mostly transported down under NEGIS and adjacent regions. A lesser amount of the extra basal meltwater is transported towards the west coast. There is no change in basal water thickness along the valley route north of 76°N towards Petermann Fjord, indicating that no water melted in the interior is finding its way down the valley when using the BedMachine topography. The same comparison is made in Figure ~~7~~5d, however this time the two simulations compared both have an open valley. Comparing Figure ~~7~~5c with d, the basal water distribution is similar down NEGIS, is reduced towards the west coast, and is increased along the valley down to Petermann, with the two paths~~down the Petermann Ice Stream~~, described earlier, down the upper Petermann Glacier and down the valley, evident in the ~~lower reaches~~northern section. This result demonstrates that simulated meltwater generated solely in the deep interior can be transported down the entire length of the valley and it is notable that it is only at Petermann where there is any significant change to the basal water ~~depth~~ thickness across northern Greenland north of 80°N. The other consequence of this is that the down-valley basal water flux upstream of the NEEM zone increases from $\sim$10,000 $\mathrm{m^2\,a^{-1}}$ in Valley to $\sim$50,000 $\mathrm{m^2\,a^{-1}}$ in ValleyS which corresponds to an increase in thin film discharge across 5 km grid points from $\sim 1.6\,\mathrm{m^3\,s^{-1}}$ to $\sim 7.9\,\mathrm{m^3\,s^{-1}}$.

5 Discussion

The ~~formation of subglacial water channels has long been known to be a fundamental evolutionary property of subglacial water flow. Röthlisberger (1972) and Shreve (1972) proposed that subglacial water can form channels that cut upwards into the ice. These have come to be referred to as "R-channels". Channeling of subglacial water occurs because the initial film of water at the ice base can become unstable due to viscous dissipation which initiates the development of R-channels. For this transition to occur the discharge has to increase beyond a threshold (Schoof, 2010).~~

~~The R-channel theory requires a hard bed and therefore ignores potential bed erosion from such a channel. If the channels are over a sufficiently hard bedrock and move position then this assumption should hold, however if they remain quasi-stationary, due to basal topography or persistent ice overburden pressure distribution influences, then the effects of bedrock erosion or sediment deposition should manifest. In the case where there is sufficient sediment deposition in a stationary channel an esker could develop lifting the water channel above the bedrock. In the case where there is not sufficient sediment deposition, erosion downwards into the bed will inevitably occur if the channel remains stationary. Nye (1973) suggested that channels incised upwards into the ice are more vulnerable to closure due to ice overburden pressure and ice movement and concluded that channels incised into the rock were expected to be much longer-lived than channels incised upwards into the ice. Nye concludes that "while there may be temporary channels incised upwards into the ice, there will be comparatively permanent channels cut downwards into the rock bed."~~

~~There are other reasons to suppose that flowing water in a subglacial valley could be a favourable mode of water transport under an ice sheet. These are associated with the resistance to freezing of water in such a channel. Firstly, because the ice sheet surface will likely not have as pronounced an indentation as an incised valley in the bedrock beneath has, the ice thickness and therefore ice overburden pressure will be higher at the base of the valley than under the ice over the surrounding bedrock. This increases the likelihood of the ice at the base of a valley being at the pressure melting point.~~

~~Secondly, an incised valley under an ice sheet will tend to have higher geothermal heat flux at its base and particularly along its sides. This is because of the distortion of isotherms beneath the valley that increases the isotherm gradient and consequently also the heat flux (e.g., van der Veen et al., 2007). For example, Lees (1910) found that a depth to width ratio of 0.5 increases heat flux by around 50% while van der Veen et al. (2007) found a 100% increase in heat flux in a Jakobshavn-scale idealized simulation. Essentially the deeper and steeper the valley, the greater the heat flux increase will be at the valley bottom. In the case of a melting ice base, if the valley sides are steep enough to overcome any opposing overburden pressure forcing on water flow, then meltwater will collect at the base of the valley which could also further enhance melting there.~~

~~Thirdly, flowing water generates heat through frictional heating, increasing the temperature of the water. Sediment movement will also generate frictional heat. Water and sediment flow can also transfer heat downstream so factors such as the upstream water heat capacity and the duration of cooling will determine whether the water freezes or not. Fourthly, applicable to all basal water, is one of the odd properties of water. As water cools below $4°C$ it starts to become less dense causing the coldest water to rise up. Thus, freezing occurs at the top, which in the scenario of a subglacial river would be at the base of the ice sheet.~~

~~This new ice acts to insulate the liquid water below as is observed in frozen rivers and lakes. This allows liquid water to persist beneath the ice in situations where it would not if water did not have this property.~~

~~These are some factors that may enable flowing water and sediment to continue in a valley under an ice sheet even in some situations where the ice sheet is frozen to the bed outside of the valley. These factors are presented here as indicators that positive feedback processes may exist that favour the development of subglacial rivers incised into the bed. The possibility remains that the present day valley form developed as a consequence of erosion under some or all of the following 1) under current conditions, 2) under last glacial maximum conditions, 3) during ice sheet retreat, 4) under reduced ice sheet cover, and 5) under ice free conditions. We simply do not have enough information. Tunnel valleys provide one demonstration of how subglacial water erosion can erode into hundreds of metres of bedrock. Given that the source is close to a proposed geothermal warm spot, past episodic subglacial down-valley discharges of water and sediment are a possibility. Much smaller amounts of erosion and deposition would be needed to maintain a base slope favourable for water routing, as is typical of rivers in general.~~

~~The~~ model results indicate that the valley follows a path down a gentle ice surface slope (Figure ~~5~~8) which would imply that the ice overburden pressure lowers as the valley progresses towards Petermann Fjord. In this scenario, if a water channel were to be maintained along a relatively flat uninterrupted valley base, the overburden pressure should propel water towards the ocean outlet. This is providing that water does not escape out the sides of the valley as appears to happen to some of the water as the valley crosses NEEM zone. If down-valley water propulsion occurs, a possibility is that it does so sporadically through the build-up, and release, of water in reservoirs along the valley route.

The results also indicate that the course of the valley in the interior runs in the vicinity of the boundary of the east and west subglacial hydrological catchments (Figure ~~3~~6a,b and shown schematically on Figure ~~8~~10). This catchment boundary occurs in this region because it is below the gentle northward ridge of highest surface ice (Figure ~~5~~8) which broadly forces the division between these hydrological basins. A consequence of this positioning is that the valley enters the Petermann surface catchment at its southernmost location (Figure 1a). Because the gentle ice ridge is the region where water flux directed towards the east or west is at a minimum, it represents the most favourable location in the interior of northern Greenland for the development of a hydrological pathway directed towards the north. This possible relationship to the ice sheet shape could be ~~a further~~ an indication that the path of this valley has developed as a consequence of the ice overlaying it. However, while the valley appears to intersect the east and west hydrological basins in the interior it does not follow the water flux streamlines exactly, particularly as it crosses NEEM zone. South of the Petermann surface catchment, the valley tracks roughly parralel, and to the west of, the basal hydrological divide, while ~~Tributary~~ a second possible valley at "Tributary" (Figure 1) projects towards the east of it (Figure ~~8~~10). If the bedrock were flat, there would be only one basal water route towards the north and it would be directed exactly along the hydrological divide. Perhaps a subglacial valley perfectly aligned with present day basal water flux streamlines is not to be expected given the long period required to erode it and the different shape of the ice sheet in the past. As an example Bamber et al. (2013, Figure 3b) indicates that the interior basal hydrological divide is shifted to the west under conditions at the last glacial maximum. Nonetheless the valley still follows a path not far off the basal hydrological divide so it is possible that conditions favourable for subglacial down-valley water routing ~~may~~ have existed for a long time as has already been implied by the results of Bamber et al. (2013).

