Response to Reviewers

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Response to Reviewer 1

Thank you very much for taking the time to review our paper. Please find below our responses to your comments. *Reviewer statements are in italics.*

"This appears to be a poorly conceived study or, at least, a poorly conceived description of the study. It reproduces a key inference from a paper published six years ago and presents it as a new result or inference."

This study is the first demonstration of how the opening of a long valley in the bedrock can impact the subglacial hydrology and ice sheet sliding in northern Greenland. Bamber et al. 2013 (B2013a) did not demonstrate that an uninterrupted water pathway was possible from Interior to Petermann. Their figures show water pathways along numerous independent sections of the valley. They infer that the valley is probably continuous but do not present scientific evidence of the potential effects the continuity of the feature could have on the basal hydrology or ice sheet sliding. Our results are new and we hope will be useful for progressing forward in our understand of subglacial valley features. Areas of the introduction and discussion have been reworded to reference the inferences made in B2013a and additional results are presented to further the originality of this study which we hope will address these concerns.

"As mentioned in the already posted comment, this study is actually about the influence of a continuous subglacial canyon on water flow and ice dynamics. While that is a topic that could be interest, almost all of the discussion presents flawed, hand-waving supposition that has little evidential basis and has little, if anything, to do with the model experiments."

The discussion outlines the potential significance of the valley based on the model results and current form of the ice sheet and known bed topography. We are combining the techniques of model analysis with observational data and discuss the implications in the context of past research on subglacial hydrology. Responses to specific comments raised concerning the discussion are below.

"The paper would benefit from a substantial rewrite and refocusing on the actual topic of the experiments conducted: what is the impact of a continuous canyon on the subglacial hydrology beneath the Greenland ice sheet? However, as the hydrology model used assumes thin film flow and no sources from surface melting are included, it is debatable to what extent the experiments can address this question with adequate confidence."

We have made changes to the manuscript to firm up our investigation, including considering discharge estimates. The thin-film model is used as a guide for where subglacial water is moving and collecting under the ice sheet. The following statement has been changed:

“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 subglacial river system.”

Contributions from surface melting to basal water are currently impossible to accurately assess but would only serve to enhance the probability of a subglacial river being present within the valley. Given the path of the valley mostly within the ice sheet interior, it may be difficult for surface melt water to reach the base, at least under present conditions. It’s an interesting and important issue and is briefly mentioned in the discussion:

“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.”

Specific Comments
1) As already mentioned in the posted comment, the title is not only extremely misleading it addresses a question that was tackled previously and this study provides no new evidence to answer it. The entire abstract needs to be rewritten focusing on the results of the model experiments and nothing else.

The finding of an uninterrupted water pathway along the valley from Interior to Petermann was not demonstrated in previous work. B2013a Figure 3 demonstrates the effects that errors in bedrock data have on water pathways that consequently fail to follow the valley route. We demonstrate for the first time the potential consequences of accounting for these errors by opening one single valley. We think it is better to use model results in conjunction with observations for this type of study rather than solely focus on the model results.

2) It is unclear to me why the authors have to introduce or replace existing terminology. They need to remove the word “river” throughout and replace with either conduit, R channel, or thin film as appropriate. In addition, why do they rename the canyon, “valley”. Their explanation (p1, l23) is nonsensical.

The term “subglacial river” is used here to cover a variety of possible subglacial river forms such as within R-channels, canals, Nye channels, or braided rivers. We will add our definition of this to the introduction.

We use the term “valley” because in areas of the interior the feature does not appear to take the form of a canyon as for example defined as “a deep valley with steep sides”. In regions the valley does not have steep sides, so we think the broader term “valley” is more appropriate as it better accounts for a wider range of forms. In work prior to B2013a the feature was referred to a “bedrock trough” or “trench” by Ekholm et al. (1998) , and a “channel” or “subglacial valley” by van der Veen et al. (2007). In addition, the term “tunnel valley” has been widely used for subglacial water incised channels. The terminology can be changed if the editors, reviewers and co-authors think that “canyon” is a more appropriate term to use for the feature as a whole. The following statement has been edited:

“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 as a in the broadest term as a subglacial “valley”.”

3) The introduction is misleading and needs to be rewritten. Quoting directly from Bamber et al

2013 (B2013a), they state "we present evidence from ice-penetrating radar data for a 750-km-long subglacial canyon in northern Greenland that is likely to have influenced basal water flow from the ice sheet interior to the margin"; "In all cases, above ~76° N and within the entire length of the Petermann catchment, the canyon exerts a control on basal water flow. For ~200 km, it provides an uninterrupted hydraulic pathway (Fig. 3 and fig. S3A) that ends at the terminus of Petermann Gletscher" and so on. I do not understand why the authors are proposing this as something entirely new.

These are not the same as the results presented in our paper. B2013a present evidence in their Figure 3 of water flow along some sections of the valley but not along the whole length in any of the scenarios. With present day ice sheet cover they find an uninterrupted water pathway for only the northernmost section ~200 km in Petermann catchment as stated. This demonstrates the strong forcing for water flow along this section when ice is present because this occurs even in these cases that contain large and unrealistic artificial blocks in the valley. Nonetheless even in these cases, it is worth noting that water is diverted away from the valley just prior to entering the Petermann Glacier basin due to a large artificial block in the bed topography there. This error also occurs in the results of Chu (2017) Figure 4.6c. Further inland the situation is more serious with water flowing in and out of the valley in numerous locations in all of the cases presented in B2013a. The only result in our paper that is similar to the distribution in B2013a Figure 3c is our Figure 4a which presents our control case. This is because it also contains these unrealistic blocks in the valley.

4) P2 l1. The authors appear to be unaware that the bed topo in BedMachine v3 and that which was used in B2013a are essentially the same. The only difference is in the use of mass continuity near the margins where IPR coverage is poor. Any conclusions drawn in B2013a will be identical for BedMachine.

Our tests are focused on the effects of the removal of blocks in the valley in BedMachine v3. We are not presenting any results or discussion concerning differences between BedMachine v3 and the data used in B2013a.

5) P4, l35. Fig 5 does not show slope, it shows surface elevation. The slope in the interior of ice sheets is small everywhere. This is not the same as "near flat" which is meaningless. Eyeballing the Fig it looks like the canyon follows the surface slope quite closely in the interior. This sentence is a good example of the hand-waving vagueness that pervades other parts of the paper.

Surface elevation plots indicate slope through the distribution and concentration of contours. We have changed:

"Figure 5 indicates that the along-valley component of the ice surface gently slopes down-valley all the way to Petermann Fjord."

6) P5, l5-6. I don't understand the logic of this statement. The canyon is not linear and doesn't follow the streamlines when it is not present (Fig 4a). This is nonsensical

In this section we are trying to establish whether the current form and path of the valley is consistent with what could be expected for a subglacial river under the current ice sheet configuration. While the valley appears to intersect the east and west hydrological basins in the interior it does not follow the streamlines, particularly as it crosses NEEM zone. A perfectly aligned valley with present day streamlines is probably not to be expected given the different extents of the ice sheet in the past. B2013a Figure 3b is a good indicator of this as the basal hydrological divide is shifted to the west under LGM conditions and the valley still follows a path not far off the basal

hydrological divide. We have reworded and added some sentences discussing this issue and reference B2013a Figure 3b:

“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 projects towards the east of it (Figure 8). 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).”

7) Section 4 Discussion. I found this section far too speculative, hand-waving and non-scientific. The first part is a qualitative overview of subglacial water flow theory. The arguments for why water may be present in the canyon are OK, in general although the discussion of enhanced GHF was a bit muddled and unclear. It could have all been stated in half the space as basal frictional heating, warmer ice at depth are all well established concepts.

The overview on subglacial water theory is necessary to address the key issue of the paper on whether water flow within the valley is likely to be in the form of a subglacial river. Numerous changes have been made to the discussion and new results on the role of interior GHF are presented.

By page 7, l9 the discussion becomes too speculative.

Given the possible large extension of the valley catchment to Basin we think it is important to discuss this in this section. We try to make it clear in the discussion where we are uncertain.

The authors appear to be unaware that B2013a examined hydraulic potentials for the isostatically compensated bed (Fig 3A) and discuss this in some detail. In addition, the authors do not explain how 300-800 m of bedrock erosion from subglacial water flow is possible during the Holocene. That would be a challenge even for rapid basal sliding over a soft bed, neither of which is the case here. At LGM, ice flow and hydraulic routing was different due to larger ice sheet cover.

The LGM hydraulic routing issue is addressed above. The following has been added to the discussion on this erosion issue:
“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.”

P7, l27. Why?

The concept here is that it seems unlikely that, in the absence of subglacial river erosion, a river formed when there was no ice sheet would take a form that would end up also being favourable for subglacial water flow under thick ice. In this sense the substantial changes to the form of the bedrock caused by the build up of km thick ice should make a roughly level paleo river valley capable of routing subglacial water all the way out from the interior, unlikely. Having said that the valley base does not appear to be perfectly level by any means, and does not follow the hydrological divide perfectly. We have added various points clarifying this issue to the discussion and Figure 8 to aid in explaining the points made.

