Response to Reviewers

December X, 2019

General response

Our thanks to Nicholas Holschuh and Signe Hillerup Larsen, your suggestions greatly improved the manuscript. We are grateful for your insights in both observations and modelling of NEGIS. The major changes to the manuscript are outlined here:

- We scaled down the misleading language in our statements, included an extended caveat section in the discussion. We also modified the abstract to underlining that this is model results, and the conclusion now includes model caveats and uncertainties. With a more detailed abstract and conclusion including model assumptions, we avoid being too conclusive, and allowing the reader to think critically about the numbers presented For this reason, we would like to keep the title as is.

- We have provided more detail on the comparisons to previous studies throughout the manuscript, following your suggestions. In addition, we included a figure of the gridded melt dataset from MacGregor et al. 2016, interpolated onto our model mesh. This allows for an improved an more direct comparison, as this was unclear in our previous manuscript. We also carefully restructured the section comparing our geothermal heat flux results to previous findings in the discussion, to clearly state how unrealistic high the value presented here is.

- We included a new equation on the viscosity

- Following recommendations from Irina Rogozhina during Smith-Johnsens PhD defence and discussion therein, we have decided to make some additional changes regarding terminology. We explain our high values (970 mW/m^2) by advective heat transport (hydrothermal circulation) and the term "geothermal heat flux" is incorrect, as it only comprises pure conductive heat transfer. We removed 'geothermal' from the title, and expanded the abstract, discussion on and conclusion to include this.

On behalf of the authors,
Silje Smith-Johnsen (PhD)

RC1: Nicholas Holschuh

Comment

In addition, I am curious about the other output fields of the model. For any model that relies on a substantial basal melt anomaly, I think it is important to show the surface elevation field that is produced. If there is a measurable surface depression at the site of the plume according to the model, that would highlight an important source of disagreement between model and data, as there is no surface depression at the onset of NEGIS. It is likely that the radar methods of Fahnestock and MacGregor overestimate the actual basal melt rates at NEGIS –if similar melt rates applied in this model produce a surface profile much different than the real NEGIS, that must be presented. Regardless, it is impressive that the flow-speed pattern can be explained by large volumes of basal melt, but a fuller comparison of model and data will help the reader understand if it does explain the flow-speed pattern.

Response

We agree that this is an interesting point to investigate and we looked at the model surface of Ctrl and plume970 and compared to observations (Scambos and Haram 2002). We found that our Ctrl simulation underestimates the surface elevation over the model domain. To disentangle the surface lowering caused directly by introducing the plume, we investigated surface differences between the plume970 and the Ctrl simulation. We found that there is no evidence of a local surface depression above the plume. We do observe a regional surface lowering of the entire domain upstream of the plume, and a slight thickening downstream (and hence the surface becomes closer to the observed surface in the downstream area).

These findings are in line with previous idealized experiments we have conducted where we found that the plume melts the above lying ice creating an local depression, if no subglacial hydrology model is included. However if one do include a subglacial hydrology model like this study, the ice is allowed to slides in response to the extra water added at the base. the surface signal of the plume becomes more regionally disperse due to both effective pressure changes and most importantly the advection of ice downstream redistribute the surface signal. To investigate if this is the case for a NEGIS model too, we launched a simulation with effective pressure from the Ctrl and the geothermal heat and thus basal melt rates from the plume970. In this set-up the ice dynamics only responds due to thermal changes, not basal sliding. The resulting surface expression above the plume display a deep local depression, and is this strikingly different from our 970plume experiment in the manuscript.

The lack a surface signal from the local plume in our model thus agrees with observations. In addition we would like to state that our basal melt rate estimate (100 mm/yr) for the plume970, falls between the values from preliminary radar estimates for EastGRIP presented at the NEGIS consortium meeting in Copenhagen (!!waiting for numbers from Dorthe and Angelika!!)

Comment

Line#: 10-11

This statement, in isolation, is too strong. It should include something like "Within our model experiment, a minimum heat flux value ... was required to reproduce observed NEGIS velocities.

Response

Thanks, done

Comment

Line #: 22

"information that is needed"

Response

Thanks, done

Comment

Line #: 30-32

One thing that we found in a modeling study of NEGIS we performed was that the shear margins are likely characterized by a complex velocity and viscosity structure. What did you do for your viscosity initialization in this model? Does it evolve with ice temperature? I am not trying to imply it needs to be cited here, but you may find some of the results from our study interesting and relevant: Holschuh, N., Lilien, D., and Christianson, K. (2019). Thermal Weakening, Convergent Flow, and Vertical Heat Transport in the Northeast Greenland Ice Stream Shear Margins. Geophysical Research Letters, 46, 8184–8193. https://doi.org/https://doi.org/10.1029/2019GL083436

Response

Yes, ice viscosity is temperature dependant, and evolves trough time with changes in temperature. This is now included in equation 2 in the ice sheet model description, LXX. For temperature we initialize with prescribed surface temperatures, and the basal boundary condition, we run a thermal steady state. No climatological spin-up is used, and therefore the overall thermal state may be too warm. We also use the 3D Higher-Order approximation to compute vertical velocities, important in the shear margins. As stated by the reviewer Signe Hillerup Larsen, we have a rather coarse mesh in the shear margins an may thus underestimate the strain heating that occuring here. We included a caveat section on how this may influence our results in the discussion (LXX).

Comment

Line#: 40

Unless there is extraordinary need, you should not cite work in review. It makes it impossible for a reader to evaluate this statement, as it has not been vetted by the peer review process.

Response

Thank you, we removed the Smith-Johnsen et al. A as this is still in review. We chose to keep the Smith-Johnsen et al. B, as it manuscript is now accepted.

Comment

Line#: 43-44

Again, I would remove references to papers in review. Without more context, I cannot tell what this sentence means, and I cannot evaluate the claim. What do you mean by uncertainty in the ice flux, our observations of ice thickness and velocity near the grounding-line are quite good?

Response

In this paper we show how uncertainties in model inputs (GHF) propagate through the ice flow model and cause a large range of modelled mass (ice) flux through NEGIS, and therefore large uncertainties. This is relevant for future predications, as we don't have observations.

Comment

Line#: 47

This paragraph should include the statement that you make in line 221-224, making very clear to the reader you do not think a mantle plume is presently beneath NEGIS. You are simply using a plume model to generate feasible scenarios that can be tested with the model.Without the sentence at 221, It would be easy to walk away from this paper thinking you believe there is a mantle plume presently under NEGIS (which would require substantially more evidence to justify).

Response

Thank you this is a good point and we agree. We have changed this paragraph accordingly by including this statement earlier in the paper, LXX, and removed it from the discussion.

Comment

Line#: 55

How was the model changed from Schlegel to the in review paper? If you are including those modifications here, it is important that the reader know what they are, but they cannot be determined as the paper referenced is not published. This is a case where an in review citation may be acceptable, but you need to include the salient details from the paper in the text here.

Response

Thank you for pointing this out to us. The most important change is that the thermomechanical ice flow model is coupled to a subglacial hydrology model. We changed the sentence to include this, and keep the reference to the Smith-Johnsen et al. paper, as it is now accepted.

Comment

Line#: 58

Could you provide justification for your choice in sliding law here?

Response

This is the most commonly sliding law used in ISSM. It was used by Schlegel et al. 2015 and Smith-Johnsen et al. accepted, so to avoid a complete new model set-up with following spin-up, we decided to keep it. Instead of justifying the choice of sliding law here, we included a discussion on the implications of using this in the new caveat section of the discussion (LXX).

Comment

Line#: 87-88

This statement does not agree with the seismic results collected at the onset of NEGIS, where there was no apparent relationship between topography and till strength. You should reference whether or not this argument is observationally substantiated. It would be helpful to include discussion here from Christianson et al: Christianson, K., Peters, L. E., Alley, R. B., Anandakrishnan, S., Jacobel, R. W., Riverman, K. L., ... Keisling, B. A. (2014). Dilatant till facilitates ice-stream flow in northeast Greenland. Earth and Planetary Science Letters, 401, 57–69. https://doi.org/10.1016/j.epsl.2014.05.060

Response

Thank you for this reference. We do compare our friction coefficient distribution to roughness observations in line X. The friction coefficient includes everything unknown at the bed, in addition to till strength. We are aware of the limitations by using this very crude and simple approach for the friction coefficient, and have included the this in the new caveat section in the discussion.

Comment

Line#: 101

The plumes discussed here are not very consistent with MacGregor et al 2016, who find large areas of basal melt (> 100km x 100km) well upstream of NEGIS. I think the agreement between Fahnestock and MacGregor throughout the manuscript is generally overstated.

Response

We tried to explain that the plumes here compares well to the northeastern branch of the anomaly of MacGregor et al 2016. We have made this clearer by removing the references to figures within this paper, and instead included a plot of the MacGregor gridded dataset for our model domain in a new figure (X). Hopefully this will improve the understanding of the reader, and allow for a more direct comparison of the basal melt rates from our 970plume to the dataset.

Overall in the paper we have modified the comparison of the GHF and basal melt to previous studies, by providing more details for each comparisons.

Comment

Line#: 137

Clarify what you mean here, Fahnestock and MacGregor did not have identical results.

Response

Thank you, we mean the maximum magnitude of geothermal heat flux (970 mW/m^2) proposed by Fahnestock et al. We have clarified this, and we removed the MacGregor reference.

Comment

Line#: 163-164

Here is an example of potentially misleading language –you show the elevated heat required by your model to initiate NEGIS. Much less heat may be required if the bed were uniformly weaker, if you included fabric evolution or imposed viscosity transitions, if the water transmissivity at the bed were lower, etc. All of the values you provide are contingent on the physical processes included in the model, the assumptions about the flow law form and parameters, and the experimental design.

Response

Thank you, we toned down the statement by writing "indicate" in stead of "show", and we included "in our model". In addition, we have included a caveat section in the discussion where we provide several reasons for why we may overestimate the geothermal heat of the plume, due to model uncertainties and assumptions (friction law, shear margin softening, subglacial hydrology parameters).