The ~~current simulations do not include subglacial channelized water flow, such as within R-channels, in the hydrology module. Channelized water flow could funnel different amounts of water away from, and to, particular locations leading to focused areas of suppressed and enhanced sliding. This may effect the sliding model results that should be seen as a view of the potential for change in different regions rather than a prediction for the valley's influence on sliding speed. The valley could extend further southward and there is evidence of tributaries that could increase the main valley's discharge potential. The most prominent possible tributary, shown as "Tributary "~~ secondary valley, Tributary in Figure 1~~projects towards a~~ , projects towards the northern section of the region of higher basal melt associated with NEGIS (Fahnestock et al., 2001) and could therefore be an additional source of basal meltwater. Also the main valley appears to continue past Interior by taking a sharp turn towards the east. This directs it to begin at ~~an~~ the area of enhanced basal melt associated with the very source of NEGIS shown in Fahnestock et al. (2001, Figures 2 and 3). If this is ~~an active~~ a subglacial river, then this location seems the most probable source of the majority of the discharge down the valley given the frozen or more slowly melting ice base elsewhere in the valley catchment. A distinct source at a region of high basal melt is also more consistent with subglacial water erosion rather than erosion prior to ice sheet inception when ice would not be available to melt and water sourced from precipitation would presumably be spread across the entirety of Greenland.

The valley ~~originates from under some of the thickest and highest ice in Greenland (Figure 5). The valley~~ we have inserted in the simulations has its upper end at "Interior"~~but given the basal topographic basin at "Basin" (Figure 1), could it be possible that basal water and sediment is transported from Basin to Interior? Between these two regions the ice surface slope is relatively flat so water flow should be more heavily influenced by the basal topography. In this inter-basin region the basal topography is poorly resolved and it is unknown whether the ice sheet is frozen to the base. It is therefore unclear whether a basal water connection could exist between Basin and Interior. A~~ , however a smaller channel is evident between "Interior" and "Basin" on most, but not all, flight lines that passed over this region (Figures 1b, ~~5 and A1). In the simulations presented here, Basin is frozen at the ice base and so no basal water is produced there (Figure 3a,b). This is due to the geothermal heating distribution used by SICOPOLIS which is, as with all Greenland geothermal distribution estimates to date, highly uncertain due to severely limited observations at the base (e.g., Rezvanbehbahani et al., 2017).~~ 2 and 8). If these basins are connected hydrologically, it could significantly extend the catchment of the valley and imply a subglacial river over 1400 km long. ~~At present there is not enough data on the bedrock heat flux or topography to know if this is the case and the fact that we are in the dark on such a potentially large feature on the Earth's surface, expresses the importance of observation campaigns that can improve our understanding of the conditions at the bed.~~

The path of such a long basal valley down an ice surface slope that appears to roughly intersect the east and west basal hydrological basins in the interior could be an indication that this feature has developed over a long period in conjunction with the ice sheet covering it. The alternative is that it eroded due to a paleo-river flowing when the ice sheet was much smaller, or absent. At that time the topography would have been significantly different due to bedrock isostasy. In addition, the water flow would have been governed by gravity when conditions were ice-free. This different water flow environment would mean that it was coincidental that the same valley follows a path that is today favourable for water transport from the deep interior all the way to the coast under a thick ice sheet. Since the relationships with the ice sheet are not perfect and speculative in nature, the significance, or lack thereof, of this coincidence will need to be investigated further. However, additionally, the apparent flatness of the valley base in the interior where the ice surface is relatively flat, is, just like any other river, the ultimate erosional and depositional form of a long-term active waterway. Due to bedrock isostasy it would, again, seem to be coincidental that a paleo-river system would have a relatively flat base today. One can imagine that a paleo-river valley pushed down by the weight of the ice as the ice thickened would end up today having an uneven base that depended on the evolution of the competing pressures from the ice and crustal rock. ~~As stated earlier, the~~ The base today is not perfectly level as it appears to vary between -250 to $-500\,\mathrm{m}$ but there is no obvious along-valley trend over its $1000\,\mathrm{km}$ length. ~~Whether a paleo-river valley could end up having a very long fairly level base in this situation is worthy of future investigation.~~ In the absence of adequate direct observations, perhaps the topographic form of the base of this valley could, with further work, help us deduce whether this is ~~an active subglacial river (or wet sediment channel)~~ a subglacial river or not.

Estimating the discharge down ~~an active~~ a subglacial river, that we don't know exists, in an extremely poorly observed environment is a fool's errand. However the following notes on this issue are provided as a thought experiment and to encourage future investigations. The SICOPOLIS simulated thin-film down-valley discharge upstream of NEEM zone is estimated as being $\sim 1.6\,\mathrm{m^3\,s^{-1}}$ with the standard geothermal heat flux (Valley) and $\sim 7.9\,\mathrm{m^3\,s^{-1}}$ with an included hot spot (ValleyS). Only a very rough estimate of the total discharge generated by the hot spot found by Fahnestock et al. (2001) can be made given the limited coverage of their analysis. Based on a rough outline of the detected areas of melt of $0.1\,\mathrm{m\,a^{-1}}$, a value of order $100\,\mathrm{m^3\,s^{-1}}$ can be obtained. The majority of this may flow northeastward under NEGIS, however at least part of the region of consistently highest melt around the interior tip of NEGIS lies beyond the NEGIS basal hydrological catchment. A very rough estimate gives $\sim 30\,\mathrm{m^3\,s^{-1}}$ that could be routed into the source of the valley. If the basal water that lies outside of the NEGIS basal water catchment is not being evacuted from the region, then substantial resevoirs could be continually filling until the time of release. A constant discharge of $30\,\mathrm{m^3\,s^{-1}}$ can build up 2,592,000 $\mathrm{m^3}$ (2,592,000,000 litres) in one day. Alternatively, refreezing to the ice base could reduce or eliminate this small potential discharge. Analyses such as MacGregor et al. (2016, Figure 11) indicate that along most of the valley length, the base of the ice sheet is "likely frozen". However, since water has been inferred to be present from IPR data in a limited number of locations (Ekholm et al., 1998), and unless this water was entirely melted in place, then, based on both Bamber et al. (2013) and the results presented here, some of the detected water likely came from upvalley. As the valley approaches closer to Petermann Fjord, contributions to the discharge from summer surface melting become more likely and have the potential to overwhelm any discharge from interior basal melting. These discharge calculations are limited in many ways beyond those already mentioned, for example there is no accounting for refreezing to the ice base or melting due to channelized water flow.