9) P7, l30-32. This appears to demonstrate a complete lack of understanding of how the lithosphere responds to changes in ice loading. Why would there be a differential viscous response of the mantle across a < 10 km wide channel? In addition, how flat is the canyon and how flat is it after isostatic compensation? This is really incoherent.

We are referring to the along-valley differential viscous response, not the across valley one. A present day relatively level valley base over such a long distance is consistent with subglacial erosive and depositional water activity but does not prove it. The isostatic correction in B2013a Fig. S5 implies that on an ice-free Greenland the valley would be 600 m higher than present in the interior progressing to 200 metres higher near the coast. Today the valley base appears to be consistently between -300 and -500 metres with no clear trend along-valley. The following has been added:

“As stated earlier, the base today is not perfectly level as it appears to vary between −250 to −500 m but there is no obvious along-valley trend over its 1000 km length.”

10) Section 5. As for the abstract, title and Discussion, this section needs to be rewritten, focusing on the actual results and not wild and unsupported speculation.

We hope that our responses address some of your concerns. We have made changes to the title, abstract, and discussion.
We refer to a the possiibility of a long subglacial river in the title having considered the following points:

- The article is about the “possibility of a long subglacial river” and as such presents evidence for such a system while recognizing that the huge void in data precludes a conclusive result.
- The word “river” is appropriate when defined as “subglacial river” which has different properties to a river over open land. In addition, many “rivers” on Earth do not flow at all times, or flow at certain times only along certain sections.

Our definition of a subglacial river is clarified in the introduciton:

“The term “subglacial river” is used here to cover a variety of possible non-film subglacial hydrological conduit forms such as within R-channels, canals, Nye channels, or braided rivers. 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 a terrestrial river.”

Response to Reviewer 2: Andy Aschwanden

Thank you very much for taking the time to review our paper. We hope the responses below address the issues that you raised. *(Reviewer statements are in italics).*

“First (as already pointed out by Jonathan Bamber), the title is misleading because Bamber et al (2013) [B2013a] already demonstrated the existence of a long subglacial channel. I suggest to change the title to something that more closely reflects the core of this manuscript. E.g. along the lines of "On the influence of a long subglacial channel on basal hydrology and ice flow”.”

The title has been chosen because the focus of our investigation has been on the possibility of a currently active long subglacial river system along the valley route. We would prefer to keep the original title after considering the following points:

- The article is about the “possibility of a 1000 km long subglacial river” and as such presents evidence for such a system while recognizing that the huge void in data precludes a conclusive result.
- The word “river” is appropriate when defined as “subglacial river” which has different properties to a river over open land. In addition, many “rivers” on Earth do not flow at all times, or flow at certain times only along certain sections.” We are going to add this definition to the introduction to be clear and we are considering adding an additional appendix that discusses potential discharge estimates. A definition has been added.

Regarding the originality of the study, B2013a did not demonstrate that an uninterrupted water pathway was possible under present day conditions from Interior to Petermann in the evidence they presented. Their figures show water pathways along numerous independent sections of the valley. They infer that the valley is probably continuous but do not present scientific evidence of the potential effects the continuity of the feature could have on the basal hydrology or ice sheet sliding. Therefore our results are original. We have added references to B2013a beyond what was already included to make it clear what their results showed, how they differ from ours, and how our results relate to inferences made in B2013a.

“The hydrological and ice flow modeling, which is the most novel aspect of this manuscript, is ill-conceived. The authors compare a simulation “Valley” to a “Control” simulation which to me has limited value. Why not compare the simulation to the readily-available surface velocity measurements, as one would hope that better physics leads to a closer agreement with observations?”

Thanks for the suggestion to compare with observations. Our goal in relation to ice sheet sliding is to provide an assessment of what impact an open valley introduced into a simulation can have. To do this it makes sense to compare two cases that are identical aside from the topographic modification, as we have done with “Valley” and “Control”. The results therefore only show the consequences of the topographic change and so reveal the influence it has. For assessing whether the introduction of a valley improves the simulation with respect to observations it would be valuable to make the comparison you suggest, however this has not been our aim up to this point. All simulations have been rerun with a more advanced setup. The new results have a less marked impact on sliding and we have added the following statement to the results regarding this:

“Considering other uncertainties and inaccuracies, the differences are too small to allow assessing which case is better compared to observed surface velocities.”

“In Figure 6 the differences between “Valley” and “Control” exceed 10 m yr-1. Looking at observation of surface speeds, I find no clear signature of a channel, contrary to what is expected. I wonder if this means that the sliding model is too sensitive to changes in basal water.”

The simulations have been re-run with a shallow-ice--shelfy-stream scheme that captures the dynamics of fast-flowing grounded ice more realistically. The effects on sliding are less, however the increase in surface speeds over the valley are still present. It is possible that there is no subglacial river, or significant subglacial water within this section of the valley, i.e. it is mostly frozen to the bed. Alternatively since the model relies on a thin film basal hydrology it fails to model any type of subglacial river. Consequently it fails to channelize the water, potentially causing an unrealistic distribution of water in a wide film that has a greater influence on sliding. Generally the addition already mentioned is relevant here:

"Considering other uncertainties and inaccuracies, the differences are too small to allow assessing which case is better compared to observed surface velocities."

"Furthermore, with a channel width of 5-10km, it is not clear to me how well a model resolution of 5km is able to capture the dynamics that the authors are interested in."

This is a significant model issue and it is one that important to highlight. Unfortunately we are currently unable to simulate the Greenland Ice Sheet at higher resolutions than 5 km and this restricts our ability to correctly reproduce basal topographic features. We can only present the results we have and detail potential error sources. Judging by the basal water fluxes we present, we have successfully removed the blocks along the valley route, which was our goal. From a modeling perspective, this is a first step to demonstrate the potential extent of the impacts.

"Right now the manuscript consists of a lot of material that was already discussed by B2013a, an interesting but not well thought out modeling part, and a very speculative discussion on geothermal flux. While the manuscript has potential, I cannot recommend it for publication in its current form; a conclusion I did not reach lightheartedly. Maybe these suggestions can help to rewrite the manuscript, with focus on 1. what is novel compared B2013a 2. the ice flow modeling and how the inclusion of the channel improves agreement with the observed flow structure."

We present new scientific evidence that was not presented by B2013a and will reference B2013a further where appropriate. We hope that the points above help to address the issues presented on the modeling aspects. The geothermal heat flux discussion in relation to the NEGIS hot spot and the valley form are based on the published research of Fahnestock et al. (2001) and van der Veen et al. (2007) respectively.

"Detailed comments:
P2, L 1: Please note that in the interior of the ice sheet, BedMachine is based on kriging, mass conservation was only used near the coast. It is thus more or less equivalent to bed map of Bamber et al (2013) [2013b]."

This is noted as below. Our study is focused on adjustments made to open the valley rather than changes in the data since B2013b.

"However, 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."

"P2, L 11: change "when you consider", this is too colloquial".

We have changed this to "after accounting for".

“P2, L23: Maybe I don’t understand the initialization procedure correctly, but why is 1990 the target date? P2 L 30 that corrections are made to bring the simulated ice thickness in agreement with observations. But to the best of my knowledge there is no 1990m DEM of Greenland available that can be used as a target?”

Our SICOPOLIS model setup is based on that used for the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6). The reason why we chose 1990 as the initialization date for ISMIP6 is that the Greenland ice sheet was approximately in balance around that time, while its mass balance has become more and more negative since then. You are correct that there is no DEM for 1990. The nominal date for BedMachine Greenland v3, from which we also took the surface DEM, is 2007 <https://sites.uci.edu/morlighem/dataproducts/bedmachine-greenland/>.
However, the difference between the overall topography 1990 and 2007 is very small, so that it doesn't really matter. More important is that the climate forcing for the spin-up run ends in 1990 and produces an ice sheet that is very much in balance.

“P5, L5: “extremely gently” sounds awkward. Maybe just “gently” or “very gently”?
P5, L 25: “where you get” is too colloquial.”

We have changed “extremely gently” to “very gently” and have deleted “where you get”.

“Figures: To increase readability, I recommend using the same color scales for bedrock elevation in all figures. Currently there a 3 color scales (Fig 1, 2, 5).

Thanks for this suggestion, This scales are now the same across these figures.

Fig 4: A close up of the NEEM zone would be helpful, the flow lines are hard to distinguish here.”

Close ups of NEEM zone are now included in Figure 4.

References

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Wing Yin Chu 2017 Variability of Subglacial Drainage Across the Greenland Ice Sheet: A Joint Model/Radar Study. PhD thesis, Columbia University

Marked up manuscript

On the possibility of a 1000 km long subglacial river or wet sediment flow under the north Greenland ice sheet

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Abstract. Does a long subglacial river, or wet sediment flow, with a source at a known area of basal melting deep in the interior of the Greenland ice sheet, ~~drain into~~ reach the sea at the Petermann Glacier grounding line? 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 is due to data interpolation. ~~Simulations~~ Therefore, simulations where the valley is opened are used to investigate its effects on basal water ~~and ice sheet sliding~~movement and distribution. The simulations indicate that the opening of this valley ~~results~~ can result in an uninterrupted water pathway from the interior ~~along the valley that alters ice sheet sliding in the Petermann catchment and in areas of west Greenland~~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 ~~along~~ near the interior ice divide that roughly intersects the east and west basal hydrological basins, is presented as evidence that its present day form ~~developed as a consequence of the~~ may have developed in conjunction with an overlying ice sheet~~rather than prior to ice sheet inception. Though considerable uncertainty remains, the~~ . Experiments where basal melting is increased solely within the deep interior near a 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 system~~. The results raise issues concerning the need to better observe, understand, and simulate the complicated basal hydrology of the Greenland and other ice sheets~~, 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~~ km of ice. Ekholm et al. (1998) found two, roughly 75 ~~km~~ km long, elongated depressions in the surface of the ice that were connected by a “more than 100 ~~km~~ 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, ~~they~~ 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 ~~as a~~ in the broadest term as a subglacial "valley".

