Interactive response to reviewer comments on "Simulating ice thickness and velocity evolution of Upernavik Isstrøm 1849–2012 by forcing prescribed terminus positions in ISSM"

by Konstanze Haubner and co-authors

We thank both reviewers for their constructive comments on our manuscript. We feel the requested changes have improved the clarity of the paper and appreciate their feedback. The author response to reviewers is structured as follows:

- Reviewers' comments in blue
- Authors' response in black

We significantly rewrote some sections of the manuscript, to improve clarity. The major changes include:

- Model evaluation includes now comparisons of observed and simulated ice thickness instead of surface elevation
- Additional figures in the supplementary showing the basal friction coefficient and spatial comparisons for simulated and observed ice thickness, velocity
- New table visualising model initialisation steps
- Including the co-authors Eric Rignot and Todd K. Dupont (TC editorial support (Svenja Lange) is informed)

Our conclusions remain unchanged. The reviewed manuscript with tracked changes is attached.

Referee #1 (anonymous)

General comments

This study simulates the dynamic response of the 3 main Upernavik Isstrom glaciers to prescribed changes in terminus position and surface mass balance, both from observations, over the period 1849–2012. The authors model ice dynamics using SSA in ISSM and make use of inverse methods to initialise basal conditions. The results of the simulation indicate the importance of terminus position change in driving dynamic change in this glacier system. Overall this paper presents interesting results, but I have significant concerns with regards to the interpretation of the results and the presentation of the methods which lead me to believe it is not yet ready for publication.

This study's approach allows the authors to investigate dynamic response to calving, while circumventing the issue of calving law uncertainty. However, the nature of this approach is such that a large amount of the mass balance change comes from prescribed model inputs. This is not a problem in itself, but the authors have not untangled this model input from model output (i.e. dynamic response) when presenting comparisons with observations. For example, in Section 4.2 and in the supplementary material, the authors show comparisons between modelled and observed mass loss. However, much of this mass loss is actually prescribed through terminus retreat and surface mass balance. It should be trivial to subtract these prescribed components from both the simulated and observed MB. Without this correction the comparison is somewhat misleading, and makes it impossible to assess the performance of the model.

In our manuscript, we divide the simulated mass changes into mass change due to prescribed SMB and dynamic component DIL. We agree that a division of ΔDIL into mass change prescribed by terminus position change and the simulated dynamical mass change improves assessing model performance. Figure 2b is adapted accordingly. We gain knowledge about the contributions to mass loss from prescribed SMB, terminus change and resulting thinning and acceleration: "[...] while 30 % of total ice mass loss simulated by $\mathrm{ISSM_{PT}}$ was prescribed, with ΔSMB accounting for 9 % (-50 Gt) and prescribed terminus position change contributed 21 % (-121 Gt). Thus, 70 % of by $\mathrm{ISSM_{PT}}$ simulated mass loss is caused by thinning and acceleration."

However, the choice of dividing the mass loss into ΔSMB and ΔDIL is motivated by the cited publications Khan et al. (2013) and Larsen et al. (2016). They compute mass change by comparing Upernavik's ice surface elevation in different periods, compute ΔSMB between the dates of the surface elevations and compute ΔDIL as residual of computed mass change and SMB. By comparing our simulated ΔDIL with those observations, we find it important to use the same measure and compute prescribed ΔSMB and simulated mass changes on the domains observed in Khan et al. (2013) and Larsen et al. (2016). We also use the same term: dynamic ice loss.

We include explanations about the background of the mass comparison with Khan et al. (2013) and Larsen et al. (2016) and re-write the subsection 4.2.

My most serious concern with this manuscript is the claim made in the abstract and in the text that the model matches observations within 20%. In the abstract, the claim applies to the surface elevation and velocity over the period 1990–2012, while in the conclusions, the authors seem to claim that the entire 164 year simulation matches observations within 20%. From the data provided in Figures 4 and 5, and in Sections 4.3 and 4.4, neither claim appears to be accurate. This might be simply fixed by qualifying the statements somewhat, but it leads me to question the accuracy of the other (currently unverifiable) claims about the match between model and observation. I would like to see additional figures showing the mismatch in elevation and velocity across the domain to back up the claims made in Sections 4.3 and 4.4.