However, if the bed were uniformly weaker the entire domain would speed up, resulting in an even lower surface, and increase the underestimation of ice thickness. In addition, the outlet glaciers are too fast in our model, and a uniformly weaker bed would intensify the problem. We agree that this is a very crude estimate of basal friction, and we also included this in the caveat section in the discussion.

Comment

Line#: 168
"metshould be "melt"

Response

Thanks, done

Comment

Line#: 173-174
This shows that plumes with a restricted extent, 50km x 50km, produce model results more consistent with the observed flow behavior in the upstream reaches of NEGIS.-something that clarifies that this is not a necessary condition for NEGIS.

Response

Thanks, done

Comment

Line#: 197-198
Perhaps change this sentence to read the geothermal heat flux needed to induce the observed upstream velocity of NEGIS in our model is 970, consistent with values presented in Fahnestock et al. (2001)."What you are stating here (and in your next sentence) is essentially "high melt water production rates are required to drive fast flow in the upstream regions of NEGIS, assuming the absence of other variations in bed strength driven by substrate heterogeneity". I think that last caveat is important to make here and elsewhere in the paper; you are forcing all of the variation to be driven by hydrology, but it need not be the only property that varies in space.

Response

We agree, and changed the sentence to what you suggested. However, your next statement is not exactly true, as our friction coefficient is spatially varying not uniform, and represents everything that varies at the base. We show the importance of spatially varying bed properties, by running two simulations where we have a spatially uniform friction coefficient (simulation “Uni Ctrl” and “Uni 970”) where the velocity pattern is less confined and less similar to observations.

Thank you, we agree that it is important to state, that we keep everything constant in our model and only vary GHF, and try to explain the observed velocities by hydrology only despite many model assumptions and uncertainties. We stated this at the beginning of the new caveat section in the discussion, LXX.

Comment

Line#: 211-212

The comparison with Jarosch and Gudmundsson (2007) here seems odd, as they apply their geothermal flux anomaly over 500m. No one would argue that their anomaly could exist at the scale of your plume. However, their results do highlight something that I think you should present to your reader –substantial melt anomalies manifest in the ice sheet surface. I imagine the ice sheet surface in your models has a similar (albeit smaller)melt featureas the one in Jarosch and Gudmundsson. If so, somewhere in this work you should state that localized, substantial melt under NEGIS would be visible at the ice sheet surface, but is not apparent in altimetry data. Any discrepancy (or, if present, agreement) in the effect of basal melt on the ice surface profile must be discussed.

Response

Thank you, we agree and have removed this reference. In addition, Iceland is generally not a representative comparison as it is situated on a mantle plume and a spreading ridge, thus an extreme geothermal heat flux example. This is a very interesting topic. As mentioned earlier, by comparing the plume970 simulation to the Ctrl, to disentangle the direct impact of the plume, we do not see a significant local surface depression. We think this is due to the hydrology might disperse the signal, and most importantly the advection of ice redistributes and dampens the surface signal. However, we think the case would be different if the ice above the local plume was not sliding. It would be interesting to test our plume in an areas where a local mantle plume would not trigger fast flow, only local melt, to see if the surface expression would look different.

Comment

Line#: 218-219

This seems to imply that your results differ because you are fitting to velocities instead of temperatures, but that is not the primary factor. Greve has no constraints near the onset of NEGIS, while your study does. If the anomaly you argue for existed, Greve would have no way of knowing with the data he has available. Greve's data set is actually a much more direct measure of geothermal flux–if he had broader observational coverage it would be hard to argue with his results.

Response

This is true and a good point, and we removed this reasoning from the paper. We compare our GHF values to the highest estimate of Greve, and clearly state that this is from NGRIP. We have restructured this entire section and the following section to be more reader friendly.

Comment

Line#: 221-223

As stated earlier, this sentence should come much sooner in the paper. Without additional data, we have no means of explaining why there might be a heat flux anomaly at NEGIS, and it is not likely a modern plume.

Response

Thank you, as indicated earlier, we moved this sentence to the introduction LXX.

Comment

Line#: 227-228

MacGregor et al. have abnormally high melt rates in several places in Greenland, including over a broad region upstream of NEGIS and in SW Greenland. This citation here seems inconsistent with the statement made.

Response

Thank you, we removed the statement as it did not contribute to the section. We did, as mentioned, include a plot of the melt anomaly by MacGregor (Fig 6) for an improved, direct comparison of both magnitude and spatial extent.

Comment

Line#: 273-277

A broader discussion of the role of the friction law would be useful. What if you used a non-linear sliding law? What direction would that change your results? It would be useful for the reader to understand how the plume characteristics you describe would need to vary to reproduce NEGIS using arange of different model set-ups.

Response

Yes this is a caveat of our model set-up, and after your recommendation we extended the discussion of the linear friction law in the new caveat section of the discussion (LXX). We agree that the plume would change given a different model setup, and this is discussed in more detail in section starting at LXX.

Comment

Line#: 290

"confirms previous studies"is too strong. "is consistent with"would be better

Response

Thank you, we changed this to your suggestion.

RC2: Signe Hillerup Larsen

Comment

1. Structure of method and result section: a) The storyline in the experiment and result section does not match. In the results section the focus is on the study testing the hypothesis of the existence of a geothermal heat flux anomaly of 970 mW/m2. The rest of the experiments are described as sensitivity studies to this main hypothesis. This is not the story line in the experiment section.

Response

Thank you for noticing this, we have changed the storyline in the experiment section to match the one in the results. More specifically we removed the range of GHF in the sensitivity studies in the beginning of the experiment section. The storyline in the experiment section is now the following, first we present the 970 plume experiment, explain why we need a Ctrl, and finally we present the sensitivity simulations and explain the purpose of them. In the results we start with the Ctrl in order to explain the background values for all the simulations.

Comment

2. Results section: a) Presentation of results: I think it's a good idea to use the 50 m/yr contour to compare results. Maybe add some meta text in the beginning explaining that this is your approach and if possible add the observed contour line on all result plots for comparison?

Response

Good suggestion, we added a description of how we evaluate the performance of each model simulation using these contours in LXX. We agree, and originally tried to include both modeled and observed velocity contour in the results plot. However it was messy and too much information in one plot. We therefore decided with showing observed on the results apart from the velocity where we plotted modeled velocity contour.

Comment

b) In the first paragraph of the results section the Ctrl simulation is described as a way to obtain the basal melt rate, and then in the same paragraph the resulting velocity field is explained. I find this a bit confusing. Maybe just stick to the explanation about the velocity field, because the method to obtain N is already described in the methods section.

Response

Thank you expressing this, we removed the methods part and hope it is less confusing now. In fact, we removed all the part of this section concerning methods to avoid unnecessarily repetition.

Comment

3. Discussion section:
a) the discussion is purely focussed on the ice/bed interface, but I am wondering about how the resulting flow pattern depends on uncertainties within the ice such as viscosity and the fact that shear margins are not resolved by the 15km grid. Thus a short discussion of ice viscosity, shear margins and model resolution should in my opinion be included.

Response

Thank you, this is very good point that we did not include originally. We added a caveat section where we discuss how we could obtain similar high velocity as 970 experiment, by changing other parameters in the model and then getting away with lower geothermal heat flux values. In LXX we discuss the softening of shear margins and how we may overestimate the lateral drag. Thank you for this suggestion.

Comment

b) The aim is to have a model that is independent of present day observations. This is not strictly met in the way N is obtained, which is clearly explained. However, the bedmap is also based on modelling using present day velocity observations, which could bias the results, this makes the basal friction coefficient relate to observed velocities in a more diffuse way. This should also be mentioned somewhere.

Response

Thank you, we agree. We included this caveat in LXX .

Comment

4. Conclusions: a) Conclusions appear a bit too conclusive, and the authors should make an effort to make it clearer that they are aware that this is a relatively simple test of the hypothesis that a geothermal heat flux anomaly could explain the onset of NEGIS.

Response

We modified the conclusion and added a sentence on model caveats, allowing the reader to understand how the number presented is dependent on model uncertainties (LXX). As explained above we added a section in the discussion where we suggest other ways we could trigger fast flow of NEGIS in our model, apart from the geothermal heat flux.

Comment

Line#: 60-65
Effective pressure is defined in words twice.

Response

Thank you, we fixed that.

Comment

Line#: 153-154
The last sentence of the paragraph makes it sound a bit like that the 970 mW/m^2 experiment represents reality. Maybe just explain how the ice stream signature becomes weaker with lower forcing.

Response

Thanks, we toned down and included 'given our model set-up' in this statement.

Comment

Line#: 199
I am wondering if the width of the modelled ice stream could be related to model underestimating viscosity?

Response

This is very good point, and may explain the more diffuse modelled velocity pattern and lack of sharp gradients in the shear margins. We added your suggestion about width in the shear margin viscosity discussion, LXX, thanks.

Comment

Line#: 212-213
The sentence starting with: 970 mW/m^2 is only...should be moved to methods section.

Response

We agree that it is too late to include here. We find it more a result than a method, as this is computed by the plume model and not prescribed. We removed this statement from the discussion, as it is not important. We generally restructured the section in the discussion where we compare our findings to previous studies, and try to better explain why our values are so high.

Comment

Line#: 222
Maybe refer to Martos et al, 2018 or other paper that describes the continental passage over the Icelandic hotspot. This information should probably be included inthe introduction or methods section.

Response

Thank you, we agree and we moved this statement to the introduction (LXX). And for the high background geothermal heat flux due to Iceland plume we refer to Rogozhina et al. 2016 and Martos et al. 2018 (LXX) and it is also included in introduction (LXX).

Comment

Line#: 281 By inverting for basal friction you not only create a basal friction map that cannot evolve in time, you also place all uncertainty from the model viscosity for example in the basal friction map.

Response

Yes this is true, everything uncertain in the model is blamed on the spatially varying 'bed properties'.

Comment

Figure 1:
Include the place names used in the text e.g. Storstrømmen and Zachariæ.

Response

Great suggestion, we included this in Figure 1c, where we introduce EGRIP and the model domain.