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 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~~and~~ ,d), it is clear that these rises occur only in regions where data was not obtained. ~~Therefore, we infer that these~~ 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~~and that~~ , there is currently no evidence to suggest that this valley is filled (see Appendix A for further detail on BedMachine error estimates). This proposition is corroborated by the continuity of the signature of the valley on the surface of the ice across regions where the bed topography data has rises ~~along~~ in the valley. This poses the question; are these rises damming subglacial water flow along this conduit ~~in~~ 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 gaps in the valley where the valley base elevation rises above ~~−100 m~~ −100 m occur where no data has been obtained and interpolation has smoothed out the valley. In fact, ~~when you consider~~ 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 m and −500 m~~ −250 m and −500 m along its length from Interior to Petermann in Figure 1b.

The term "subglacial river" is used here to cover a variety of possible non-film subglacial hydrological conduit forms such as within R-channels, canals, Nye channels, or braided rivers. 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 a terrestrial river.

The goal of our research is to investigate the impact of a continuous subglacial valley on the flow of basal water using a state-of-the-art ice sheet model. In addition, the effects on ice sheet sliding ~~resulting from opening this valleyin the basal topographic data are investigated~~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 valley base is possible.

2 Model and ~~Methods~~methods

~~1) SICOPOLIS~~

~~The simulations~~

2.1 Spin-up until 1990

We use the SImulation COde for POLythermal Ice Sheets (SICOPOLIS, www.sicopolis.net) version ~~5-dev~~5.1, a polythermal ice sheet model originally created by Greve (1995, 1997). ~~We employ the shallow-ice approximation for grounded ice and the one-layer melting-CTS enthalpy method by Greve and Blatter (2016) for solving the thermodynamics. All results presented in this paper represent the output for the year 1990. To obtain a suitable~~ To simulate the state of the Greenland ice sheet for our reference year 1990~~ice condition, a series of simulations are run for a~~, we carry out a spin-up ~~period~~ over the last glacial/interglacial cycle (134 ~~ka~~ka). The ~~set-up is detailed in depth in Greve (2019, section 3.1) and summarized here.~~

~~2) Spin-up~~

~~The spin-up runs from 134 to 9 ka ago with a horizontal resolution of 10 km, and from 9 ka ago until today (1990) with 5 km resolution. 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 4 ~~ka (Kobashi et al., 2011) . Since it is very difficult to reproduce the 1990 observed ice sheet geometry in a freely evolving simulation, corrections in thickness are made using the surface mass balance to reach an ice sheet shape consistent with observations.~~ 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., 2020) and shall only be summarized here.

During the last 9 ka, the horizontal resolution is 5 km, and the computed 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~~) Basal hydrology~~ ka (Le Meur and Huybrechts, 1996) . For the topographic and geothermal heat flux sensitivity tests (Sects. 2.3, 2.4), only the last 9 ka of the spin-up are re-computed.

~~In contrast to the simulations by Greve (2019)~~

2.2 Basal sliding and hydrology

Following the approach by Goelzer et al. (2020) and Greve et al. (2020), we use a basal sliding law that incorporates basal hydrology. The hydrology model is coupled to the ice dynamics using a modified ~~version of a Weertman-type~~ 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. ~~It is assumed that the water is moving~~ 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 are no subglacial rivers in the current formulation and so the ~~results here are presented with respect to potential water routing changes rather than simulated subglacial river development. Nonetheless, where~~ 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 subglacial river system. The flux-routing method requires that local sinks and flat areas are 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 of 10 ~~m~~ m to account for subglacial lakes.

~~4)Bedrock modifications~~ 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 ka of the spin-up sequence by minimizing the RMSD between simulated and observed logarithmic surface velocities. A detailed description of this procedure will be given elsewhere (Greve et al., 2020). Note that we do not re-compute the optimization for the topographic and geothermal heat flux sensitivity tests (Sects. 2.3, 2.4), 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.

2.3 Bedrock modifications

The bedrock topographic data is altered in a way to ensure that the valley is open from Interior to Petermann in ~~Figure 2b~~ at an average depth of around ~~−400 m~~ $-400\,\mathrm{m}$ (Figure 2b). The case with the standard topography is referred to as "Control" and the case with the open valley ~~is~~ 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))~~ (MSER; Donoser and Bischof, 2006) tracking is run to detect the trenches to be connected. Pixels between both trenches of the saddle ~~were~~ 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.

2.4 Idealized interior basal melt sensitivity experiments

Two additional sensitivity tests are designed to assess where basal water melted near the source of NEGIS is routed. The tests are referred to as ControlS that uses the standard 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 7b. 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 $\mathrm{W\,m^{-2}}$. 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).

3 Results

All results presented here ~~represent~~ are from the SICOPOLIS simulation output for the year 1990 at 5 ~~km~~ 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, basal water flux, and ice sheet velocity are presented.

For north Greenland the simulated basal water depth is affected by the introduction of the valley in several ways. In Figure 3a it can be seen that the standard topography produces ~~3 main quasi-linear sections~~ independent areas of deeper basal water along the valley but there are clear gaps between these areas. In contrast, when a continuous valley is introduced (Figure 3b) the basal water depth is both deeper and uninterrupted along the length of the valley all the way to Petermann Fjord. The thickest water depth (~~>0.01 m~~ $\geq$ 0.01 m) along the valley route occurs where the Priority Flood algorithm has been activated to represent subglacial lakes. In most interior areas away from the valley there is little or no change in the basal water depth. In particular, there is little to no effect on the basal water pathways associated with ~~the North East Greenland Ice Stream (NEGIS)~~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 ~~from~~ due to the introduction of the valley, the difference in basal water between ~~these~~ the cases (Valley – Control) is shown in Figure 3c. Doing this reveals that the increased water within the valley is surrounded predominantly by a reduction in basal water adjacent to 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 NEEM zone in Figure 3d~~)~~. The effect of these changes in the Petermann catchment is to redistribute the basal water into a narrower and deeper plume that can also be seen in Figure 3b.

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. 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~~ down-valley with streamlines getting "stuck" in the valley along certain sections~~, however confirmation that simulated water travels down the entire length of the valley will require future work~~. 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). 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. This is consistent with the increase in basal water ~~discussed earlier~~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) 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) 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 indicates that the along-valley component of the ice surface ~~slope is near flat over the interior section of the valley before gradually sloping~~ 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 ~~extremely~~ 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 ~~basal topography needs to~~ valley base topography could be either sloping downward towards the north, or ~~near-flat~~flat, for water to flow northward. It appears it could be closer to the latter, which ~~, if true, suggests that this is unlikely to be paleo river valley because itis in a location, and in a form, that favours present day basal water routing.~~ 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 m 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 final results presented here concern~~ To demonstrate the influence of the valley on simulated ice sheet sliding~~.~~ , Figure 6 shows the ice surface velocity difference between Valley and Control to highlight the locations where Valley increases or decreases sliding. ~~In the interior the~~ The sliding changes are relatively modest ~~with a region of reduced sliding of 1 to 10 $\mathrm{m\,a^{-1}}$ to the west of the valley increasing towards the coast. This has two smaller regions of sliding increases of 1 to 10 $\mathrm{m\,a^{-1}}$ to~~ 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 6b) where sliding increases over the valley and very weakly ($\sim$0.5 $\mathrm{m\,a^{-1}}$) in the Petermann Ice Stream. These increases are consistent with the redistribution of basal water seen in Figure 3. The sliding changes should be viewed as demonstrations of the potential for change due to the ~~north and south. The region of decreased sliding is consistent with a region downstream of a reduction in basal water depth (Figure 4c). There is no increase~~ 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 occur at certain outlet glaciers such as Ryder Glacier and several along the west coast. These changes, away from the valley and Petermann, are inconsistent across different model setups. 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 2.4. The simulations compare scenarios with and without the open valley that also include an area of enhanced interior basal melting as shown in Figure 7a,b. Figure 7c shows the change in basal water depth ~~associated with the regions of modest increased sliding so these two regionsmay be occurring due to mass balance to compensate for the reduced westward mass flux over the region of reduced sliding.~~

~~The more pronounced sliding changes occur in~~ that occurs when you introduce the enhanced basal melting region into simulations with the standard 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. The same comparison is made in Figure 7d, however this time the two simulations compared both have an open valley. Comparing Figure 7c 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 and down the valley, evident in the lower reaches. 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 ~~Petermann catchment (Figure 6b) where the greatest sliding increases are 50–60 $\mathrm{m\,a^{-1}}$ around the eastern half of the Petermann Glacier grounding line in the Valley simulation. Sliding increases to a lesser extent over both the valley and the Petermann Ice Stream leading to two separate branches of increased sliding. These pathways are consistent with the redistribution of basal water seen in Figure 3. The valley increases water flux in the region of Petermann ice stream probably due to water piracy from the valley as it bends to track more perpendicular to~~ basal water depth across northern Greenland north of 80°N. The other consequence of this is that the down-valley basal water flux upstream of the ~~ice-sheet slope~~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 $\mathrm{m^3\,s^{-1}}$.