~~A potentially important factor when considering the erosional capability and mass volume transported down valley is the role of sediment and ice. Sediment within subglacial rivers could increase erosion rates and frictional heating. Alternatively basal water could become incorporated into eroded sediment enabling the mobilization of sediment flows or the development of porous flow through the sediment. If mobilized, sediment confined in a relatively level valley should also be transported~~

~~along the valley in the direction of the along-valley component of ice surface slope gradient. Finally there is the role of the ice that lies within the valley. Basal ice flow could be modified within the valley and move partially, or wholely along-valley. The possible roles of high pressure subglacial wet or liquified sediment transport, as well as of ice, could be considered in future investigations of this valley.~~

6 Conclusions

The Greenland bedrock data indicates that a subglacial valley extends from Petermann Fjord into the center of Greenland. The valley is segmented along its route in the current bed topographic datasets used in ice sheet simulations. The rises occur where data is interpolated to fill in gaps between where radar has obtained reliable data. This suggests that the valley rises ~~are not~~ may not be real. Therefore, as a thought experiment, simulation tests have been completed to investigate the consequences of removing these rises. Opening up the valley in SICOPOLIS simulations causes water to be re-routed leading to localised modest ice sheet sliding changes. The valley progresses gradually from thicker to thinner ice ~~causing~~ such that a lowering of ice overburden pressure ~~that~~ could enable water ~~and sediment flow~~ along its path towards the sea. If this is the case, some of the basal water routed to Petermann Fjord may originate from melting of the deepest and oldest part of the ice sheet. ~~When~~ Moreover, when melting is increased only in the deep interior at a known region of basal melting near the source of NEGIS, the simulated discharge is increased down the entire length of the valley only when the valley is opened. This suggests a quite finely tuned relationship between the valley form and overlying ice can allow a very long down-valley water pathway to develop only if the valley is unblocked. The results show that even small adjustments in the bed topography to include probable features can have consequences that could affect simulations of the future ice sheet. The possibility is raised of a long ~~active subglacial river , or wet sediment flow system~~ subglacial river that is poorly realized in current ice sheet simulations. If this potential hydrological system has formed and/or is maintained due to the presence of the ice sheet, then it is a fundamentally different system that requires a different understanding to that of a paleo-fluvial river valley that eroded prior to ice sheet formation.

Appendix A: ~~Error estimates~~

~~A map of error estimates from BedMachine v3 (Morlighem et al., 2017) shows the variation in error across north Greenland (Figure A1). Errors range from 2 to ~ 600 metres with a median of 158 metres along the valley. Bed elevation is improved in the lower part of the Petermann catchment (< 250 in our profile in Figure ??g) as it is derived from mass conservation and from a dense IceBridge campaign (see Figure 1b for an outline of the mass conservation region). The kriging interpolation is applied to the rest of the interior of the ice sheet and thus most of the valley. The kriging algorithm is described in Morlighem et al. (2017) as "The variogram is modeled as a Gaussian function, with a sill of 100, a range of 8 and a nugget effect of 50, to account for uncertainty in ice thickness measurements". The along valley profile (Figure ??g) indicates that our introduced valley is deeper in the interior than in the BedMachine data. The cross-sections along 3 flight lines across the valley (Figure ??a,b,c)~~

~~indicate the valley sides have similar slope angles on the 5 grid to the observed. 3 more example cross-sections (Figure ??d,e,f) in regions of high BedMachine error (away from flight lines) show the consequent failure to resolve the valley.~~

Appendix A: Sensitivity tests

The results from four additional simulations are presented here that test the sensitivity of the water routing to the valley base topographic elevation. ~~Three of the tests use~~ The first three of the four tests insert 26 ~~linear~~ straight 10 km wide ~~idealized valleys~~ channels to form an uninterrupted valley from Interior to Petermann. The ~~valleys~~ channels are created using the Matlab function "inpolygon" that sets bedrock elevation grid point values within ~~an along-valley rectangle to be a specified value. The lithosphere is then relaxed in a short SICOPOLIS simulation to produce an isostatically relaxed bed topography~~a rectangle that is aligned along the path of the valley. This method is used as it creates a flatter base than the method used in simulations Control and Valley. Consequently it is more suitable for testing the sensitivity to a particular valley base elevation. Tests are done with inserted idealized valleys at constant maximum depths of $-100\,\mathrm{m}$, $-300\,\mathrm{m}$, and $-500\,\mathrm{m}$ and are compared to a ~~4th~~ fourth test which uses ~~standard SICOPOLIS~~ the unmodified BedMachine topography as a control simulation. The $-100\,\mathrm{m}$ simulation effectively removes most of the segmented valley while the $-500\,\mathrm{m}$ case best represents the slopes of the sides of the valley. The tests use an otherwise identical method to that described in section 3.1.

The subglacial water flux for the four cases is in Figure ~~??~~A1. There are large differences in water routing in and around the valley, between these cases. For a $-100\,\mathrm{m}$ valley (Figure ~~??~~A1f), the northward water flux signature associated with the valley is largely eliminated. If the valley base is lowered to $-300\,\mathrm{m}$ (Figure ~~??~~A1g), increased valley water flux occurs from Interior to NEEM zone where water then appears to be entirely evacuated from the valley into a plume directed towards ~~Petermann~~upper Petermann Glacier. For the $-500\,\mathrm{m}$ case (Figure ~~??~~A1h) the valley water flux is continuous high from Interior to Petermann and the plume out of the valley at NEEM zone is largely eliminated. The results confirm the finding that NEEM zone is the region most prone to water leakage from the valley. The result for a valley base at $-500\,\mathrm{m}$ suggest that the valley side slopes on the $5\,\mathrm{km}$ grid in this case are steep enough to overcome the northwestward directed hydropotential component due to the ice surface slope. From a modelling perspective the results highlight the need to improve the bedrock topography data in the NEEM zone region.

Author contributions. Chris Chambers initiated the study. Chris Chambers and Ralf Greve set up and carried out the numerical experiments with the SICOPOLIS model. Bas Altena performed the primary subglacial topography alteration operation, while the topography for the sensitivity tests was processed by Chris Chambers and Ralf Greve. Pierre-Marie Lefeuvre prepared data, produced the topographic cross-sections, and analyzed the radar flight lines. Chris Chambers interpreted the results and wrote the manuscript with contributions from all co-authors.

Code and data availability. SICOPOLIS is available as free and open-source software at www.sicopolis.net.