We remove claims similar to simulation matching $\pm20\%$ observations and change all evaluations of simulated ice surface elevation to ice thickness. We add figures to the supplementary, showing spatial absolute and relative differenced between simulated and observed ice thickness.

Comparing simulated and observed ice thickness changes the percentage of accuracy. We adapt the text accordingly.

The description of the model setup, physics, boundary conditions and initialisation is somewhat unclear and significantly lacking in detail. What does the model domain look like? Is it defined by the ice catchment? Does it extend to the ice divide?

The model domain is defined by the ice catchment and extends to the ice domain, marked as a red area Figure 1. The following sentence is now included in the model description: "The model domain is set to the Upernavik catchment, which is defined by the flow direction given by the 2008/09 surface velocity from Rignot and Mouginot (2012) (red area in Fig. **??**)."

What velocity data are used to invert for basal friction? What happens to the basal friction condition when flotation is achieved?
Velocity gained from relaxation is used to invert for the basal friction coefficient. Now, Table 2 provides more information about the model initialization steps. The section describing model initialisation is re-written to improve clarity.
Friction is not applied on floating areas.
In comparing surface elevations, the authors state that the surface lies within 20% of observations, and similar percentage comparisons of surface elevation are made throughout the results section (e.g. 84% surface lowering at UI-2 2012 terminus). This should be restated in terms of ice thickness, which is altitude-agnostic and which, after all, is the variable of interest from an ice dynamics perspective. A 20% error/change in surface elevation translates into quite different thickness errors/changes depending on whether the ice is floating or resting on bedrock at 500 m.a.s.l.
As explained above, we change surface elevation comparisons to thickness comparisons and adapt all numbers accordingly.
I found quite a few grammar/language errors, some of which I have highlighted in ‘technical corrections’ below.
We improved the study regarding grammar and spelling.

Specific Comments

P1 L3: make it clearer that you prescribe changing terminus position. “Observed glacier terminus changes” could be e.g. oceanic or atmospheric conditions.
Sentence has changed during revision.
P1 L5: I think you used 2012 velocities to invert for basal drag (though I’m not sure), and terminus positions (and SMB) are prescribed. As such, I don’t think a <20% error in elevation and velocity at the end of your simulation would necessarily imply that your model is realistic from 1849-2012. It would tell you that your basal inversion worked properly. But more importantly, this is not accurate! For example, Fig 4 shows UI-1 observed surface elevation in 2009 at 5–10km of over 500 m.a.s.l., but modelled is less than 400 m.a.s.l. Fig 5 shows UI-2 0-5km 08/09 observed velocity is just under 2500m/a, but modelled is over 3000 m/a. You explicitly state in the text that simulated 2012 upstream surface elevation is 56-62% of that observed. And these are data averaged over a large area. In the shear margins, you mismatch by 100%. This in itself is not a problem – shear margins are tricky, but you cannot claim that you match elevation and velocity within 20%.
We agree, the statement is too strong and formulated misleadingly. Conclusions and abstract are revised and focus now on different mass loss periods, the different contributors and how PT could be used to improve ice sheet models.
P2 L12: What is a “dynamic ice loss event”? In the context of Kjaer et al (2012), it seems to be a multi-year period of sustained accelerated calving. You should clarify this.
We re-phrase to "periods of increased dynamically driven ice loss".
P2 L14: The final sentence of this paragraph feels out of place. Perhaps move it to the start of the next paragraph. “Hence” here implies that the focus of previous studies is a result of the two dynamic mass loss events.
We moved the sentence to the next paragraph and start the sentence with "Previous studies [...]"
P3 Fig 1: This is a good figure, but the poor contrast in the landsat image between rock and ocean makes it slightly tricky to pick out the historic positions of the individual glaciers. Perhaps you could tweak the bands a little?

We changed the color bands and contrast aiming for better rock-ocean contrast.