4 Discussion

The formation of subglacial river 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 ~~where you get a switch from film or cavitation to R-channels~~ (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 ~~would be the favoured~~ 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 ~~can~~ could also further enhance melting there.

Thirdly, flowing water generates heat through frictional heating, increasing the temperature of the water. ~~It also transfers heat~~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~~ 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 ~~when~~ 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 river channels 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) which would imply that the ice overburden pressure lowers as the valley progresses towards Petermann Fjord. In this scenario, if ~~an open~~ 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 ~~the upper Petermann catchment (NEEM zoncin Figure 5). If this~~ NEEM zone. If down-valley water propulsion occurs, a possibility is that it ~~occurs~~ does so sporadically through the build-up, and release, of water in reservoirs along the ~~channel~~ valley route.

The results also indicate that the course of the valley in the interior runs ~~close to the~~ in the vicinity of the boundary of the east and west subglacial hydrological catchments (Figure 3a,b and shown schematically on Figure 8). This catchment boundary occurs in this region because it is below the gentle northward ridge of highest surface ice (Figure 5) which broadly forces the division between ~~the east and west basal~~ 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 ~~hydro potential~~ water flux directed towards the east or west is ~~lowest~~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~~to develop. This may~~ . This possible relationship to the ice sheet shape could be a further 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 projects towards the east of it (Figure 8). 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 rivers in the hydrology module. Rivers could funnel ~~greater~~ 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 ~~several~~ tributaries that could increase the main valley's discharge potential. The most prominent possible tributary, shown as ~~"Tributary"~~ "Tributary" in Figure 1 projects towards a region of ~~high~~ higher basal melt associated with ~~the interior of the NEGIS~~ NEGIS (Fahnestock et al., 2001) and could therefore be ~~a significant~~ 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 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 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"~~ "Interior" but given the basal topographic basin at ~~"Basin"~~ "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 ~~more~~ 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 smaller channel is evident 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). If these basins are connected hydrologically, it could significantly extend the catchment of the valley and imply a subglacial river over ~~1600~~1400 ~~km~~ 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.

~~It could be argued that the~~ The path of such a long basal valley down an ice surface slope ~~is, in itself, evidence of a feature that~~ 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 ~~as a direct consequence of~~ in conjunction with the ice sheet covering it. The ~~logic behind this reasoning can be understood by asking the question; why would a paleo-valley in the bedrock below an ice sheet follow a path that is favourable for subglacial water transport under 2 to 3 km of ice today? A~~ alternative is that it eroded due to a paleo-river ~~that developed~~ flowing when the ice sheet was much smaller, or absent~~, would have formed when the topography~~

~~was~~ . 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 ~~where~~ when conditions were ice-free. This different water flow environment would ~~make it highly unlikely to follow~~ 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. ~~In addition, the~~ 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 ~~there~~ it would, again, seem to be ~~no reason for~~ coincidental that a paleo-river system ~~to~~ 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 ~~ascended and descended depending on the complicated~~ depended on the evolution of the competing pressures from the ice and crustal rock. ~~A~~ As stated earlier, 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 ~~that ended~~ could end up having a very long fairly level base in this situation ~~would be a remarkable coincidence~~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 ~~the likelihood of this being~~ whether this is an active subglacial river (or wet sediment channel) or not.

Estimating the discharge down 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 already been detected in the valley (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.

5 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 real. Therefore, 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~~including modest slowing in interior west Greenland and an increase in the Petermann Ice Stream region. Since the model relies on a thin-film hydrology model, it is possible that much larger quantities of water are transported in this valley that could have a greater impact on the basal water distribution.~~. The valley progresses gradually from thicker to thinner ice causing 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. ~~These results raise the possibility~~ 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. 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 subglacial river or wet sediment flow system that is poorly realized in current ice sheet simulations. If this potential subglacial river/sediment 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 ~~. Questions remain over how much a complete depiction of this feature could affect ice sheet predictions under climate change scenarios.~~ 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 km~~ $< 250\,\mathrm{km}$ in our profile in Figure A2g) 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 "~~Morlighem et al. (2017) as "The variogram is modeled as a Gaussian function, with a sill of 100~~m~~ m, a range of 8~~km~~ km and a nugget effect of 50~~m~~ m, to account for uncertainty in ice thickness measurements~~"~~". The along valley profile (Figure A2g) 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 A2a,b,~~and~~ c) indicate the valley sides have similar slope angles on the 5~~km~~ km grid to the observed. 3 more example cross-sections (Figure A2d,e,~~and~~ f) in regions of high BedMachine error (away from flight lines) show the consequent failure to resolve the valley.

Appendix B: 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. ~~3~~ Three of the tests ~~uses~~ use 26 linear 10~~km~~ km wide idealized valleys to form an uninterrupted valley from Interior to Petermann. The valleys are created using the Matlab function ~~"inpolygon"~~ "inpolygon" that sets 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. Tests are done with inserted idealized valleys at constant maximum depths of ~~-100 m, -300 m, and -500 m~~ $-100\,\mathrm{m}$, $-300\,\mathrm{m}$, and $-500\,\mathrm{m}$ and are compared to a 4th test which uses standard SICOPOLIS topography as a control simulation. The ~~-100 m~~ $-100\,\mathrm{m}$ simulation effectively removes most of the segmented valley while the ~~-500 m~~ $-500\,\mathrm{m}$ case best represents the slopes of the sides of the valley.

~~The tests are 100 year long simulations that are initialized with the 1990 SICOPOLIS result and run with constant 1990 atmospheric forcing.~~ The tests use an otherwise identical method to that described in section 2.1.

The subglacial water flux for the four cases ~~at the end of the simulation (year 100)~~ is in Figure A3. There are large differences in water routing in and around the valley, between these cases. For a ~~-100 m~~ $-100\,\mathrm{m}$ valley (Figure A3f), the northward water flux signature associated with the valley is largely eliminated. If the valley base is lowered to ~~-300 m~~ $-300\,\mathrm{m}$ (Figure A3g), increased valley water flux occurs from Interior to NEEM zone where water then appears to be entirely evacuated from the valley into a plume ~~directly~~ directed towards Petermann. For the ~~-500 m~~ $-500\,\mathrm{m}$ case (Figure A3h) 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 m~~ $-500\,\mathrm{m}$ suggest that the valley side slopes on the 5~~km~~ 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.

Competing interests. The authors declare no competing interests.