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Figures

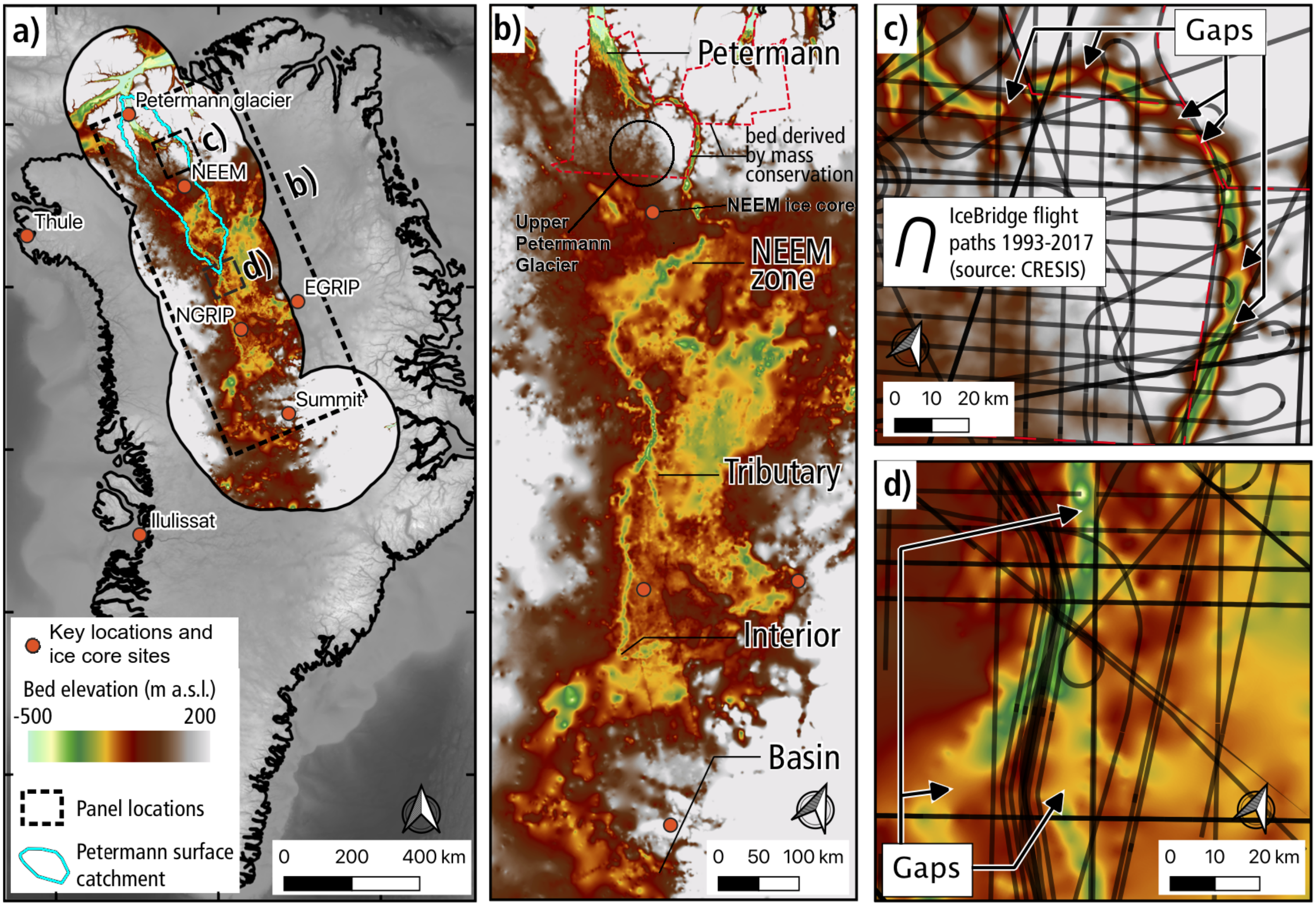

Figure 1. BedMachine v3 bed topography (Morlighem et al., 2017) between −500 to 200 metres above sea level for a) Greenland overview with boxes for b) the valley region and c) and d), two regions showing the IceBridge flight paths.

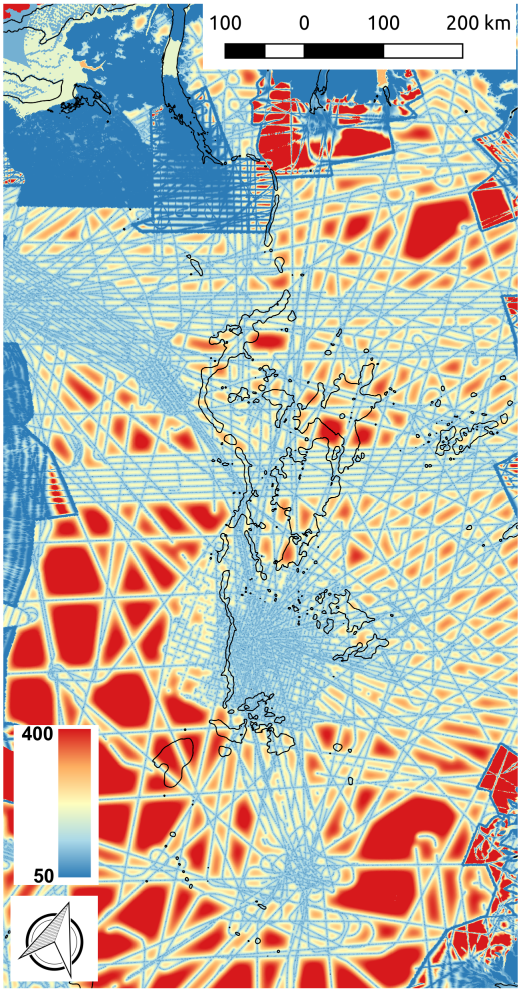

Figure 2. BedMachine basal topography error (Morlighem et al., 2017) in metres for the region from Petermann to Basin. The black contour indicates −200 metre elevation.