P3 L4,5: This sentence is quite unclear. It starts by describing SSA (approximation for stokes, long. stress), but "neglecting lateral drag" is not a fundamental part of SSA. I guess you mean that you choose to neglect lateral drag on the sides of your domain? Given the width of the domain, this is quite justifiable, but explain it better and give this justification. I also think you could give a more technical and less clunky description of longitudinal stress gradients.

We re-write the paragraph to: "Ice flow is calculated applying the Shelfy Stream Approximation (SSA; MacAyeal, 1989), that integrates vertically averaged ice properties (e.g. ice rheology, thickness, velocity) and neglects vertical shear stresses. The SSA is well suited for fast-flowing glaciers like Upernavik, where the ice flow is primarily driven by basal sliding."

P3 L10: Can you show, or at least properly describe, the domain somewhere?

The model domain is the UI catchment and shown in Figure 1. The figure caption now contains information about the model domain and the following sentence is added to the model description:

"The model domain is set to the Upernavik catchment, which is defined by the flow direction given by the 2008/09 surface velocity from Rignot and Mouginot (2012) (red area in Fig. 1)."

P3 L6: Why use surface air temperature for depth integrated viscosity? Is there any reason to think that surface air temp is equal to, or even correlates with, internal temperature?

We divided the explanation for ice viscosity, and moved some parts of the explanation to section 3.1, Model Initialisation. The first part remains in the Introduction section in section 3:

"Ice viscosity follows Glen's Flow law (Glen, 1955). The initial viscosity is taken from Table 3.4 in Cuffey and Paterson (2010, p. 75), assuming ice temperature of $-5°C$ and will be refined in section 3.1"

Further explanation is given in section 3.1 ("Model initialisation"):

"Given computed ice velocity and thickness from the first relaxation, ice viscosity and basal friction can be redefined. The ice viscosity is calculated by extruding the model with 15 layers and solving for the thermal steady state based on forcing the surface with 1854–1900 UI mean surface air temperature (Box, 2013)."

P4 L8: Can you give more details on the extrapolation of velocity? Is this done using a mass conservation approach? I assume that is what is meant by "following fjord bathymetry"? If so, were changes in glacier width also accounted for?

We re-phrased the paragraph to clarify the initialisation steps and added Table 2 to give an overview, which steps are performed including their goals.

The initial velocity is derived from stress balance solution, given GIMP surface elevation extended to the 1849 terminus as described in section 3.1. For the initial ice velocity, we asume driving stress to be equal to basal stress at any given point.

P5 L7: It took me some time to figure out your strategy here, but now I see that your interpolated surface elevation and bathymetry tells you whether the ice should be floating or grounded, and therefore gives you a thickness. Maybe you could clarify this?

We reduce the explanation to "The ice thickness is set to floatation height or to the maximum thickness, defined through the initialised ice surface elevation and bed topography. "

P5 L19: What about floating regions? I guess driving stress is small (but non-zero) here.

Friction is not applied on floating regions. The driving stress is small.

P5 L23: Authors state “the first relaxation... provides ice thickness and velocity for the second relaxation. Given computed ice velocity from the first relaxation, basal friction can be redefined”. So, is the inversion done with respect to observed velocity or simulated velocity from the previous relaxation? I guess the former, in which case you should clarify the above statements; given the instantaneousness of the stokes equations, I don’t think the velocity from the first relaxation really feeds into the second relaxation at all, except perhaps to provide the initial guess for viscosity in your first iteration. If the latter, this feels questionable – using velocity from SIA basal drag in SSA model to invert for new basal drag...

We invert for previously relaxed surface velocity after improving the ice viscosity by obtaining a thermal steady state.

New inversion description: "Given computed ice velocity and thickness from the first relaxation, ice viscosity and basal friction can be redefined. The ice viscosity is calculated by extruding the model with 15 layers and solving for the thermal steady state based on forcing the surface with 1854–1900 UI mean surface air temperature (Box, 2013). The basal friction coefficient is constant in time, but varies in space, and is calculated by an adjoint-based inversion, following Morlighem et al. (2010) and MacAyeal (1993), given the updated ice viscosity from the thermal steady state simulation."