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Figures

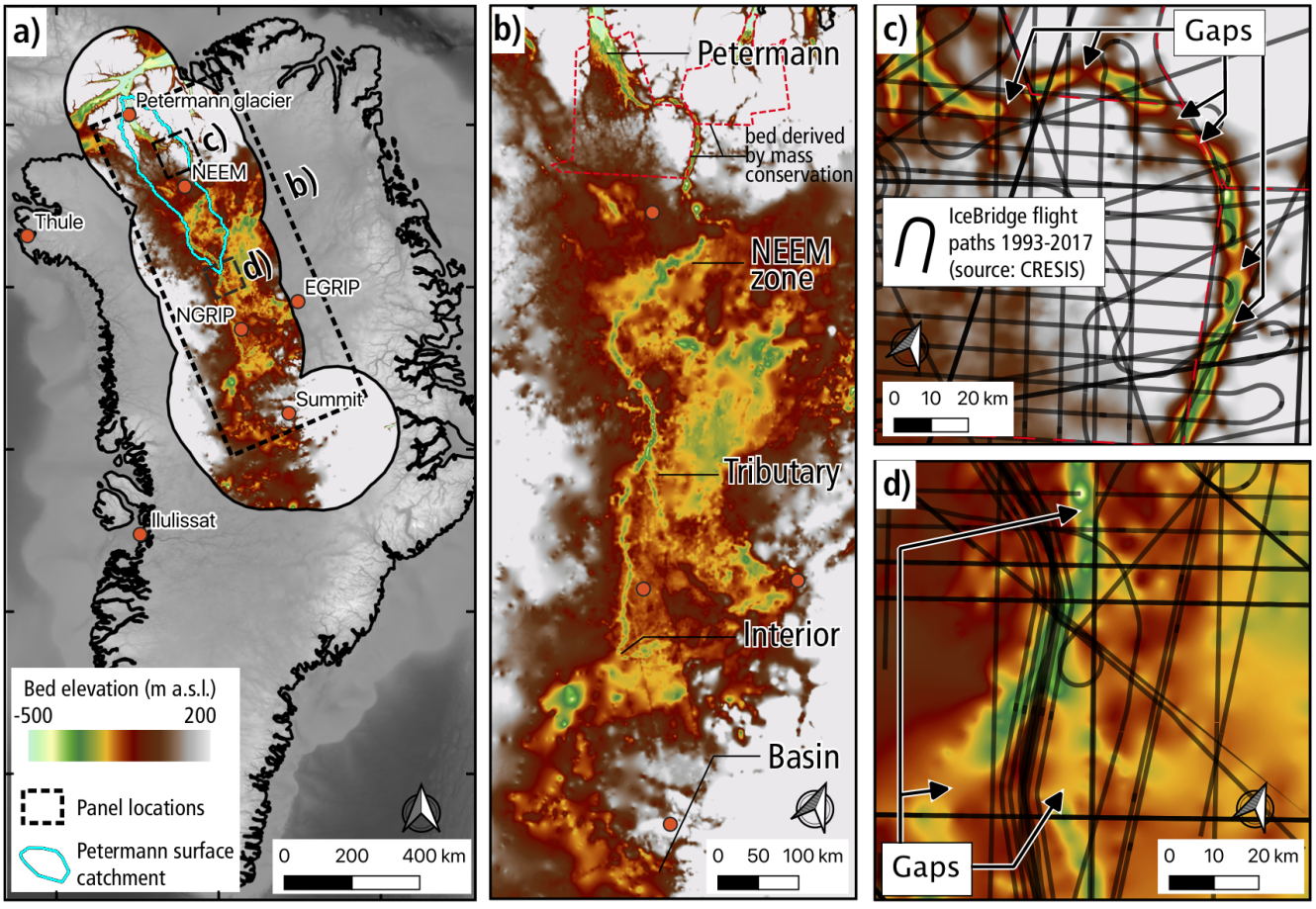

Figure 1. BedMachine v3 bed topography (Morlighem et al., 2017) between −500 to 200 metres above sea level for a) Greenland overview with boxes for b) the valley region and c) and d), two regions showing the IceBridge flight paths.

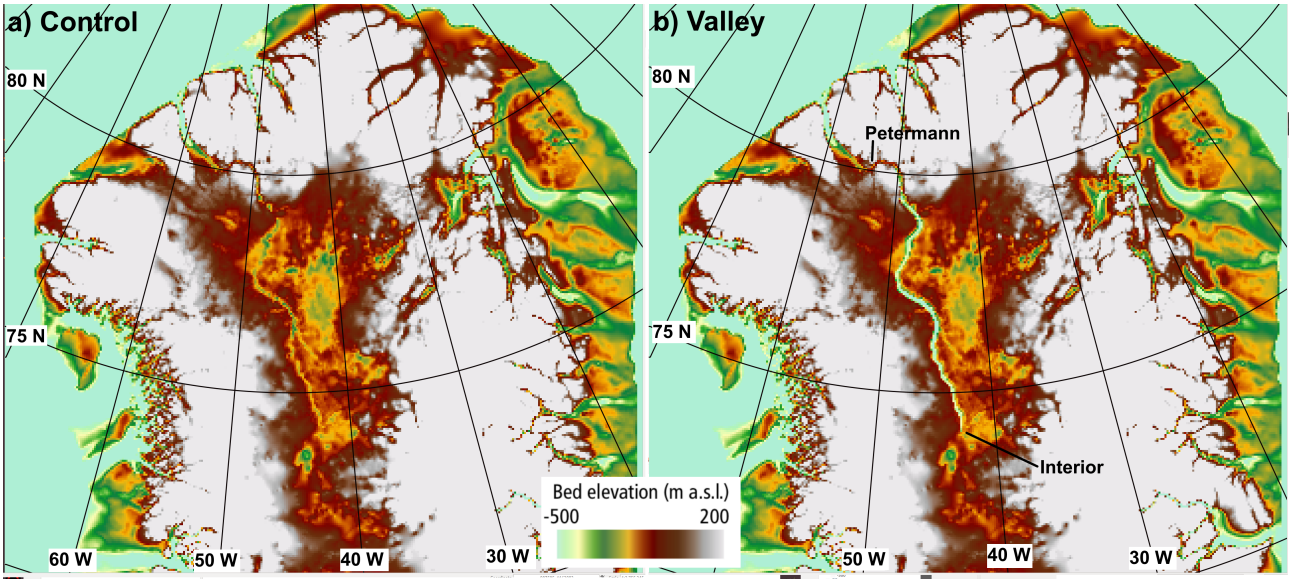

Figure 2. Basal topographic height between ~~−800~~ −500 and ~~800~~ 200 metres above sea level for a) Control (standard SICOPOLIS input derived from BedMachine), and b) Valley (manually adjusted from Petermann to Interior).

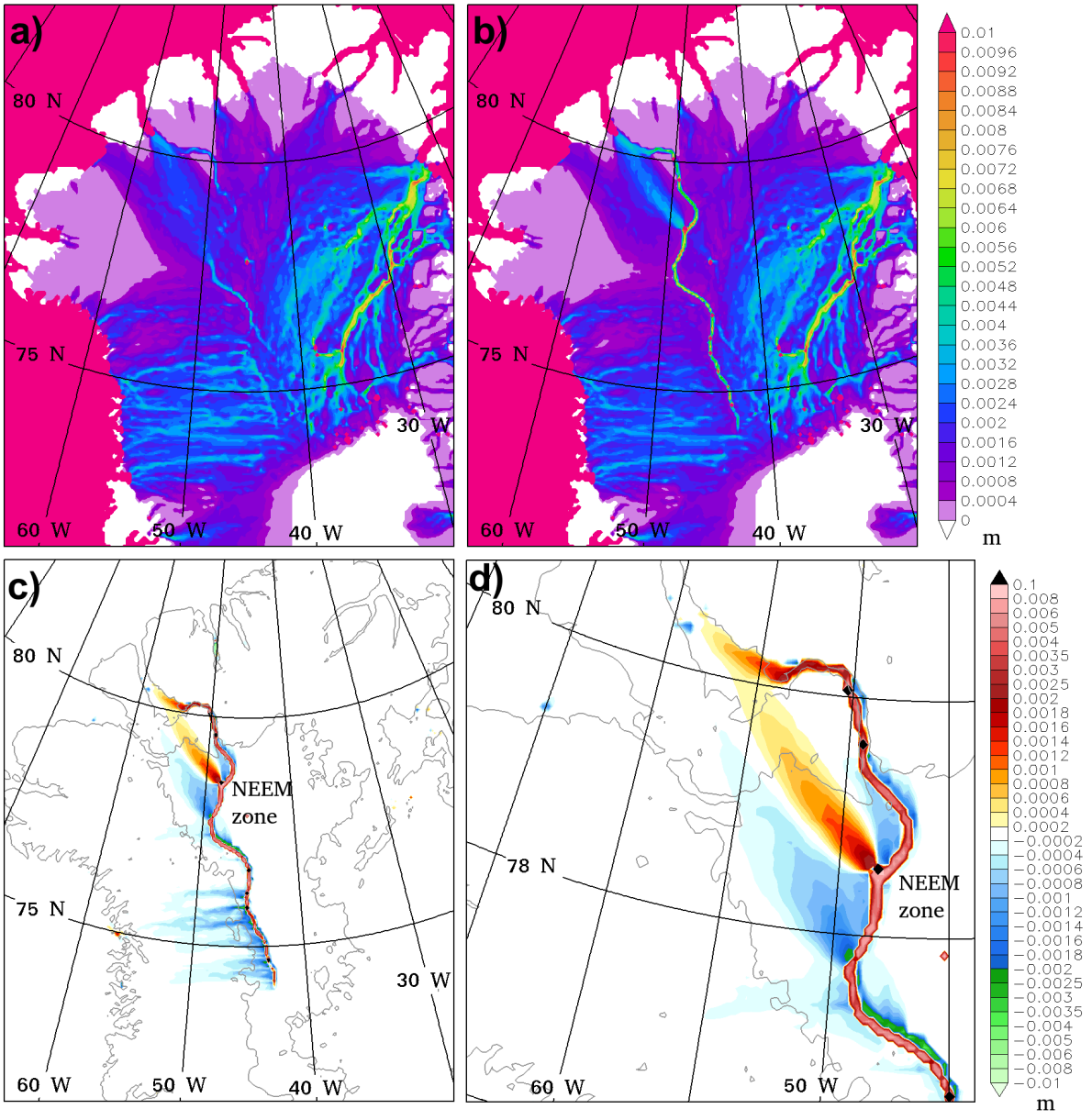

Figure 3. Basal water depth (m) for a) Control and b) Valley, from SICOPOLIS simulations for the year 1990. Basal water depth difference (m) (Valley – Control) for c) northwest Greenland and d) Petermann catchment region.