Comment

> Figure 2, 3, 4 and 5:
> Maybe show the observed (white) 50 m/yr contour in all the velocity plots where only the modelled contour is shown.

Response

As stated above, we originally tried this, but it looked so we avoided this.

Comment

> References:
> The reference to the Fox Maule paper or data is incomplete.

Response

Well spotted, we included journal volume and pages in this reference, thank you.

Exceptionally High ~~Geothermal~~ Heat Flux Needed to Sustain the Northeast Greenland Ice Stream

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Abstract. The Northeast Greenland Ice Stream (NEGIS) currently drains more than ~~10~~10 % of the Greenland Ice Sheet area, and has recently undergone significant dynamic changes. It is therefore critical to accurately represent this feature when assessing the future contribution of Greenland to sea level rise. At present, NEGIS is reproduced in ice sheet models by inferring basal conditions using observed surface velocities. This approach helps estimate conditions at the base of the ice sheet, but cannot be used to estimate the evolution of basal drag in time, so it is not a good representation of the evolution of the ice sheet in future climate warming scenarios. NEGIS is suggested to be initiated by a geothermal heat flux anomaly close to the ice divide, left behind by the movement of Greenland over the Icelandic plume. However, the heat flux underneath the ice sheet is largely unknown, except for a few direct measurements from deep ice core drill sites. Using the Ice Sheet System Model (ISSM), with ice dynamics coupled to a subglacial hydrology model, we investigate the possibility of initiating NEGIS by inserting ~~hotspots~~ heat flux anomalies with various locations and intensities. ~~We find that a minimum geothermal~~ In our model experiment, a minimum heat flux value of ~~970 mW/m^2~~ 970 mW m^{-2} located close to ~~EastGRIP~~ The East Greenland Ice-core Project (EGRIP) is required locally to reproduce the observed NEGIS velocities, giving basal melt rates consistent with previous estimates. The value cannot be attributed to geothermal heat flux alone and we suggest hydrothermal circulation as a potential explanation for the high local heat flux. By including high ~~geothermal~~ heat flux and the effect of water on sliding, we successfully reproduce the main characteristics of NEGIS in an ice sheet model without using data assimilation.

1 Introduction

The Greenland Ice Sheet (GrIS) displays large spatial variations in surface velocity, with a few fast-flowing outlets draining most of the interior (Rignot and Mouginot, 2012). It is therefore critical to capture the complex flow pattern of GrIS in models used for future sea level projections. Recent developments in ice sheet models such as efficient parallel computation (Khroulev and PISM-Authors, 2015), better representation of flow equations (Larour et al., 2012), detailed basal topography (Morlighem et al., 2014) and the inclusion of subglacial hydrology have contributed to greatly improve the representation of this spatially varying flow (Aschwanden et al., 2016). In addition to these advances, inversion for basal friction using surface velocities has proved to be a powerful tool (Morlighem et al., 2013), and models are now able to capture most of the complex flow pattern of the ice sheet. Inversions are useful to capture present day velocity, but mask information that ~~are~~ is needed to evolve these conditions in time. Therefore, we cannot fully rely on inversions for future projections, as basal conditions may evolve as a result of a changing climate and in turn influence ice dynamics.

The Northeast Greenland Ice Stream (NEGIS) drains more than ~~10~~ 10 % of GrIS and is exceptional by displaying high velocities all the way to the ice divide (Rignot and Mouginot, 2012). Despite its large impact on the GrIS mass balance, NEGIS is not accurately represented in ice sheet models without inverting for basal friction (Goelzer et al., 2018). Aschwanden et al. (2016) simulated NEGIS in the Parallel Ice Sheet Model, capturing high velocities using a simple hydrology model, however, lacking the far inland onset of the ice stream. Beyer et al. (2018) used the basal melt rates from the model by Aschwanden et al. (2016) in a more sophisticated hydrology model to reproduce NEGIS in the Ice Sheet System Model (ISSM). They capture the high velocity flow of the outlets well, but the representation of the transition areas outside of the main trunk are more diffuse compared to the observed values. These studies illustrate how we are getting closer to reproducing present day NEGIS in ice sheet models. However, the characteristic clearly defined shear margins and high velocities upstream at the onset of the ice stream are still lacking.

To understand why high upstream velocities are not reproduced in models, one must look into how the ice stream is initiated. The origin of NEGIS has been explained by a geothermal heat flux (GHF) anomaly left behind by the passage of the Icelandic plume (Fahnestock et al., 2001; Rogozhina et al., 2016; Martos et al., 2018; Alley et al., 2019). Interpretation of radar data points to unusually high basal melt rates at the head of the ice stream, corresponding to an exceptionally high geothermal heat flux of ~~970 mW/m^2 (Fahnestock et al., 2001; Macgregor et al., 2016; Alley et al., 2019)~~970 $\mathrm{mW\,m^{-2}}$ (Fahnestock et al., 2001; Macgregor et al., 2016; Alley et al., 2019; Keisling et al., 2014). A local increase in GHF intensifies basal water production and potentially enhances basal sliding~~(?)~~. Unfortunately, geothermal heat flux maps for Greenland display a large spread of values (Rogozhina et al., 2012; Shapiro and Ritzwoller, 2004; Fox Maule et al., 2009; Martos et al., 2018; Rogozhina et al., 2016; Greve, 2019). These large uncertainties in the estimates of the GHF have been shown to dominate the uncertainty on the ice flux in this region ~~(?)~~(Smith-Johnsen et al., 2019). In addition, the GHF maps are coarse and may not capture local anomalies like the one suggested to exist at the head of NEGIS (Fahnestock et al., 2001; Macgregor et al., 2016; Alley et al., 2019). Accurately capturing such a feature and explicitly representing the effect of high melt rates on basal sliding, is key to reproduce the distinct velocity pattern of NEGIS in ice sheet models.

Here, we study the impact of the presence and intensity of a mantle plume, at the head of NEGIS on the ice flow structure. We do not suggest the presence of a mantle plume, but rather use an existing mantle plume plume model to generate feasible GHF scenarios in the model sensitivity study. We use a sophisticated hydrology model (de Fleurian et al., 2014, 2016) coupled to ice dynamics in the Ice Sheet System Model (ISSM; Larour et al., 2012) to capture the influence of enhanced basal melt on ice dynamics. We first describe the models and different plume experiments. Finally, we present and discuss resulting basal conditions and surface velocities corresponding to the various plume configurations.

Table 1. Definitions and values of variables in the subglacial hydrology model

Description	Unit	Value
effective pressure	~~*Pa*~~ Pa	
compressibility of water	~~Pa^{-1}~~ Pa^{-1}	~~5.04e-10~~ 5.04×10^{-10}
leakage factor	~~*m*~~ m	~~1e-09~~ 1×10^{-9}
inefficient compressibility	~~Pa^{-1}~~ Pa^{-1}	~~1e-08~~ 1×10^{-8}
inefficient porosity	-	~~0.4~~ 0.4
inefficient thickness	~~*m*~~ m	~~20~~ 20
inefficient transmitivity	~~m^2/s~~ $\mathrm{m}^2\,\mathrm{s}^{-1}$	~~0.002~~ 0.002
efficient compressibility	~~Pa^{-1}~~ Pa^{-1}	~~1e-08~~ 1×10^{-8}
efficient porosity	-	~~0.4~~ 0.4
efficient initial thickness	~~*m*~~ m	~~0.005~~ 0.005
efficient collapsing thickness	~~*m*~~ m	~~8e-05~~ 8×10^{-5}
efficient maximal thickness	~~*m*~~ m	~~5~~ 5
efficient conductivity	~~m^2/s~~ $\mathrm{m}^2\,\mathrm{s}^{-1}$	~~25~~ 25

2 Methods

2.1 Ice Flow Model

To simulate the NEGIS ice flow, we apply the model configuration from Schlegel et al. (2013, 2015) further developed and ~~adapted by (?)~~ coupled to a subglacial hydrology model by (Smith-Johnsen et al., 2019). We use the Ice Sheet System Model (Larour et al., 2012), a 3D thermomechanical ice flow model, and explicitly represent the effect of high melt rates on subglacial hydrology (de Fleurian et al., 2014, 2016), which provides the effective pressure (N, the difference between ice overburden pressure and water pressure at the bed) that controls basal sliding through a linear friction law (Cuffey and Paterson, 2010):

$$\tau_b = -\alpha^2 N \mathbf{v}_b, \tag{1}$$

where τ_b is the basal drag, α basal friction coefficient ~~, N effective pressure,~~ and $\mathbf{v}_b$ the basal velocity. The hydrology model takes the basal melt rates as input, and computes the effective pressure. Nodes with no basal melt are given an effective pressure equal to the ice overburden pressure. The hydrology model consists of two porous sediment layers, representing the inefficient and efficient drainage system. The efficient drainage system is activated when N reaches zero, and may be deactivated as the water is evacuated and N increases again. Definitions and values of variables in the subglacial hydrology model are given in Table 1. The hydrology model and its implementation in ISSM are described in detail in de Fleurian et al. (2014, 2016).