P6 L9: If you want to show relative changes, you should be looking at thickness, as mentioned above.

Done. (see answer above)

P7 L1: How much of this -585 Gt was prescribed?

We added "99 % of simulated $ISSM_{control}$ mass loss was prescribed by ΔSMB while 30 % of total ice mass loss simulated by $ISSM_{PT}$ was prescribed, with ΔSMB accounting for 9 % (-50 Gt) and prescribed terminus position change contributed 21 % (-121 Gt). Thus, 70 % of by $ISSM_{PT}$ simulated mass loss is caused by thinning and acceleration."

P7 L8: “hereafter anomalies deltaSMB and deltaDIL” - I see what you mean, but this isn’t a sentence.

Now: "hereafter referred to as anomalies ΔSMB and ΔDIL"

P7 L16-21: This paragraph and associated table are not very intuitive and could be improved. “2002/05 – 2010” should be clarified in the text – it’s not clear what this range represents. The authors state that mass balance corresponds to three sets of cited observations, but only two are present in the table. It’s also somewhat confusing that you mix comparisons of observed and modelled mass balance with comparisons of DIL % - this is made even more confusing by the lack of these % DIL values in the table. I’d recommend adding some data on the % DIL and SMB from simulation and observations to Table 2. This would significantly clarify the last sentence, in which the authors state that % DIL agrees with Khan and Larsen – the reader is drawn to Table 2 for evidence of this agreement, but none is provided. Also, as mentioned in general comments, you need to untangle the prescribed and resultant mass loss before comparing with observations.

P8 Table 2: I guess the simulated changes don’t appear to correspond because Khan 2013 don’t measure changes in the whole domain of your model? It would be worth explaining this, otherwise readers might wonder how the 2002/05-2010 simulated mass loss is 32 Gt, but the 2000–2011 mass loss totals 133 Gt.

We added a paragraph and extended Table 3 to address both comments above:

"Khan et al. (2013) and Larsen et al. (2016) measure surface elevation changes from aerial photographs, satellites and digital elevation models between 1985 and 2010. These yield a total mass change during different time periods and congruent to our calculations ΔDIL is estimated as the residual of mass change and ΔSMB. Both studies refer to different areas within the UI catchment. Table 3 presents a comparison of the observed mass changes and our simulation results, recalculated for the particular areas. Due to sparse data coverage Khan et al. (2013) combine surface elevation measurements acquired between 2002 and 2005 to quantify elevation changes and refer to this period as 2002/2005. The average of simulated ice mass loss between 2002 and 2005 is taken for comparison with the 2002/2005 observations from Khan et al. (2013)."

P8 L4: As mentioned in general comments, I think you should discuss thickness changes, or else stick to absolute values.

Answered above.

P10 L9: Source for these winter velocity maps?

The winter velocity maps are produced from data available from http://esa-icesheets-greenland-cci.org/ and described in Nagler et al 2017.

We added the information to Table 1 and the caption of Figure 5.

P10 L23: "ice surface elevation. . . velocity observations". This doesn't seem to make sense.

The sentence changed during revision.

P11 L15: "The simulation reproduces not only the retreat..." - I don't think you can say that the model reproduces the observed retreat and advance. You prescribe these changes.

This sentence was changed to clarify its statement: "Although we primarily discuss prescribed ice margin retreat, it is worth mentioning that our method also includes advancing observed terminus position changes at UI-1 and UI-2 in summer 2012 and at UI-3 in the summers 2001, 2003 and 2007."

P11 L27: "matching observed velocity, surface elevation and mass changes within 20% of observations". As stated in general comments above, I think your comparisons with observations are flawed at present. Furthermore, Table 2, Fig. 4, Fig. 5 demonstrate that this figure of 20% is not accurate.

Changed. (See general comments above).

Technical Corrections

P1 L6: "and are within"

We deleted "and".

P1 L7: "Increased ice flow acceleration", surely its just "ice flow acceleration" or "increased ice velocity"?