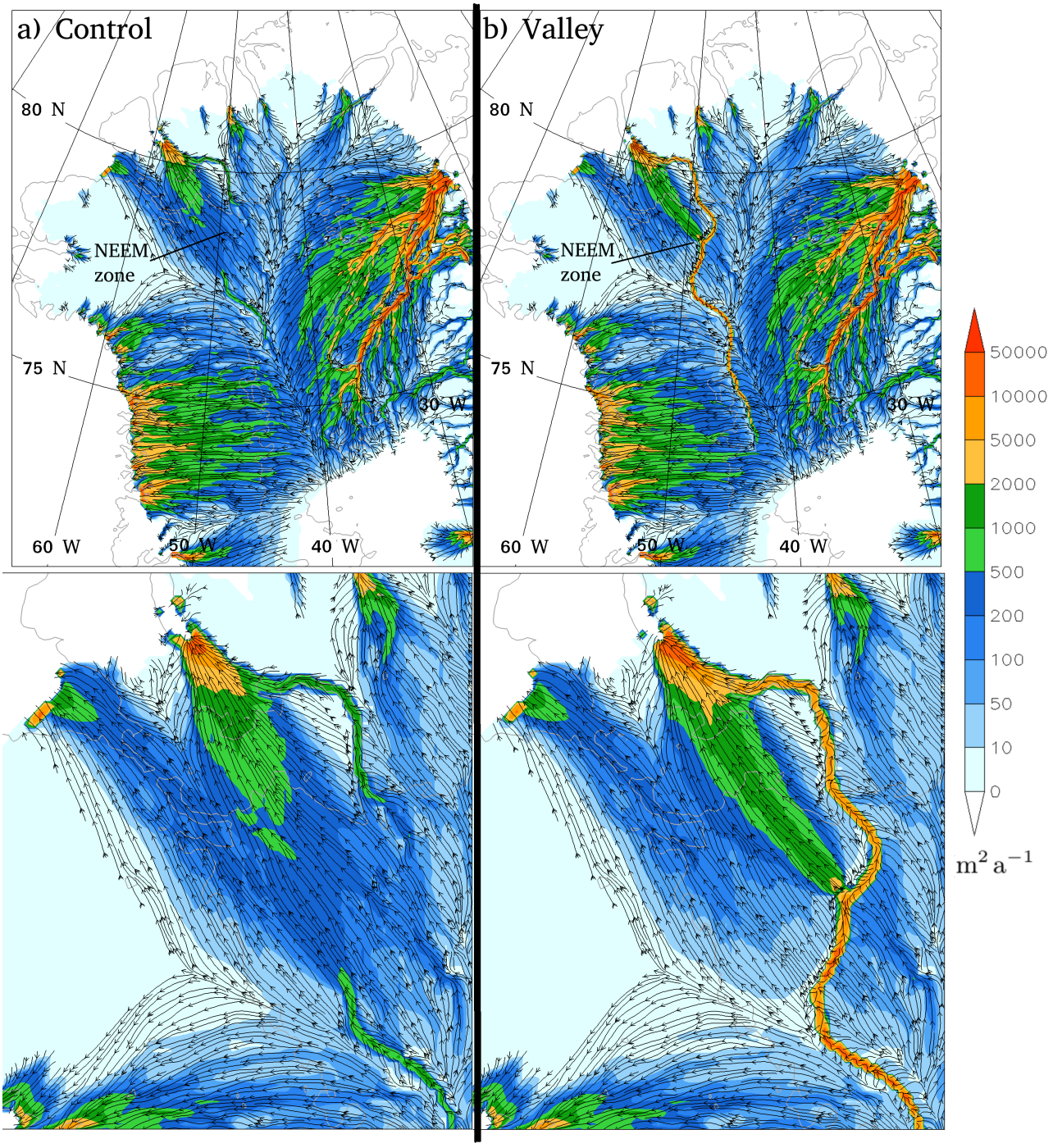

Figure 4. Basal water flux magnitude (~~m^2 a^{-1}~~ m^2 a^{-1} colours) and streamlines for north Greenland for a) Control and b) Valley. NEEM zone marks where the greatest change occurs out of the valley as discussed in the text and the lower plots zoom into this region for the respective cases above to show detail.

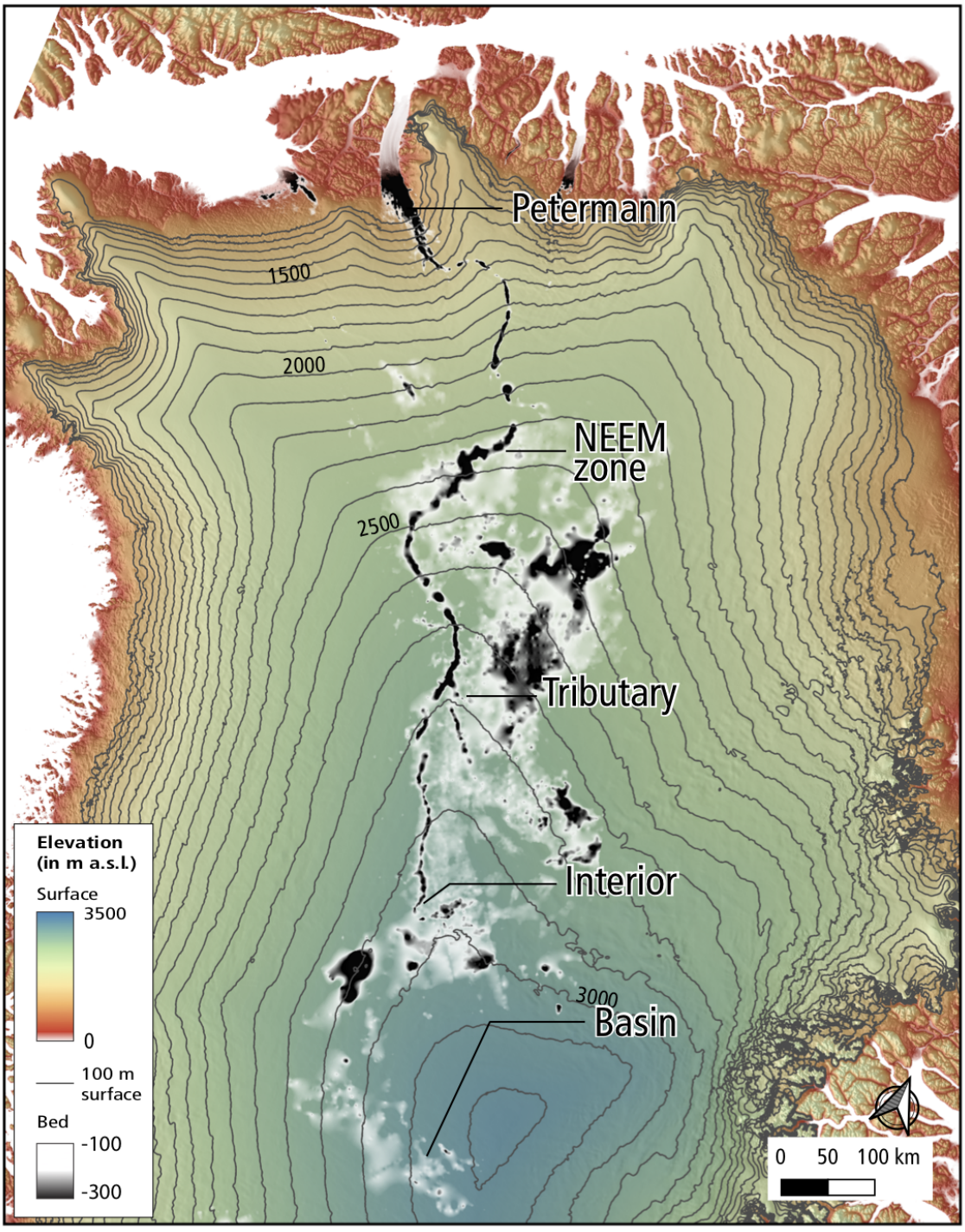

Figure 5. Surface elevation (m) with bed elevation for ~~100 m~~ 100 m or lower overlayed in grey to indicate the path of the valley.

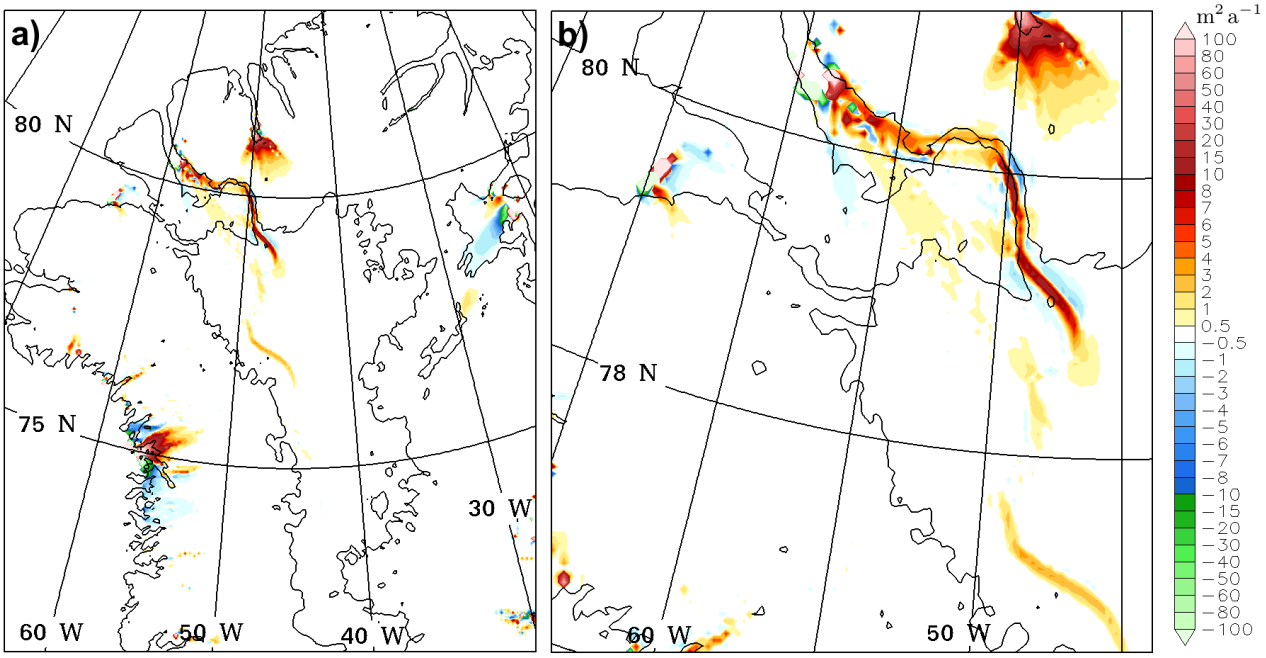

Figure 6. Surface ice velocity difference (Valley – Control) in metres per year for a) north Greenland and b) the Petermann catchment.