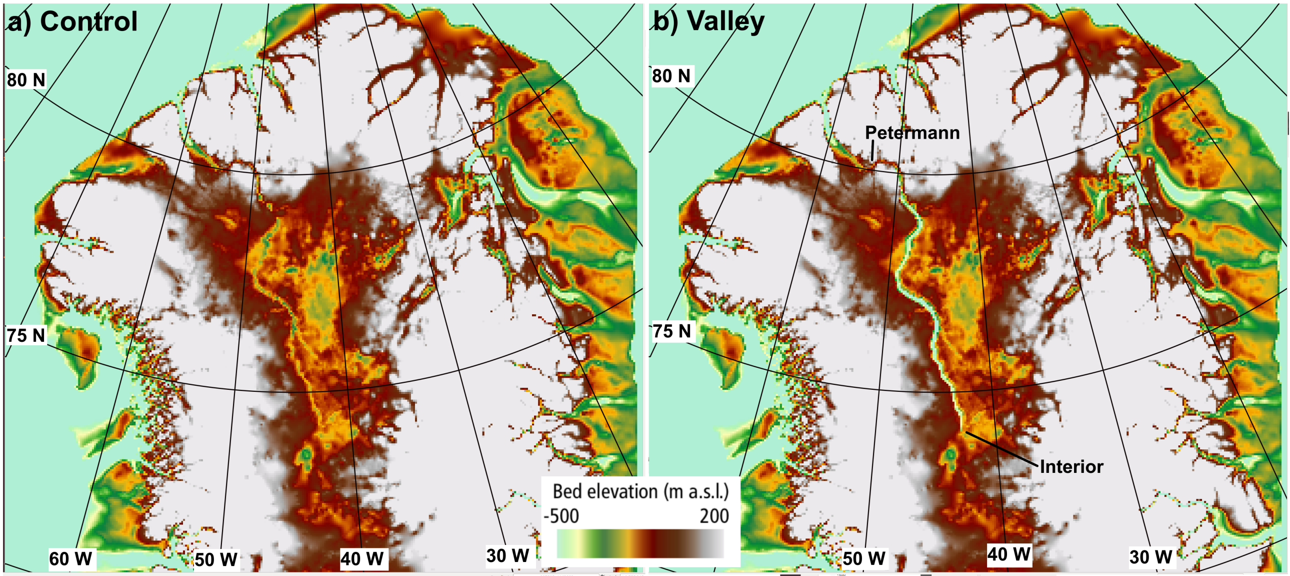

Figure 3. Basal topographic height between −500 and 200 metres above sea level for a) Control (standard SICOPOLIS input derived from BedMachine), and b) Valley (manually adjusted from Petermann to Interior).

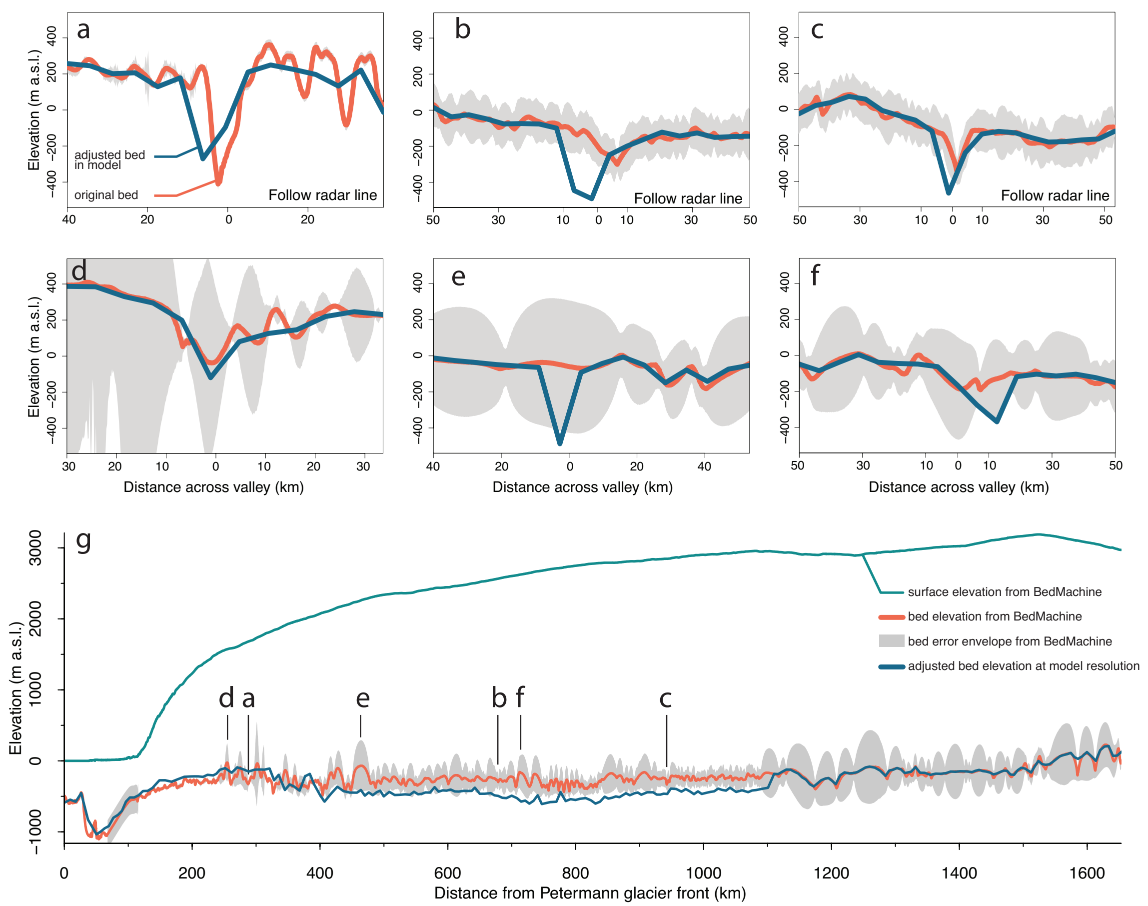

Figure 4. Across (a-f) and along (g) valley profiles from BedMachine v3 bed topography (Morlighem et al., 2017) and the adjusted bed elevation used in our model. The error envelope is derived from error estimates provided in BedMachine. Reduction in error depends on the proximity to radar data as shown in lines a-c that are parallel to flight lines or the use of mass conservation to derive bed topography which covers the region between 130 and 250 km in g).

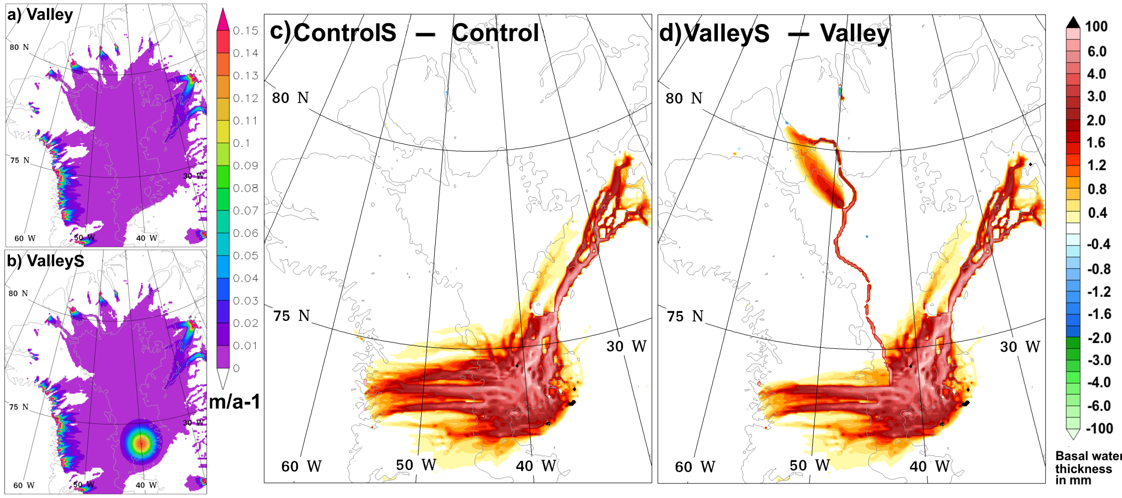

Figure 5. Basal melt rate $\mathrm{m\,a^{-1}}$ for a) Valley and b) ValleyS, and basal water ~~depth~~ thickness differences (~~m~~mm) for c) ControlS - Control, and d) ValleyS - Valley.