For the thermal model we rely on the enthalpy formulation by Aschwanden et al. (2012), implemented in ISSM (Seroussi et al., 2013) with surface temperatures from Ettema et al. (2009) and geothermal heat flux from Fox Maule et al. (2009). In addition we use a mantle plume module in ISSM to create elevated geothermal heat flux anomalies (Seroussi et al., 2017). Ice

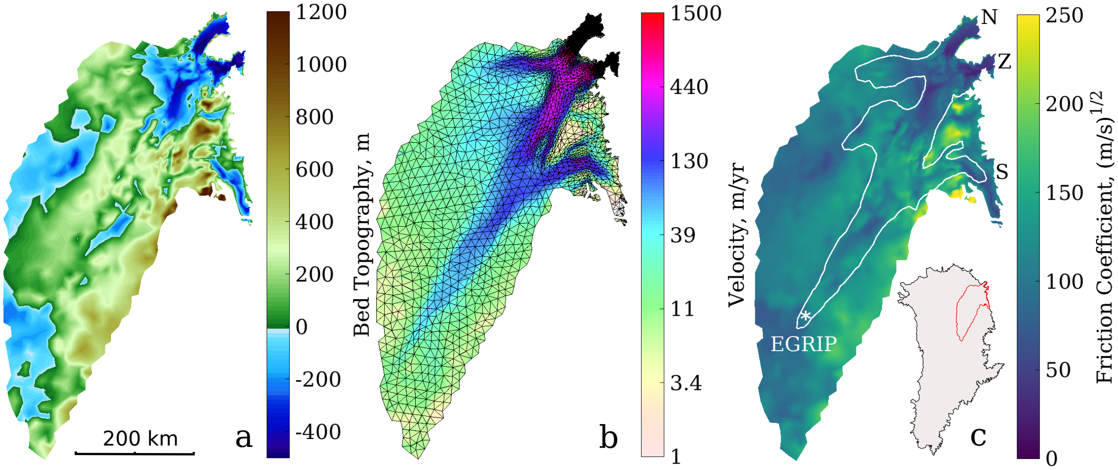

Figure 1. (a) bed topography from BedMachine (Morlighem et al., 2014) interpolated onto the model mesh, (b) InSAR-derived surface velocities (Rignot and Mouginot, 2012) and anisotropic model mesh refined in areas with high velocity gradients, (c) friction coefficient as a linear function of bed topography (Eq. 3) used in Eq. 1. The white contour shows the area of the NEGIS with observed surface velocity of ~~50~~ 50 m~~/~~ yr^{-1} and the star shows the position of the East Greenland Ice-Core Project (EGRIP). N, Z and S indicate the outlets of the ice stream; 79N, Zachariæ and Storstrømmen respectively. The inset map in the lower right corner shows Greenland with the model domain outlined in red.

is treated as a purely viscous incompressible material (Cuffey and Paterson, 2010), with viscosity, μ, defined as:

$$\mu = \frac{B}{2\dot{\epsilon}_e^{\frac{n-1}{n}}}, \tag{2}$$

where B is the temperature dependent ice hardness varying with depth, n is Glen's flow law exponent and $\dot{\epsilon}_e$ is the effective strain rate.

Basal topography is from BedMachine (Morlighem et al., 2014) (Figure 1a) and we apply submarine melt rates under the floating ice (Rignot et al., 2001). For the stress balance equation, we use a 3D Higher-Order approximation (Pattyn, 2003). Our model domain consists of 9974 horizontal elements, ranging from 1 km in areas with high velocity gradients to a maximum of 15 km at the ice divide (Figure 1b). We use linear P1 elements to solve the stress balance equations and quadratic P2 elements for the thermal analysis, in order to capture sharp temperature gradients, despite using only ~~5~~ five layers (Cuzzone et al., 2018).

We aim to represent the observed NEGIS velocity pattern in an ice sheet model without inverting for the basal friction coefficient. However, to initialize the hydrology model, we do simulate the present day ice stream by inferring basal friction from present-day velocities (Figure 1b). The basal melt rates from this simulation are used to initialize the subglacial hydrology model, which we run for ~~150~~ 150 years in order to reach an equilibrium in terms of water pressure. The resulting effective pressure field computed by the hydrology model, N, is used in the friction law (Eq.1), and kept constant in time. Finally, we run a ~~4~~ 4 kyr simulation with the basal condition generated by the hydrology model to provide steady state surface velocities.

Table 2. Mantle Plume parameter overview for the plume experiments

Parameter	Description	Value	Unit
mantleconductivity	mantle heat conductivity	2.5	~~W/m^3~~ $\mathrm{W\,m^{-3}}$
nusselt	nusselt number, ratio of mantle to plume	500000	
dtbg	background temperature gradient	0.013	~~$degree/m$~~ degree $\mathrm{m^{-1}}$
plumeradius	radius of the mantle plume	varying	~~m~~ m
topplumedepth	depth of the mantle plume top below the crust	5000	~~m~~ m
bottomplumedepth	depth of the mantle plume base below the crust	varying	~~km~~ km
crustthickness	thickness of the crust	1	~~m~~ m
uppercrustthickness	thickness of the upper crust	1	~~m~~ m
uppercrustheat	volumic heat of the upper crust	~~$1.33e-06$~~ 1.33×10^{-6}	~~W/m^3~~ $\mathrm{W\,m^{-3}}$
lowercrustheat	volumic heat of the lower crust	~~$2.7e-07$~~ 2.7×10^{-7}	~~W/m^3~~ $\mathrm{W\,m^{-3}}$

Note that we do not use the friction coefficient, α, from the inversion in the forward ice flow simulation, as it is only used to initialize the subglacial hydrology model.

Previous modelling studies lack sharp velocity gradients defining NEGIS (Aschwanden et al., 2016; Beyer et al., 2018). To capture this we let the basal friction coefficient, α, depend linearly on the bed elevation using the following equation:

$$\alpha = \cancel{min}\,\mathrm{min}(\cancel{max}\,\mathrm{max}(1, 0.13\cancel{*bed}\times bed + 100), 250), \qquad (3)$$

where ~~$100\ (m/s)^{1/2}$~~ $100\,(\mathrm{m\,s^{-1}})^{1/2}$ is the mean value of the inversion alpha used in ~~(?)~~ (Smith-Johnsen et al., 2019), and we cap the values between 1 and ~~$250\ (m/s)^{1/2}$. 0.13~~ $250\,(\mathrm{m\,s^{-1}})^{1/2}$. The factor 0.13 is tuned to approximately match the observed velocities at the grounding line of 79N. The resulting friction coefficient, α, is shown in Figure 1c. We argue that low lying topography will have more marine sediments, and thus a softer and less resistive bed, allowing high velocities of the outlet glaciers. A similar approach with basal shear stress defined as a function of bed elevation was previously used by Åkesson et al. (2018) and by Aschwanden et al. (2016). Our simple friction relationship is supported by observations, as bed topography roughness for the NEGIS region shows a pattern inversely correlated with bed elevation (Cooper et al., 2019).

2.2 Experiments

In order to capture the high upstream velocity of NEGIS, we alter the geothermal heat flux by simulating a ~~range of mantle plumes~~ mantle plume close to the head of the ice stream, at the onset of fast flow (Seroussi et al., 2017). The mantle plume module in ISSM computes the geothermal heat flux, given the plume parameters in Table 2~~, and the maximum GHF values range from 494 to 970 mW/m^2~~. To disentangle the effect of the mantle plume we run a Ctrl simulation without a mantle plume, using only the geothermal heat flux from Fox Maule et al. (2009). This GHF map is ranging from ~~40 mW/m^2~~

Table 3. Overview of mantle plume parameters, modelled GHF and friction parameters.

Simulation	Position	Radius (km)	Depth (km)	max GHF (~~mW/m^2~~ $\mathrm{mW\,m^{-2}}$)	α (~~$(m/s)^{1/2}$~~ $(\mathrm{m\,s^{-1}})^{1/2}$)	N (~~MPa~~ MPa)
Ctrl	no plume	no plume	no plume	no plume	varying	modelled
plume970	center	~~50~~ 50	~~5000~~ 5000	970	varying	modelled
plume677	center	~~50~~ 50	~~3000~~ 3000	677	varying	modelled
plume836	center	~~50~~ 50	~~4000~~ 4000	836	varying	modelled
plume909	center	~~50~~ 50	~~4500~~ 4500	909	varying	modelled
plume970SW	SW	~~50~~ 50	~~5000~~ 5000	970	varying	modelled
plume970SE	SE	~~50~~ 50	~~5000~~ 5000	970	varying	modelled
plume970NE	NE	~~50~~ 50	~~5000~~ 5000	970	varying	modelled
plume970NW	NW	~~50~~ 50	~~5000~~ 5000	970	varying	modelled
plume494	center	~~300~~ 300	~~3000~~ 3000	494	varying	modelled
plume594	center	~~200~~ 200	~~2500~~ 2500	594	varying	modelled
plume775	center	~~100~~ 100	~~2000~~ 2000	775	varying	modelled
plume792	center	~~200~~ 200	~~3000~~ 3000	792	varying	modelled
noHydro	no plume	no plume	no plume	no plume	varying	approximated
Ctrl-uni	no plume	no plume	no plume	no plume	90	modelled
plume970-uni	center	~~50~~ 50	~~5000~~ 5000	970	90	modelled

$40\,\mathrm{mW\,m^{-2}}$ in the north-west to ~~77 mW/m^2~~ $77\,\mathrm{mW\,m^{-2}}$ in the north-east below the Storstrømmen outlet, with an average value of ~~54 mW/m^2~~ $54\,\mathrm{mW\,m^{-2}}$.

In our main experiment, plume970, the plume parameters were chosen to generate a GHF anomaly coherent with the ~~one~~ magnitude of the GHF anomaly hypothesized by Fahnestock et al. (2001)~~and Macgregor et al. (2016)~~. The resulting GHF anomaly is ~~$\sim 50\ km$~~ $\sim 50\,\mathrm{km}$ in diameter with a maximum GHF value of ~~970 mW/m^2~~ $970\,\mathrm{mW\,m^{-2}}$ (Table 3), and we position it directly underneath the EGRIP deep ice core drilling site (Figure 1c).

To determine the minimum geothermal heat flux needed to initiate the onset of NEGIS close to the ice divide, we compute three alternative plume configurations with lower intensity. We obtain the lower geothermal heat flux by decreasing the bottom plume depth parameter to ~~4500, 4000 and 3000~~ 4500, 4000 and 3000 km for simulation plume909, plume836 and plume677, respectively (Table 3). Additionally, we compute four plume configurations where we change the position of the plume. We move the plume970 ~~75~~ 75 km to the south-west, south-east, north-east and north-west in the plume970SW, plume970SE, plume970NE, plume970NW experiments, respectively (Table 3). To investigate the influence of the area of the mantle plume, we compute four plume configurations with larger area, compensated for by a smaller heat flux. To obtain this we increase the plume radius to values of ~~100-300~~ 100–300 km, and decrease the bottom plume depth to values of ~~2000-3000~~ 2000–3000 km, resulting in the experiments plume494, plume594, plume775 and plume792 (Table 3).