Changed to "increased ice velocity".

P3 L10: "The grounding line", no need to capitalize.

Done.

P5 L21: "The basal friction", ditto.

Done.

P6 L7: "away form"

Done.

P6 L2: "that are causing numerical instabilities" is not good english here.

Changed to "The additional calving fronts aim to improve realistic simulation behavior by splitting large ice area changes induced by the prescribed terminus changes into smaller areas within shorter time periods."

P7 Fig 3: Caption refers to SID rather than DIL.

Caption was changed.

Referee #2 (J. Bassis)

General comments

The goal of this study is to simulate the dynamic response of the Upervnavik Isstrom glacier system from 1849-2012 to prescribed terminus changes combined with changes in surface mass balance. The authors use the ISSM model approximation to the well known shallow shelf approximation (SSA) equations. The authors find that prescribed changes in terminus position have a large effect on dynamic discharge, reinforcing many prior studies that came to similar findings. Overall, one of the strengths of this study is that it is able to simulate dynamic drawdown over a relatively long period of time. I did, however, have some questions.

1. I am a bit confused by the geometry of the glacier system. It says in several places that the grounding line is computed automatically by the model. I guess this means that the groundling line (transition from grounded ice to floating ice) is computed automatically by the model, but the terminus position or calving front position is floating and this position is specified? The existence of an ice tongue or shelf is not obvious at all from the discussion or figures: does the glacier always have a floating tongue or is the floating tongue only there part of the time. After reading through a few more times, I started to think that there is no ice tongue and the terminus is grounded, consistent with this system being a tidewater glacier system, but then there isn't a grounding line. Overall, I would like the authors to be a bit more careful with their explanation of whether the glacier has an actual grounding line and if the grounding line evolves separate from the calving front or whether there is really a calving front, which may sometimes approach floatation or something else.

We agree that the text was not very clear: the ice front position is prescribed, and ice is allowed to float depending on a hydrostatic criterion (Seroussi et al., 2014). Most of the time, the calving front is grounded (see video01, supplementary). Though, UI-3 shows an evolving floating tongue between 1900 and 1951.

In order to improve the understanding of the grounding line integration, we changed the manuscript in the following way: We removed grounding line in the abstract to take away to focus of it being a product of our method. We added the following sentences in section 3 and 3.2:

"The ice is allowed to float depending on a hydrostatic criterion (Seroussi et al., 2014)."

"Within the prescribed ice area, the grounding line is evolving freely and floating tongue formation is thereby allowed."

2. The model description could use a bit more detail. As far as I can tell the authors are using the SSA approximation as implemented in ISSM and inverting for basal friction to best match observed velocities. This is acceptable, but the authors should also tell us which sliding law was used. Back in the old days, models used to use a sliding law with friction proportional to velocity (Newtonian) because it was easy to implement. Now we know that the sliding law is rarely Newtonian, but some prefer a plastic bed, Coulomb plastic, Weertman or some combination of the three. For reasons related to my next point, it is important to provide the sliding law. The authors should also probably provide a map of the inferred basal friction parameter.

To clarify the used sliding law we include the tex below in section 3 and Figure 1 into the supplementary:

A Coulomb-like friction law is applied on grounded ice:

$$\tau_b = -C^2 \, N \, v_b \tag{1}$$

where v_b is the basal velocity, N the effective pressure on the glacier base and C is the friction coefficient (Fig 1, supplementary). Friction is not applied on floating ice.