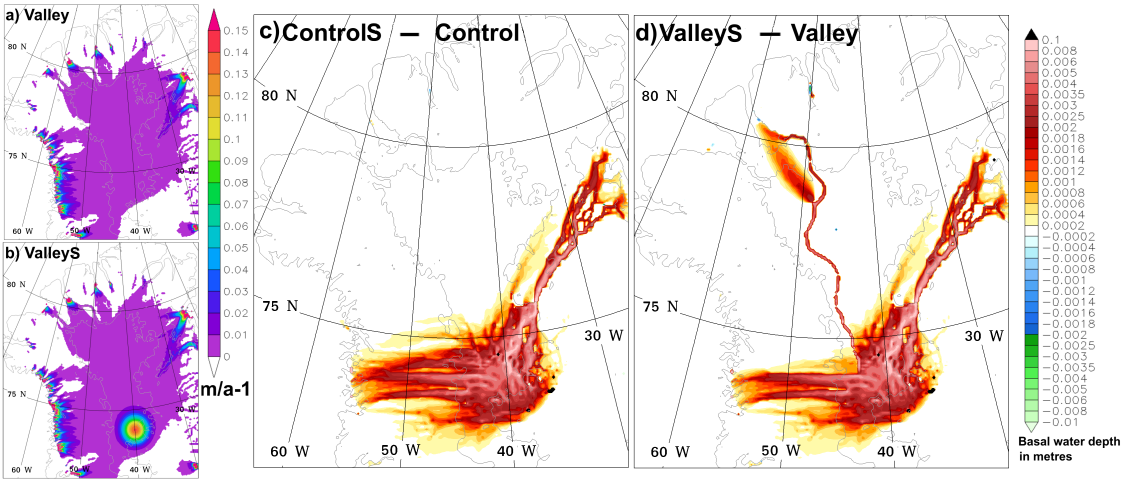

Figure 7. Basal melt rate m a^{-1} for a) Valley and b) ValleyS, and basal water depth differences (m) for c) ControlS - Control, and d) ValleyS - Valley.

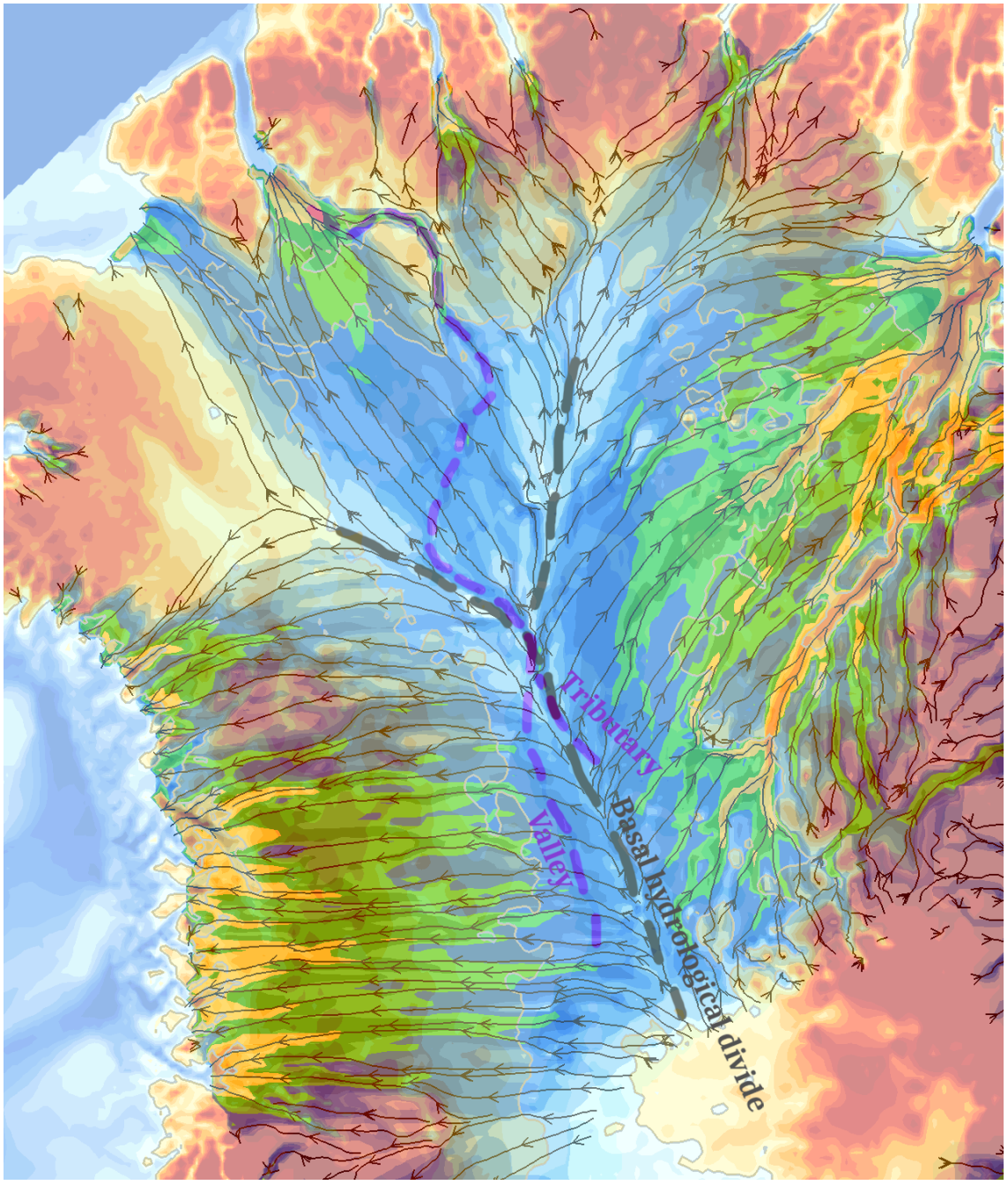

Figure 8. Schematic showing the location of the interior basal hydrological divide (grey dashes) simulated by SICOPOLIS and the path of the valley and the tributary (purple dashes). For guidance the background is the Control basal topography with the basal water flux from the sensitivity simulation that has a valley with fixed depth of $-100\,\mathrm{m}$ (valley removal described in Appendix B) overlaid at 50% opacity.