Finally, to investigate the influence of our friction coefficient distribution, we run three additional simulations. First, we run a simulation without modelled effective pressure, but instead using effective pressure approximated to hydrostatic pressure, commonly used in ISSM (no Hydro, Table 3). Then we run two simulations with a uniform friction of ~~$\alpha = 90\ (m/s)^{1/2}$~~ $\alpha = 90\,(\mathrm{m\,s^{-1}})^{1/2}$; one without a plume (Ctrl-uni, Table 3) and one with the ~~$970\ mW/m^2$~~ $970\,\mathrm{mW\,m^{-2}}$ plume (plume970-uni, Table 3).

3 Results

In the Ctrl simulation we use the geothermal heat flux from Fox Maule et al. (2009) (Figure 2a), ~~with a value of 54 mW/m^2 at the onset of the ice stream. We run a steady state solution to retrieve the~~ and the corresponding basal melt rates ~~, as~~ are shown in Figure 2f. Melt rates at the head of the ice stream (at EGRIP) are ~~$1-2\ mm/yr$. The~~ 1–$2\,\mathrm{mm\,yr^{-1}}$, and the highest basal melt rates (~~$600\ mm/yr$~~ $600\,\mathrm{mm\,yr^{-1}}$) occur at the grounding line of Zachariæ, with surface velocities reaching 1500~~m/yr~~ $\mathrm{m\,yr^{-1}}$. Friction is the dominating heat source in the fast flowing regions, and melt rates thus increase with increasing velocities towards the grounding line. Low melt rates in regions with high velocity are due to low lying bed topography causing low basal drag and hence less frictional heat. The ~~melt rates serve as input to the subglacial hydrology model, and the computed effective pressure , N,~~ effective pressure for the Ctrl experiment is shown in Figure 2k~~. In the regions where no melt occurs, we prescribe a null water pressure yielding an effective pressure equal to ice overburden pressure. Effective pressure increases~~ , and the values increase upstream toward the ice divide as ice thickness increases and basal melt decreases. The lowest values of ~~N~~ effective pressure coincide with low bed elevation in the main trunk, ~~100~~ 100 km upstream of the grounding line.

The resulting velocity field for the Ctrl simulation captures the main features of NEGIS: the three outlets with high velocities across the grounding lines and sharp shear margins (Figure 2p). The northern branch feeding into 79N is slower and less defined than in the observed velocities, and the velocities of Storstrømmen are also slower than observed. Velocities of the floating tongues of 79N and Zachariæ are not well represented, and floating shelves are not shown here. The western branch, feeding into the main trunk of NEGIS, shows a more diffuse pattern with higher velocities than observed. ~~However, the 50 m/yrmodelled velocity contour , plotted as black lines~~

To evaluate how well the model simulations reproduce the observed velocity pattern, we plot the $50\,\mathrm{m\,yr^{-1}}$ velocity contour (black contour in Figure 2~~p, reaches 305 km~~), and compare how far upstream this contour reaches (in kilometres from the ice divide~~. This is further downstream compared to~~) relative to the observed velocity (white contour in Figure 2). The modelled velocity contour in the Ctrl reaches 305 km from the ice divide (Figure 2p), and thus further downstream than the observed velocity (~~120 km), plotted as white contours in~~ 120 km, Figure 2a,f,k). The Ctrl simulation does not capture the characteristics of NEGIS; with high upstream velocities close to the ice divide.

To capture the upstream velocities, we enhance the geothermal heat flux locally at the onset of the ice stream in the plume970 simulation, to reach ~~values~~ the maximum magnitude proposed by Fahnestock et al. (2001)~~and Macgregor et al. (2016)~~. The addition of the mantle plume results in high geothermal heat flux, with values up to ~~$970\ mW/m^2$~~ $970\,\mathrm{mW\,m^{-2}}$, rapidly decreasing to the values used in Ctrl (Figure 2e) within a radius of less than ~~100~~ 100 km. High geothermal heat leads to high basal melt rates, with ~~$100\ mm/yr$~~ $\sim 100\,\mathrm{mm\,yr^{-1}}$ above the plume (Figure 2j), compared to ~~1-2 mm/yr~~ 1–$2\,\mathrm{mm\,yr^{-1}}$ in the Ctrl experiment. The increase in basal melt rates ~~is causing~~ causes a reduction in effective pressure to ~~1.2~~ 1.2 MPa directly above the plume, resulting in a local floatation fraction (ratio of water pressure over overburden pressure) of ~~0.95~~0.95. The resulting velocity field in the plume970 experiment is similar to the Ctrl experiment, except for the higher velocities simulated at the head of the ice stream. In the plume970 simulation the ~~50 m/yr~~ $50\,\mathrm{m\,yr^{-1}}$ velocity contour reaches ~~131~~ 131 km from the ice divide (black contour Figure 2t), which is close to the observed ~~120~~ 120 km. However, the spatial pattern upstream is more diffuse and the ice stream is wider than observed. The Storstrømmen outlet shows higher velocities relative to the Ctrl, but still lower than observed. The 79N and Zachariæ outlets, on the other hand, display higher velocities than observed. Overall, with this approach, we capture most of the characteristics of NEGIS, although the ice stream is more diffuse and displays velocities slightly higher than the observations.

To determine whether a lower geothermal heat flux may induce a similar high velocity pattern, we run three simulations with a less intense mantle plume. Figure 2b-d show the geothermal heat flux values computed by rising the plume depth to ~~3000, 4000 and 4500~~ 3000, 4000 and 4500 km, respectively, obtaining maximum basal melt rates of ~~70~~ ~ 70 (Figure 2g), ~~85~~ ~ 85 (Figure 2h) and ~~95 mm/yr~~ $\sim 95\,\mathrm{mm\,yr^{-1}}$ (Figure 2i). The modelled effective pressure for the three plumes (Figure 2l-n) result in slower velocities than the plume970, with ~~50 m/yr~~ $50\,\mathrm{m\,yr^{-1}}$ velocity contours reaching to ~~253, 245 and 210~~ 253, 245 and 210 km from the ice divide, respectively (Figure 2q-s). This shows that GHF values of 677, 836 and ~~909 mW/m^2~~ $909\,\mathrm{mW\,m^{-2}}$ produce weaker ice stream signatures than observed, and given our model set-up, are not sufficient to induce the upstream fast flow of NEGIS.

To investigate the sensitivity of the position of the plume in plume970, we moved the plume ~~75~~ 75 km to the south-west, south-east, north-east and north-west (Figure 3). The computed geothermal heat flux distribution is shown in (Figure 3a-d) and the basal melt rates are of the same magnitude as in the plume970. The computed effective pressure for south-west and south-east (plume970SW and plume970SE, Figure 3i, j) have minimum values of ~~3.2 and 2.9~~ 3.2 and 2.9 MPa above the plume, which are not sufficient to initiate fast flow (Figure 3m, n). When the plume is located further downstream, the effective pressure reaches lower values (Figure 3k, l) and the ice stream flows faster than in plume970 (Figure 3o, p). However, with the ~~50 m/yr~~ $50\,\mathrm{m\,yr^{-1}}$ contour only reaching ~~204~~ 204 km from the ice divide. The plume970NE induces the fastest flow, and the plume970NW creates an interesting double branched ice stream starting from the ice divide. The experiments in Figure 3 ~~show~~ indicate that the elevated heat required to initiate ~~NEGIS~~ the NEGIS in our model must be located close to EGRIP.

To determine whether a lower geothermal heat flux value over a larger area could induce high upstream velocities, we investigate the influence of four weaker plumes with larger plume radii (Figure 4). The weakest, but most extensive plume (plume494, Figure 4a), produces basal melt rates of maximum ~~51 mm/yr~~ $51\,\mathrm{mm\,yr^{-1}}$ (Figure 4e), resulting in a large area of low effective pressure (minimum ~~0.2~~ 0.2 MPa; Figure 4i). The corresponding surface velocity for the plume494 displays a faster and wider ice stream (Figure 4m) relative to the observations. Plume594 gives basal ~~met rates of 60 mm/yr~~ melt rates of $60\,\mathrm{mm\,yr^{-1}}$ (Figure 4f) and the ice stream becomes wide, reaching all the way to the ice divide (Figure 4n). The plume775 is twice the size of the plume970 (Figure 4c), and with melt rates of ~~75 mm/yr~~ $\sim 75\,\mathrm{mm\,yr^{-1}}$ over a larger area (Figure 4g), the velocity of the ice stream (Figure 4o) is similar to the plume970. However, the ~~50 m/yr~~ $50\,\mathrm{m\,yr^{-1}}$ velocity contour reaches too close to the ice divide and the ice stream is wider than the observed one. The plume792 produces melt rates of ~~75 mm/yr~~ $\sim 75\,\mathrm{mm\,yr^{-1}}$ (Figure 4d), resulting in velocities similar to the plume594 (Figure 4p). This shows that ~~the elevated heat inducing the upstream fast flow of NEGISmust be constrained to a relatively small area, with an extent of ∼50 km~~ plumes with a restricted extent, $\sim 50 \times 50$ km, produce model results more consistent with the observed flow behaviour in the upstream reaches of NEGIS.

Finally, we investigate the influence of varying the parameters in the friction law (Eq. 1), presented in Figure 5. The noHydro simulation with an effective pressure approximated to the hydrostatic pressure shows very little resemblance to the observed NEGIS (Figure 5a), with too slow velocities. The simulation with a uniform friction coefficient and no mantle plume, captures the main feature of NEGIS (Ctrl-uni, Figure 5b); with a main trunk, the northern branch and three outlets, with fastest flow in Zachariæ. However, the velocity pattern is more diffuse than the observed (Figure 5e). The high upstream velocities are better captured in the simulation with plume970 and a uniform friction (plume970-uni, Figure 5c). For plume970-uni, high velocities reach slightly closer to the ice divide than the plume970, but the velocities of the main trunk are less confined than in experiment plume970 (Figure 5d) and the observations (Figure 5e).