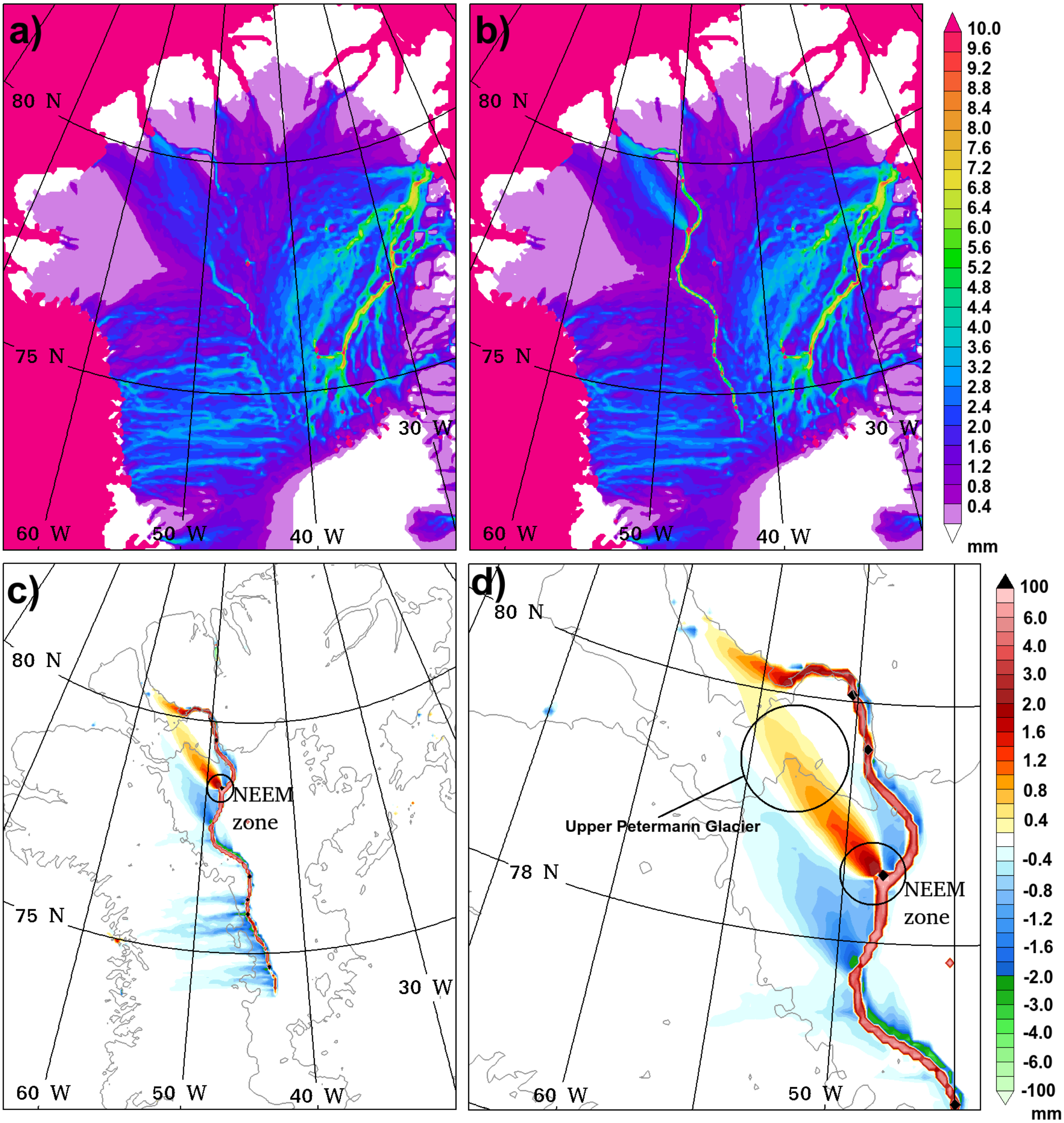

Figure 6. Basal water thickness (mm) for a) Control and b) Valley ~~, from SICOPOLIS simulations for the year 1990. Basal~~ and basal water ~~depth~~ thickness difference (~~m~~mm) (Valley – Control) for c) northwest Greenland and d) Petermann catchment region.