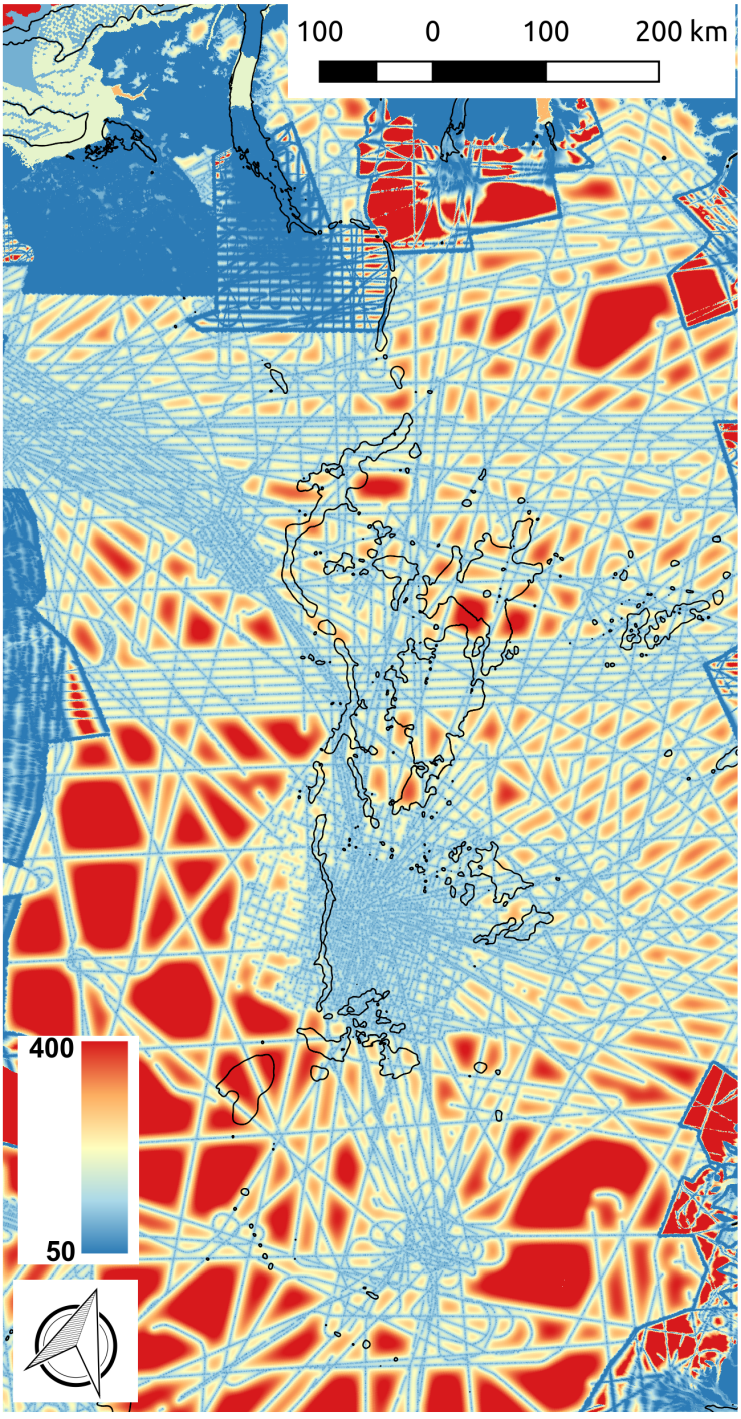

Figure A1. BedMachine basal topography error (Morlighem et al., 2017) in metres for the region from Petermann to Basin. The black contour indicates ~~-200~~ –200 metre elevation.

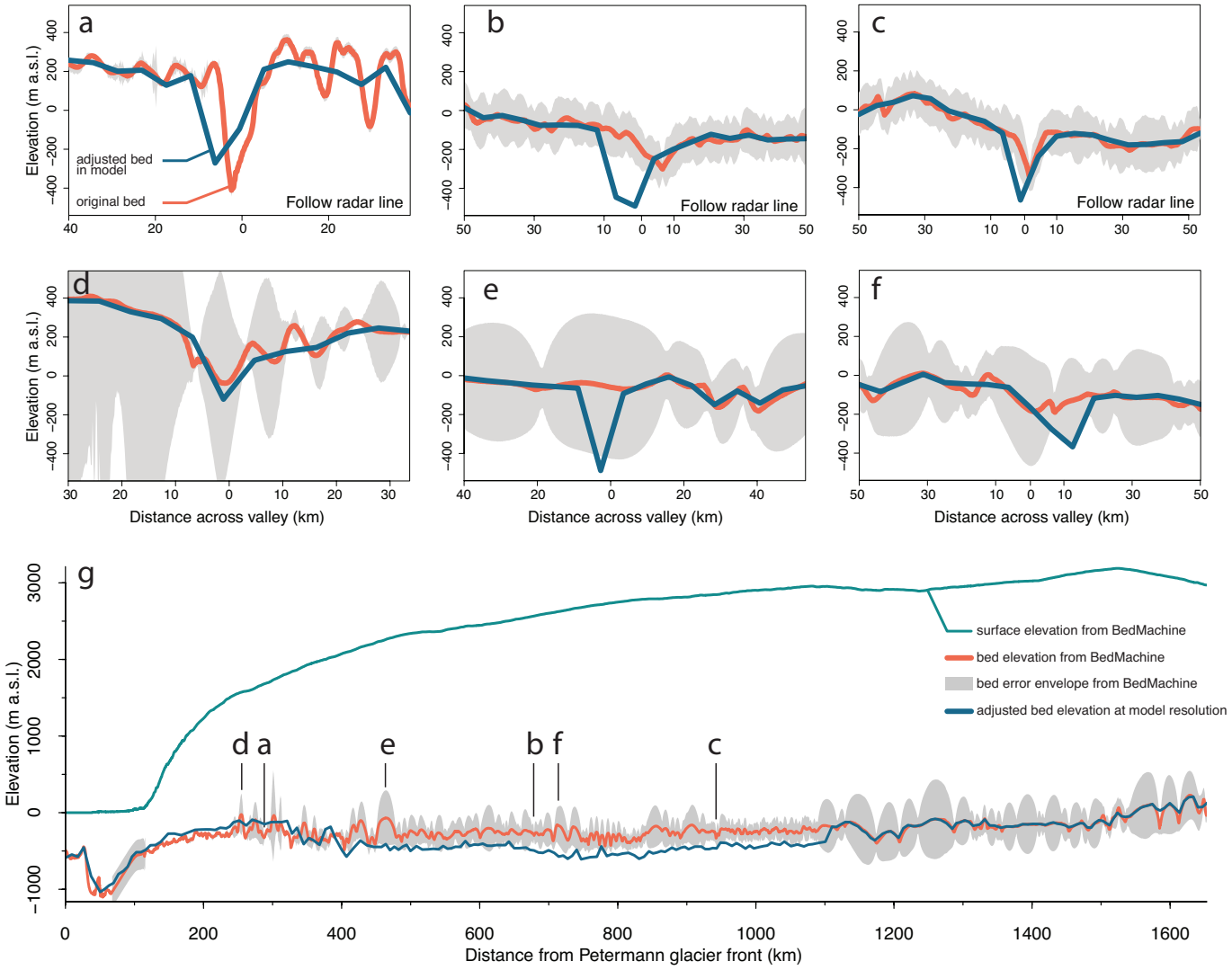

Figure A2. Across (a-f) and along (g) valley profiles from BedMachine v3 bed topography (Morlighem et al., 2017) and the adjusted bed elevation used in our model. The error envelope is derived from error estimates provided in BedMachine. Reduction in error depends on the proximity to radar data as shown 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~~ km in g).

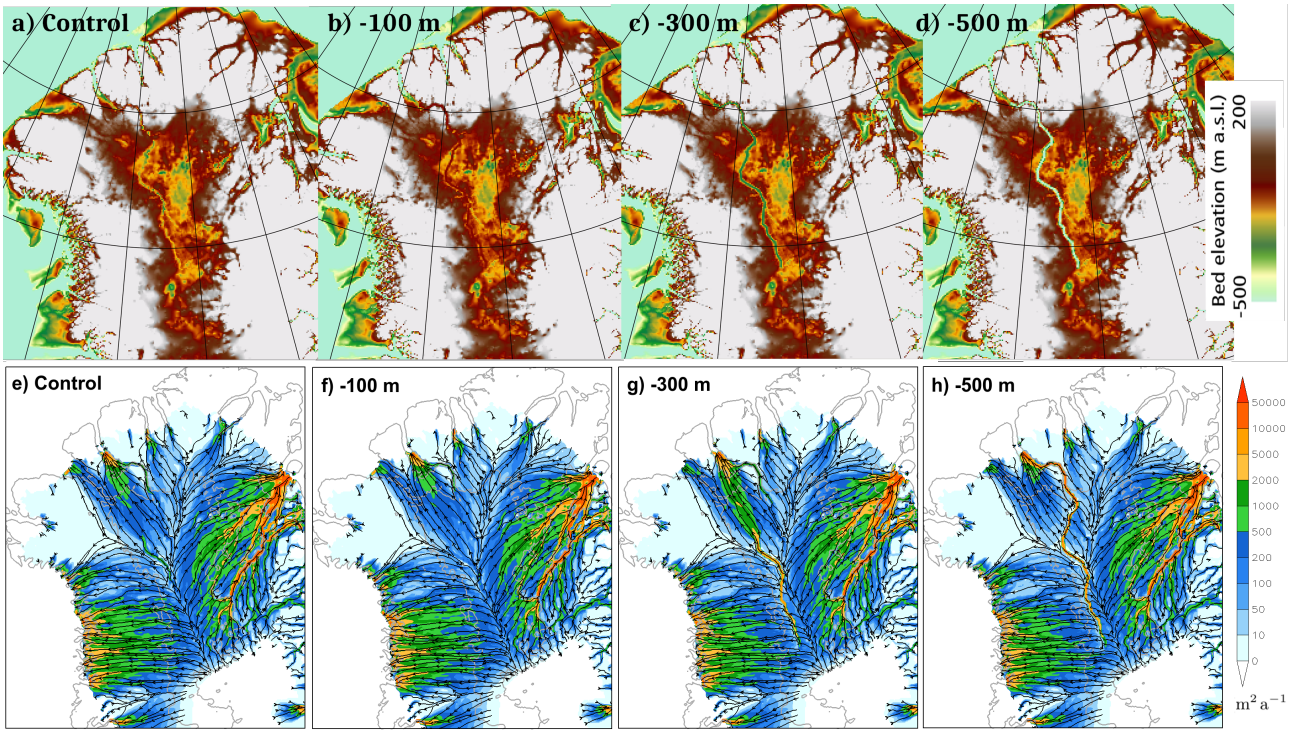

Figure A3. Sensitivity to valley depth tests. Bed topography (m) for a) Control, and for fixed valley base elevations (relative to sea level) of b) ~~-100 m~~ −100 m, c) ~~-300 m~~ −300 m, and d) ~~-500 m~~ −500 m. Basal water flux magnitude (~~$m^2 a^{-1}$~~ $m^2 a^{-1}$ colours) and streamlines for north Greenland for e) Control, f) ~~-100 m~~ −100 m, g) ~~-300 m~~ −300 m, and h) ~~-500 m~~ −500 m.