4 Discussion

Most of the spatial velocity pattern of NEGIS is represented in our Ctrl run, apart from the upstream one third of the main trunk. This indicates that the downstream area of the NEGIS catchment is largely controlled by topography, while the upstream area is controlled by its basal conditions, which is in agreement with Keisling et al. (2014). The Ctrl simulation captures the main outlets and the observed "snake" shaped velocity pattern of the trunk. High velocities coincide with low lying bed elevation. However, we do not capture the high velocity of Storstrømmen, or the floating tongues of Zachariæ and 79North outlets. This could be caused by the simple friction coefficient approach not being representative of these areas, where basal properties display a more complex pattern.

We performed experiments with various mantle plume configurations introduced at the head of NEGIS, to assess if the presence of an anomalously high GHF can explain the pattern of ice flow of this region. The different plume configurations vary in intensity, position and extent. In the Ctrl simulation we use present day surface velocity and GHF from Fox Maule et al. (2009). Without the presence of a plume, the GHF does not reach more than $54\ mW/m^2$ $54\,\mathrm{mW\,m^{-2}}$ and leads to underestimating velocities in the upstream part of the catchment. These low values of GHF are not sufficient to initiate the onset of NEGIS close to the ice divide. By testing with four mantle plume configurations of increasing intensity (Figure 2), we find that the geothermal heat flux (GHF) needed to induce the observed upstream velocity of NEGIS , is $\sim 970\ mW/m^2$, as proposed by Fahnestock et al. (2001). However, we show that lower values of GHF can induce even faster flow, when the plume is more extensive (Figure 4). However, with a larger mantle plume the ice stream becomes wider, and does not match the observed velocity of NEGIS (Figure 5e) , indicating that the heat anomaly initiating NEGIS may be local in extent. in our model, is $\sim 970\,\mathrm{mW\,m^{-2}}$.

A GHF of $970\,\mathrm{mW\,m^{-2}}$ is consistent with the maximum value presented in Fahnestock et al. (2001); Keisling et al. (2014); Macgregor et for regions in proximity of EGRIP, where the plume970 is located. These GHF values are imposed based on basal melt estimates from radar internal stratigraphy. Our modelled basal melt rates ($\sim 100\,\mathrm{mm\,yr^{-1}}$) are thus consistent with their proposed values. By directly comparing the basal melt rates of our plume970 experiment to the basal melt rate estimates from Macgregor et al.

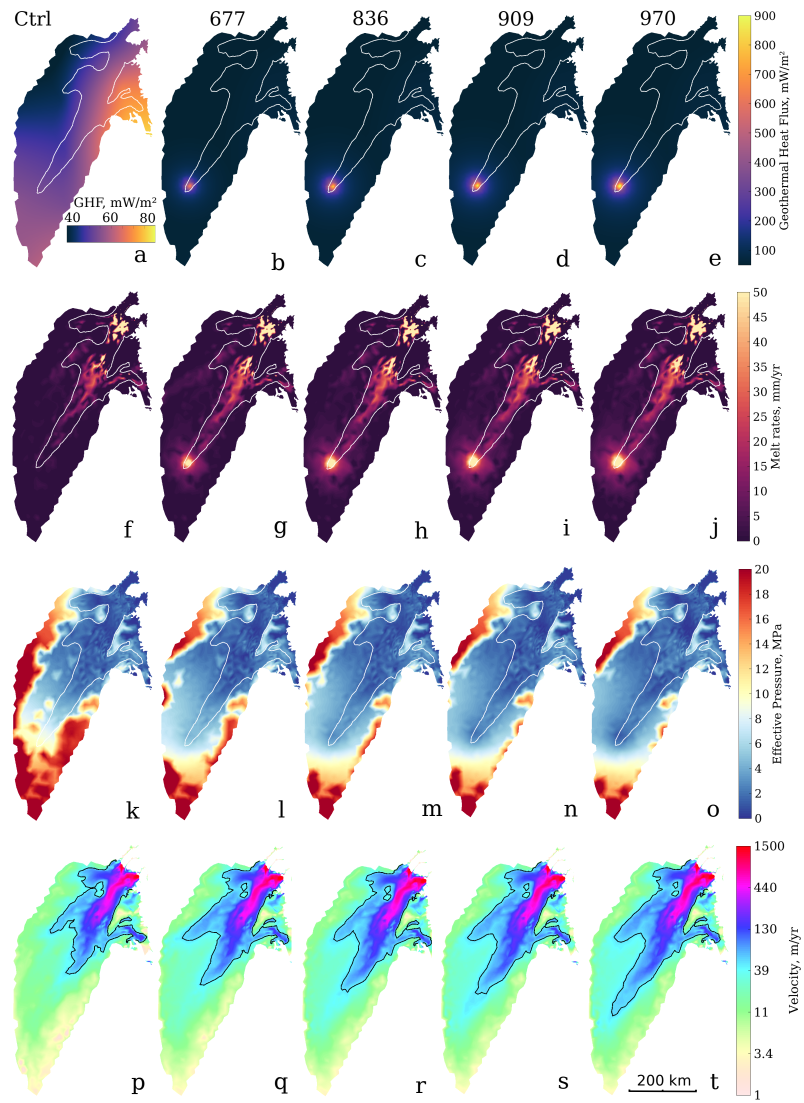

Figure 2. Model results for the Ctrl and the plume677, plume836, plume909 and plume970 simulations. a-e show the modelled geothermal heat flux (note the different color scale for Ctrl) and f-j shows the corresponding basal melt rates, forcing the hydrology model which computes the corresponding effective pressure (k-o) and finally the resulting surface velocity (p-t). White lines show the ~~50~~ 50 m~~/~~ yr^{-1} observed velocity contour, and black lines show the ~~50~~ 50 m~~/~~ yr^{-1} modelled velocity contour.

(2016) in Figure 6, it can be seen that our plume produces a basal melt pattern that matches the position, extent and values of the north-eastern branch of their anomaly~~(north of the green box in their Figure 5a). This suggest that the onset of NEGIS is triggered by this smaller basal melt anomaly, rather than the larger upstream anomaly reaching all the way to the ice divide (Macgregor et al. (2016), green box in Figure 5a)~~. The sensitivity simulations in Figure 3m,n show that more than ~~970 mW/m^2~~ 970 mW m^{-2} is needed to initiate high velocity, when the plume is located further upstream in a region with thicker ice relative

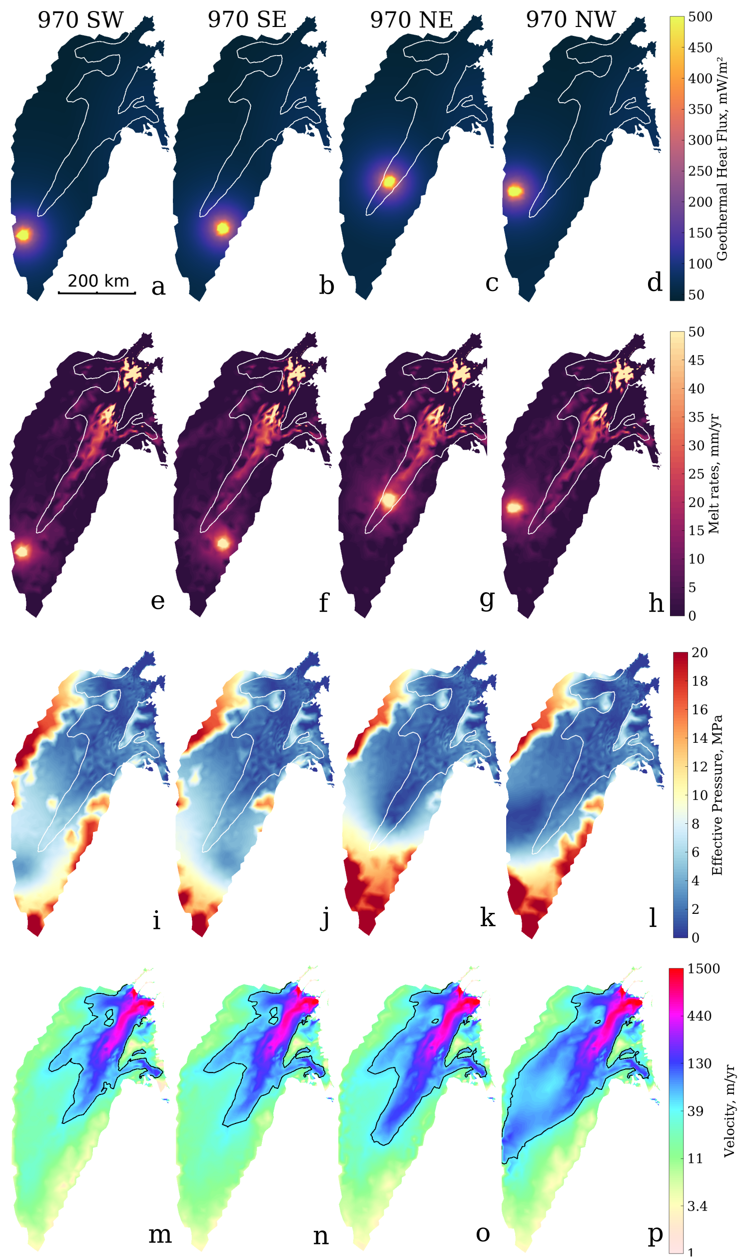

Figure 3. Model results from the sensitivity simulations investigating the position of the mantle plume by moving the ~~plume97 75~~ plume970 75 km. First column shows results from plume970SW, with a plume ~~75~~ 75 km to the south-west, second column represents 970 SE Plume, third represents plume970NE and the last column is plume970NW. a-d show the geothermal heat flux, e-h the resulting basal melt rates, i-l the computed effective pressure and m-p the modelled surface velocity. White lines show the ~~50~~ 50 m~~/~~ yr^{-1} observed velocity contour, and black lines show the ~~50~~ 50 m~~/~~ yr^{-1} modelled velocity contour.

to downstream. Thus, the larger upstream anomaly in Macgregor et al. (2016) may have less impact on the dynamics of the NEGIS. This suggest that the onset of NEGIS is triggered by this smaller area of high basal melt, rather than the entire upstream anomaly reaching all the way to the ice divide (Macgregor et al. (2016).