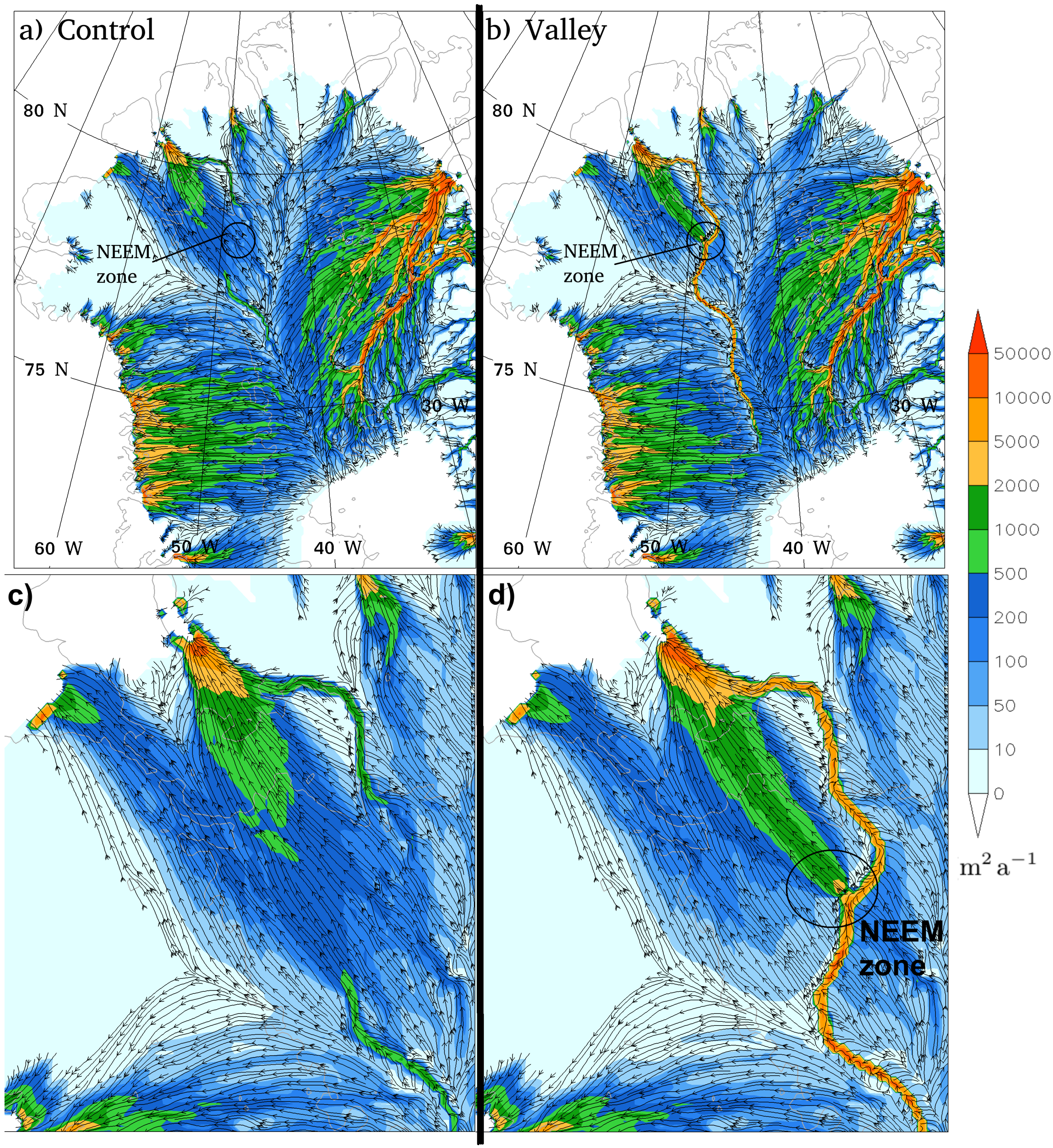

Figure 7. Basal water flux magnitude (m^2 a^{-1} colours in a non-linear scale chosen to best demonstrate the distribution) and streamlines for north Greenland for a) Control and b) Valley. NEEM zone marks where the greatest change occurs out of the valley as discussed in the text. In c) and ~~the lower~~ d) are plots ~~zoom into this region for~~ zoomed to the ~~respective cases above~~ Petermann to ~~show detail~~NEEM zone region for Control and Valley respectively.

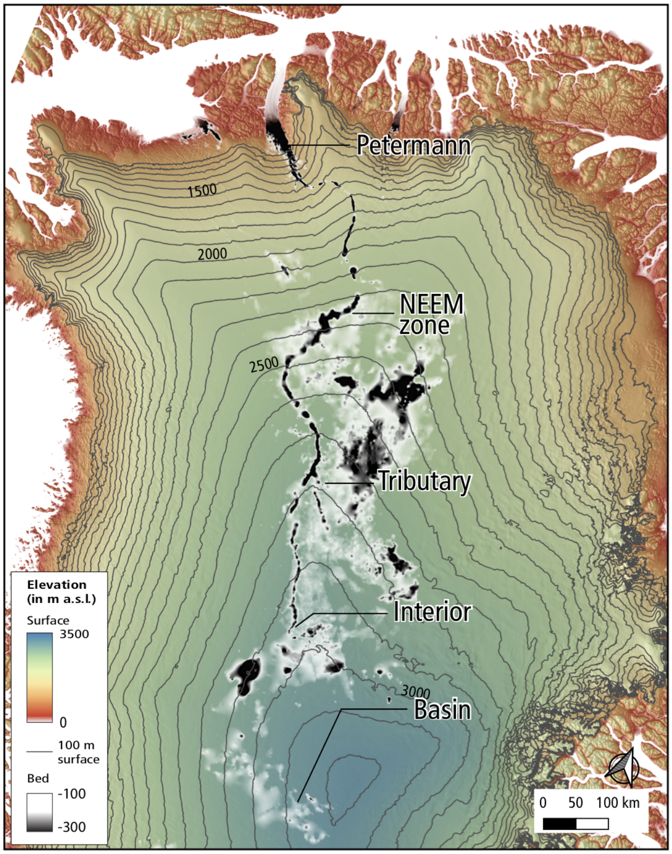

Figure 8. Surface elevation (m) with BedMachine bed elevation for $-100\,\mathrm{m}$ or lower overlayed in grey to indicate the path of the valley.

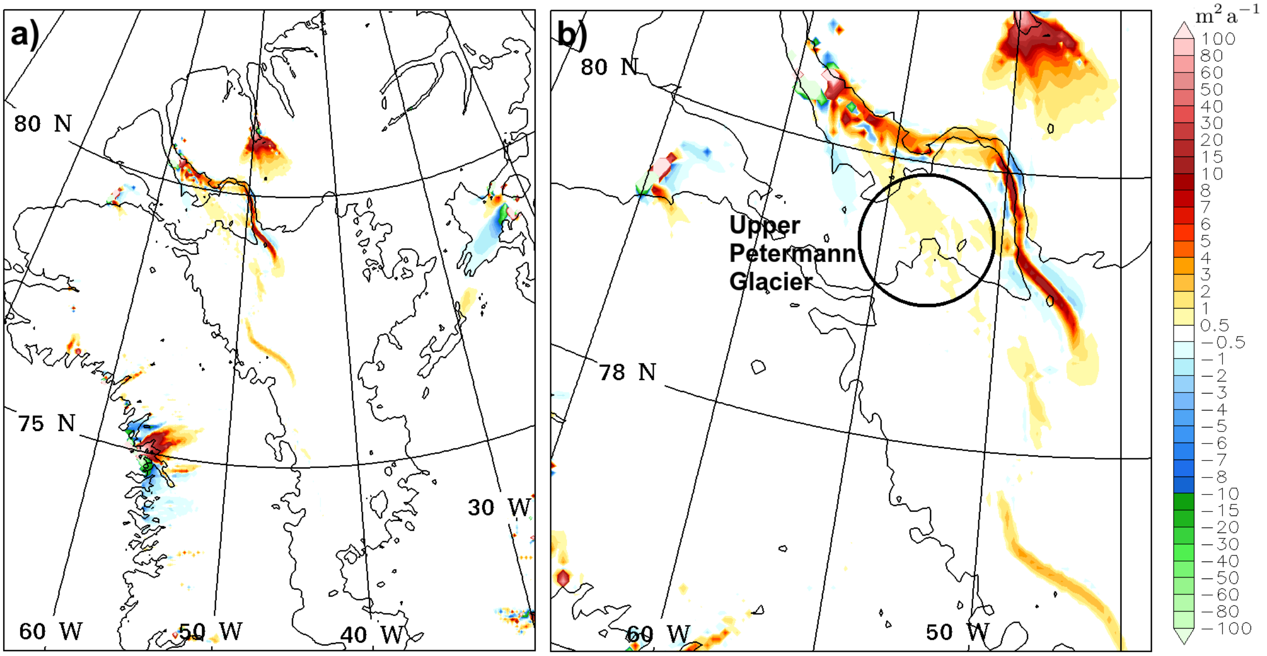

Figure 9. Surface ice velocity difference (Valley – Control) in metres per year for a) north Greenland and b) the Petermann catchment. ~~Basal melt rate m a^{-1} for a) Valley and b) ValleyS, and basal water depth differences (m) for c) ControlS - Control, and d) ValleyS - Valley.~~