To capture the observed upstream velocities we have forced the model with an extremely high GHF value (970 mW/m^2), ten times higher than the values suggested for Greenland (Rogozhina et al., 2012; Shapiro and Ritzwoller, 2004; Fox Maule et al., 2009; Marto . The required heat flux is three times as high as the highest geothermal heat flux observations in Greenland (Rysgaard et al., 2018) The GHF at the head of NEGIS is suggested to be high due to lithospheric thinning as a results of the Iceland plume passage (Rogozhina et al., 2016; Martos et al., 2018). However, it is 300 times less than estimated under Myrdalsjokull in Iceland (?). 970 mW/m^2 is only applied to one node in our model mesh, and the values are rapidly decreasing to less than half within a radius of 25 km. The magnitude of the anomaly corresponds to 970 $\mathrm{mW\,m^{-2}}$ is an extremely high GHF value, ten to twenty times higher than the values suggested by Fahnestock et al. (2001)GHF models for Greenland (Shapiro and Ritzwoller, 2004; Fox Maule et . Greve (2019) derived GHF values for five deep ice core bore holes in Greenland, using the SICOPOLIS model (SImulation COde for POLythermal Ice Sheets; www.sicopolis.net), such that the simulated and observed basal temperatures match. This resulted in a local elevated GHF anomaly around NGRIP of 135 $mW/m^2$135 $\mathrm{mW\,m^{-2}}$, located at the ice divide $\sim 150\ km$ ~ 150 km away from the head of NEGIS. Our GHF anomaly is smaller in extent, and with a magnitude 7 has a magnitude seven times higher than Greve (2019) . The large difference in magnitude may be due to the very different constraints; Greve (2019) uses observed basal temperatures, and we use observed velocities as a target. and three times as high as the highest current geothermal heat flux observations in Greenland (Rysgaard et al., 2018). In summary, the plume970 produces a basal melt pattern with magnitude and extent in line with previous estimates from the radar data, however there is a large discrepancy between the necessary GHF to produce this melt and the GHF estimates for Greenland.

Local high heat To explain the high GHF value of 970 $\mathrm{mW\,m^{-2}}$ we need to investigate processes that may locally elevate the geothermal heat fluxdoes not come from variations in the mantle, but local variations in the crustal heat production and possibly hydrothermal systems. We are not suggesting a mantle plume to be present beneath NEGIS, rather the high values are reminiscent of previously high values from the passage of Greenlandover the Iceland Plume. However, we represent the potential extra heat source using the mantle plume module in ISSM. Alley et al. (2019) and Stevens et al. (2016) explained high GHF in this region by the passing of the Iceland plume, leaving behind partly molten rock that may have migrated up in response to glacial-interglacial cycles, as the crust is loaded and unloaded. A study showed that glacial rebound may have caused young intraplate volcanism in Greenland, despite the old age of the tectonic plate and no mantle plume present (Uenzelmann-Neben et al., 2012). The plume passage could have lead to shallow magma emplacements, that may feed hydrothermal systems, causing hot fluid percolation that enhances high heat transport to the base of the ice sheet (Stevens et al., 2016; Alley et al., 2019). The mantle plume passed across Greenland, however, abnormally high melt rates are only found at the onset of NEGIS (Macgregor et al., 2016). This could be due local lithology, causing rifts or other weaknesses in the continental plate during glacial rebound, making this region unique. A study showed that glacial rebound may have caused young intraplate volcanism in Greenland, despite the old age of the tectonic plate and no mantle plume present (Uenzelmann-Neben et al., 2012)(Stevens et al., 2016; Alley et al., 2019; Mordret, 2018). It is important to note that the term

GHF is defined as the heat flux from the Earth's interior as a pure conductive heat transfer. Hence, the $970\,\mathrm{mW\,m^{-2}}$ heat flux can not be explained by GHF alone, but rather surface heat flow from locally elevated GHF due to advective heat transfer from the processes mentioned above (Artemieva, 2019).

Comparing the velocity field in the plume970 experiment to previous studies without inversion shows that combining a basal hydrology model with an elevated GHF at the head of NEGIS captures the observed high, confined, upstream velocities of the NEGIS. The simulations in Goelzer et al. (2018) show that the ice flow models capturing the upstream onset of NEGIS all rely on inversions to initialize the basal drag in the simulations (Elmer/Ice, ISSM, BISICLES, GRISLI and f.Etish). The models without inversion, underestimate the velocities in the upper part of NEGIS catchment and lack the sharp velocity gradients. Aschwanden et al. (2016) simulated the high upstream velocity of NEGIS without inverting for basal conditions in PISM, but their simulation lacks the clearly defined main trunk and underestimates the high upstream velocity. Beyer et al. (2018) further improved the simulation by using a subglacial hydrology model to compute effective pressure, which allowed higher velocities in the outlets. However, high upstream velocities are still lacking, similar to our Ctrl simulation. The two latter studies used GHF from Shapiro and Ritzwoller (2004), which proposed slightly lower values at the head of NEGIS compared to the values of Fox Maule et al. (2009) used in our study.

Beyer et al. (2018) used the same friction law as we use in ISSM, but with a uniform friction coefficient. We tested a uniform friction coefficient, which lead to a more diffuse ice stream (Figure 5b,c), but with more confined outlets compared to the Beyer et al. (2018) study. The difference can be explained by different basal melt rates used as input, and different hydrology models. In order to capture sharp gradients in the velocity field, we find it important that the areas without any basal melt have effective pressure equal to the ice overburden pressure.

We invert for basal friction to get the basal melt rates that are used to initialize the subglacial hydrology model, and the model is then free to evolve. We do not use the inverted friction in the forward ice flow simulation, instead we use the simple friction coefficient from Eq. 3. To investigate whether the modelled velocity pattern is caused by the effective pressure distribution or the friction coefficient, we run the simulation 'no Hydro', where the effective pressure is approximated to the hydrostatic pressure, commonly used in ISSM. The modelled velocity pattern (Figure 5a) does not resemble the observed, and we conclude that including the subglacial hydrology model is responsible for the improved velocity pattern in Ctrl and plume970. By using our friction coefficient distribution, combined with initializing with present-day basal melt from velocity observations, both the Ctrl and plume970 experiments display velocity patterns similar to the observations (Figure 5d, e).

The middle western branch of the ice stream displays too high velocity in both the Ctrl and plume970 experiments, correlating with low lying bed elevation (Figure 1). Too high velocities in this region were also modelled by Aschwanden et al. (2016) using PISM and a similar bed elevation dependent friction law. When performing additional simulations with the GHF values from Martos et al. (2018) this branch becomes more pronounced in velocity (not shown here). This may indicate that the GHF values in this region of Greenland are even lower than Martos et al. (2018) and Fox Maule et al. (2009), and the glacier base is frozen to the ground. This region is recognized as "uncertain" in the synthesis of Greenland's basal thermal regime by Macgregor et al. (2016). Other explanations for too high velocities in this branch may be a higher bed roughness, errors in the bed topography or "sticky spots".

Given the model configuration, an exceptionally high ~~GHF value of 970 mW/m^2~~ heat flux of 970 $\mathrm{mW\,m^{-2}}$ is needed to reproduce NEGIS. We acknowledge that this value may be overestimated due to uncertainties and assumptions in our model set-up, and we discuss these in the following sections. We use a simple friction law linearly dependent on effective pressure, and are aware that the results are likely to change with a different choice of friction law. For example, in the friction law used in the MISMIP+ experiments (Asay-Davis et al., 2016; Tsai et al., 2015), effective pressure is included only where the coulomb criterion is met, normally a few km upstream of the grounding line. This may result in a smaller dynamic response from the mantle plume in the slow upstream regions of NEGIS. However, the use of a non linear friction law may enhance the sensitivity of the ice dynamics to effective pressure, also upstream, as we compute low effective pressure above the plume. This implies that the use of a non-linear friction law may result in a lower GHF needed to sustain NEGIS in a model.

By using a coarse model mesh we may underestimate the softening occurring due to strain heating in the shear margins, and hence overestimate the lateral drag. Refining the mesh and inducing damage softening of the ice in the shear margins (Bondzio et al., 2017), would decrease the lateral drag. In this case, the observed high upstream velocity of NEGIS may have been reproduced with higher basal drag and hence lower GHF. The underestimation of modelled ice softness may also explain why our modelled upstream velocity field is wider and more diffuse than the observed.

In the simulations where we investigate the influence of an increased plume radii (Figure 4), we show that lower values of GHF can induce even faster flow, when the plume is more extensive (Figure 4). However, with a larger mantle plume the ice stream becomes wider, and does not match the observed velocity of NEGIS (Figure 5e). The basal melt pattern of Macgregor et al. (2016) in Figure 6 consists of two melt anomalies near EGRIP. It would be interesting to investigate the velocity response of two weaker elevated GHF anomalies closely located.

We parametrize the friction coefficient with a simplified estimate linearly dependent on the bed elevation. In other studies this coefficient is inverted for by matching observed surface velocity, producing low values in the main trunk of NEGIS (Smith-Johnsen et al., 2019). By lowering the friction in the main trunk, we may reproduce fast flow with a lower GHF value. However, this would make the friction coefficient relate to the velocity, which we are trying to avoid. The bed topography used is from BedMachine (Morlighem et al., 2014), so datasets used to create this map impact the choice of friction. A uniform lowering of the friction coefficient, also outside the trunk, would increase velocities all over the domain, hence we would loose the sharp velocity gradients and overestimate the outlet velocity even further. Additionally, the modelled ice surface in the Ctrl experiment is lower than the observed (Scambos and Haran, 2002), and a uniform reduction of friction will enhance this mismatch. We do not observe a local depression in the surface topography above the 970 $\mathrm{mW\,m^{-2}}$ plume, which agrees with the observed ice surface for the region (Scambos and Haran, 2002).