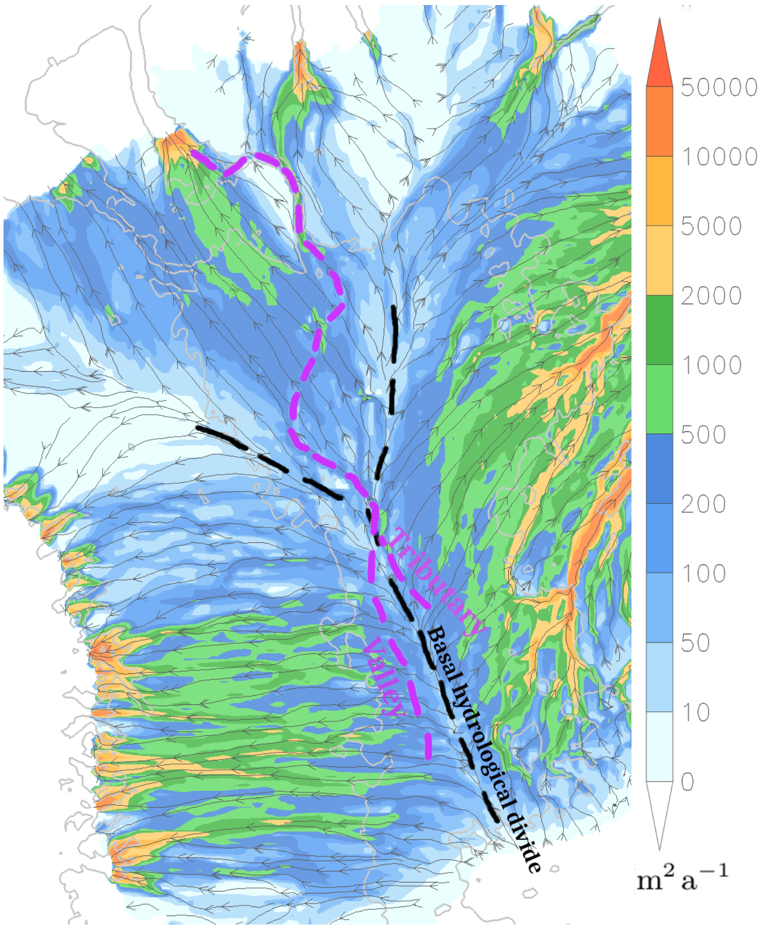

Figure 10. Schematic showing the location of the interior basal hydrological divide (~~grey~~ black dashes) ~~simulated by SICOPOLIS~~ and the path of the valley and the tributary (purple dashes). ~~For guidance the~~ The background is the ~~Control basal topography with the~~ basal water flux ($m^2\,a^{-1}$ colours) from the sensitivity simulation that has a valley with fixed depth of $-100\,\mathrm{m}$ (valley removal described in Appendix ~~B~~A)~~overlaid at 50% opacity~~.

~~BedMachine basal topography error (Morlighem et al., 2017) in metres for the region from Petermann to Basin. The black contour indicates −200 metre elevation.~~

~~Across (a-f) and along (g) valley profiles from BedMachine v3 bed topography (Morlighem et al., 2017) and the adjusted bed elevation used in our model. The error envelope is derived from error estimates provided in BedMachine. Reduction in error depends on the proximity to radar data as shown in lines a-c that are parallel to flight lines or the use of mass conservation to derive bed topography which covers the region between 130 and 250 in g).~~

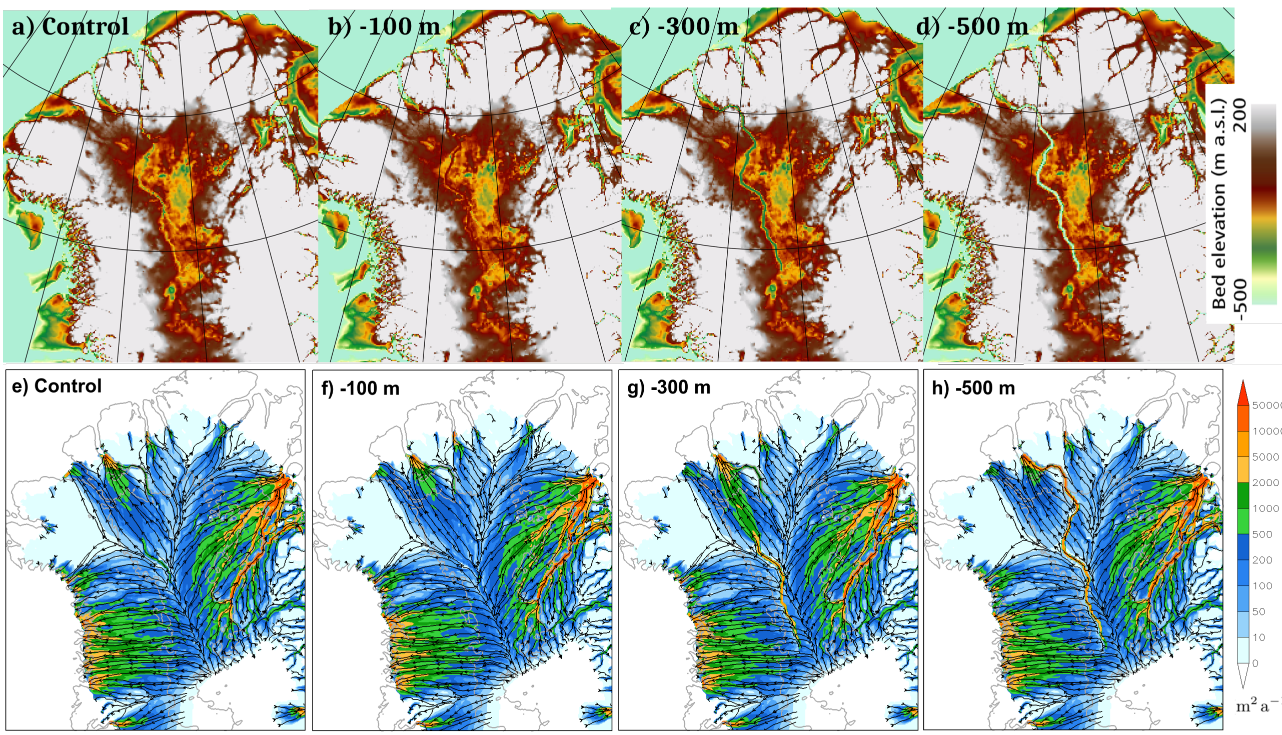

Figure A1. Sensitivity to valley depth tests. Bed topography (m) for a) Control, and for fixed valley base elevations (relative to sea level) of b) $-100\,\mathrm{m}$, c) $-300\,\mathrm{m}$, and d) $-500\,\mathrm{m}$. Basal water flux magnitude ($\mathrm{m}^2\,\mathrm{a}^{-1}$ colours) and streamlines for north Greenland for e) Control, f) $-100\,\mathrm{m}$, g) $-300\,\mathrm{m}$, and h) $-500\,\mathrm{m}$.