Hydrology parameters are unfortunately highly uncertain, and different choices would lead to a more or less responsive hydrological system and hence possibly a lower GHF value to sustain the fast flow. However, we have a rather low transmissivity of the inefficient drainage system, resulting in low efficiency in water evacuation, causing our system to be sensitive to an increase in water input. If the transmissivity was lowered further, the efficient drainage system is likely to activate in the GHF anomaly region, lowering the water pressure and becoming less sensitive to increased water input. For this reason, we do not expect that a different hydrology configuration would reproduce NEGIS with a lower ~~GHF value~~heat flux. In addition, the subglacial hydrology is only one-way coupled to ice dynamics, so we do not capture the positive feedback expected with higher velocities leading to more melt, and lower effective pressure, giving even higher velocities. With a more responsive and fully coupled system, one might be able to reproduce NEGIS with lower values for the geothermal heat flux.We use a simple friction law linearly dependent on effective pressure, and are aware that the results are likely to change with a different choice of friction law. For example, in the friction law used in the MISMIP+ experiments (Asay-Davis et al., 2016; Tsai et al., 2015), effective pressure is included only where the coulomb criterion is met, normally a few km upstream of the grounding line. This may result in a smaller dynamic response from the mantle plume in the slow upstream regions of NEGIS.

With a simple bed elevation dependent friction and hydrology model forced by melt rates from GHF, we capture the overall pattern of NEGIS velocity. This has implications for studies trying to predict the response of NEGIS to a future climatic warming. Basal friction may not remain constant in time, and thus we cannot fully rely on inversion as it masks unknown time varying basal properties. By using our approach (with or without the geothermal heat flux anomaly) one can capture complex velocity patterns, and then invert for the remaining basal properties. These may in turn be assumed to be constant in time, while the subglacial hydrology will evolve with a changing climate accounting for varying basal conditions. Unfortunately, observations and estimates of geothermal heat flux and subglacial hydrology are challenged by large uncertainties. Therefore, it is critical for future observational and modelling studies, to better constrain the basal conditions of the Greenland Ice Sheet.

5 Conclusions

Present day basal melt rates from geothermal heat flux maps and frictional heat are not sufficient to sustain the observed upstream velocities of the Northeast Greenland Ice Stream (NEGIS), as opposed to the downstream velocities which . The downstream velocities appear to be driven by topography and the spatial pattern is well captured by the subglacial hydrology model. Our findings suggest that a local geothermal heat flux anomaly may explain the characteristic high upstream velocity of NEGIS, and hence confirms is consistent with previous studies (Fahnestock et al., 2001; Macgregor et al., 2016; Alley et al., 2019). To reproduce high upstream velocities at the onset of NEGIS, a sustained basal melt rate of 100 mm/yr 100 $\mathrm{mm\,yr^{-1}}$ is needed in a local region close to EastGRIP EGRIP, where observed present day velocities reach 50 m/yr50 $\mathrm{m\,yr^{-1}}$. Hence, the minimal geothermal heat flux value needed to initiate the ice stream in our model is 970 $mW/m^2$970 $\mathrm{mW\,m^{-2}}$, as proposed by Fahnestock et al. (2001). This magnitude is too high to be explained by geothermal heat flux alone, and we suggest that processes such as hydrothermal circulation may locally elevate the heat flux of the area.

Code and data availability. ISSM software is open source and can be downloaded at https://issm.jpl.nasa.gov/. The surface mass balance forcing used in this study, from J.E. Box, is available from https://zenodo.org/record/3359192#.XUSmSpNKhR4 (Box, 2019).

Author contributions. SSJ designed the study with help from BdF and KHN. SSJ ran the simulations. NS helped greatly setting up the ice flow model, BdF helped setting up the hydrology model, and HS helped setting up the mantle Plume model. SSJ wrote the manuscript with substantial contributions from all co-authors. The research related to the paper was discussed by all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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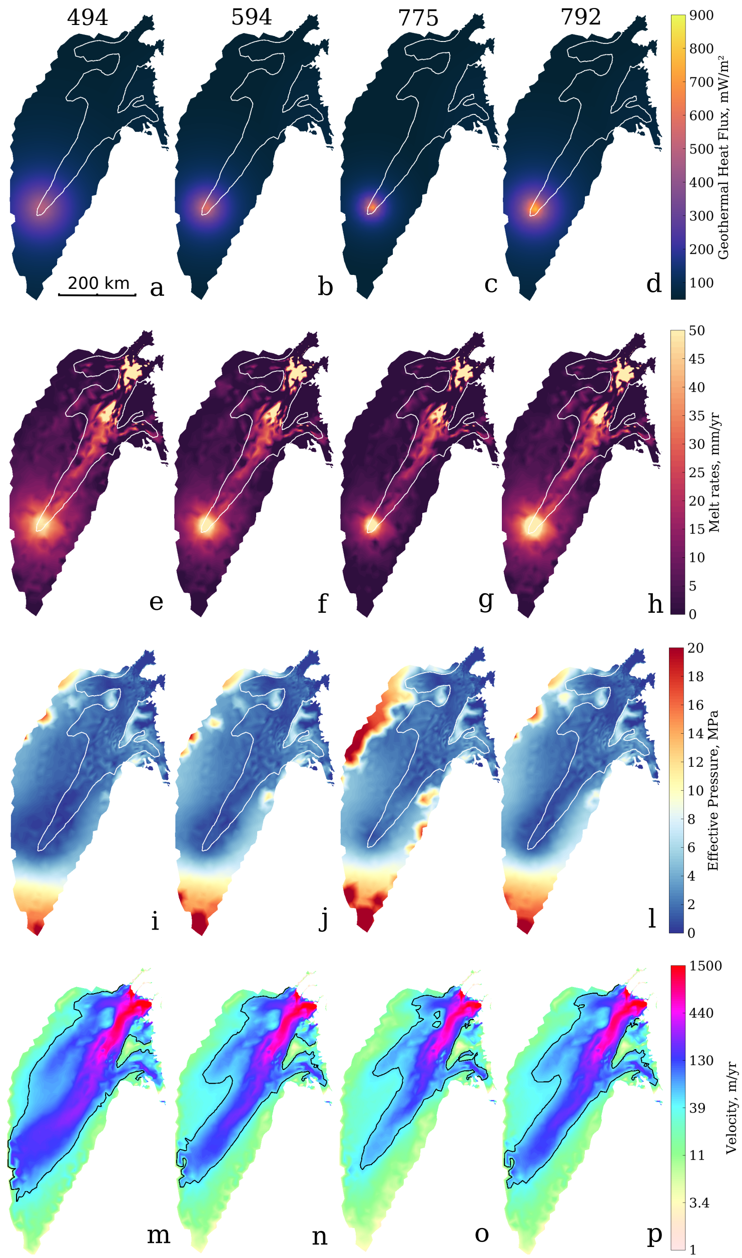

Figure 4. Model results from the sensitivity simulations investigating a reduced magnitude and increased size of the mantle plume. First column shows results from 494 Plume with a ~~300~~ 300 km radius at ~~3000~~ 3000 km depth, second column represents 594 Plume with ~~200~~ 200 km radius and ~~2500~~ 2500 km depth, third column represents 775 Plume with ~~100~~ 100 km radius and ~~2000~~ 2000 km depth the last column represents Plume 792 with ~~200~~ 200 km radius and ~~3000~~ 3000 km depth. a-d show the geothermal heat flux, e-h the resulting basal melt rates, i-l the compute effective pressure and m-p the modelled surface velocity. White lines show the ~~50~~ 50 m~~/~~ yr^{-1} observed velocity contour, and black lines show the ~~50~~ 50 m~~/~~ yr^{-1} modelled velocity contour.

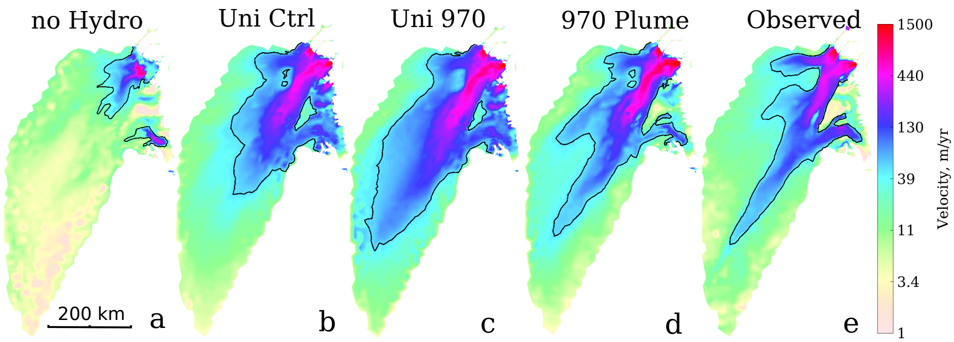

Figure 5. Surface velocity results from the no Hydro (a) with effective pressure approximated to the hydrostatic pressure assuming direct connection to the ocean, commonly used in ISSM. Uni Ctrl (b) and plume970-uni experiment (c) use a uniform friction coefficient α set equal to ~~$90\ (m/s)^{1/2}$~~$90\,(\mathrm{ms}^{-1})^{1/2}$. Corresponding geothermal heat flux, basal melt rates and effective pressure are the same as Ctrl and plume970, shown in Figure 2. For reference we include d showing the plume970 simulation (same as Figure 2t), and e showing the observed surface velocities interpolated onto the model mesh. Black lines show the 50 m~~/~~yr^{-1} velocity contour.

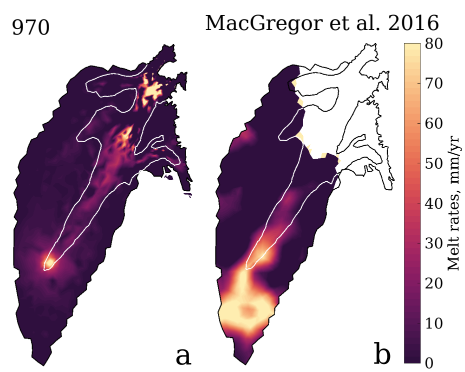

Figure 6. Comparison of the basal melt rates computed for plume970 experiment (a) and the gridded basal melt rate estimates of Macgregor et al. (2016) interpolated onto our model mesh (b). White lines show the observed 50 m yr^{-1} velocity contour.