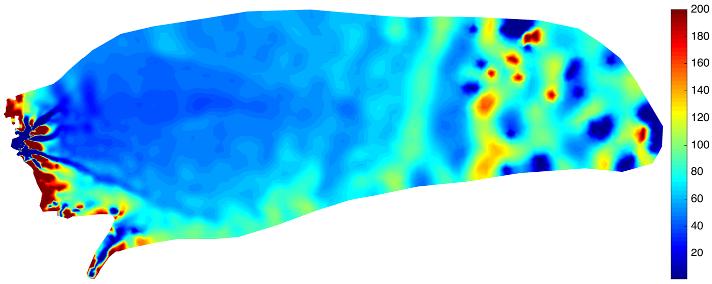

Figure 1. Inverted basal friction coefficient

3. As I understand it, the authors apply a prescribed surface mass balance along with prescribed changes in terminus position to simulate changes to the dynamics of the glacier system. Moreover, the authors use an inverse method to invert for the basal friction coefficients in their sliding law. Now ice dynamics models are based on approximations to the Stokes equations. A consequence of this is that if the geometry is appropriately specified and the boundary conditions are all correctly specified the velocity is completely determined. Because the authors are using observed velocities to tune the friction coefficients and prescribing changes in terminus position, it isn't all that surprising that they can simulate the correct dynamic response. In fact, it would be surprising if the model failed given the tuning step.

We indeed do constrain the ice margin and assume that the friction coefficient C does not change during the simulation, but the surface is allowed to change freely. We do not constrain the driving stress, which controls the ice dynamics. The fit between the observations and the model was therefore not necessarily expected since we perform our inversion reconstructed velocities from a first relaxation.

We re-formulate the description in the manuscript: "Thus, in the first relaxation basal friction is based on the assumption that driving stress is equal to basal stress at any given point using the initial geometry." and add Table 1 to give a better overview about the model initialisation steps.

What is surprising and impressive is that authors are able to get the correct dynamic response over a fairly long time interval. This seems like it is probably dictated, at least in part, by the choice of sliding law - which is why I think it is important to specify the sliding law and show us its pattern of spatial variation. Also, are the model results sensitive to the form or magnitude of the sliding coefficient. For example, do you get similar results for plastic, Coulomb and Weertman type sliding laws? How sensitive are the results to the inversion? Is the good agreement a consequence of extensive model tuning or relatively insensitive to model tuning? Related to this, the authors need to be careful when comparing observations of velocity with simulated velocity. Good agreement means the inversion was able to match surface velocities, but tells us nothing about the models skill.

As explained above, we apply a Coulomb-like friction law and invert for steady state velocity, not for observed ice surface velocity.

Table 1. Steps for model initialisation

Step	Input	Output
Relaxation 1	GIMP extended to 1849 terminus position, Ice viscosity (initial guess), Basal friction (initial guess)	Reconstructed 1849 ice thickness and velocity
Thermal	Ice thickness and velocity from relaxation 1	Improved ice viscosity
Inversion	Surface velocity from relaxation 1, Ice viscosity from thermal	Inverted basal friction
Relaxation 2	Ice thickness from relaxation 1, Ice viscosity from thermal, Basal friction from inversion	Steady state ice thickness and velocity

The control run that applies only surface mass balance to the model does not show the same pattern of acceleration. The prescribed terminus position changes lead to increasing ice flow. Previous simulations to this study did not include ice viscosity retrieved from a thermal solution and others where initialised with a previous bed topography version (Morlighem et al., 2014). The resulting velocity changes were the same. We conclude that the simulation results are not too sensitive to the inverted friction.

4. Related to this, I'm a bit confused by the metrics for model success. It seems to me as though the authors are comparing observations of mass balance to simulations of mass balance. However, surface mass balance is prescribed and changes in terminus position are prescribed so the only part of this that can vary is the increased dynamic discharge. Why not just compare simulated change in dynamic discharge predicted by their model with that inferred from observations. For example, Figure 2 shows annual mass loss along with change in mass loss from prescribed changes in terminus position. What about also showing mass loss from prescribed surface mass balance? Then we would clearly see the component that is predicted (dynamic discharge) and what is specified.

Good idea. We modify Figure 2b to visualize the portion of prescribed mass changes to simulated total mass change and add information about mass loss contributors to the text.

The more I think about it, it seems as though the observations probably give changes in trim line (or something like this) so maybe the right comparison is between predicted glacier surface elevation and observed trim lines (as opposed to ice thickness)? (I apologize to the authors if I misunderstood their data or comparisons).

Observations provide ice surface elevation from aerial photography and satellite. We only have trim line data for the little ice age extent. Following advice from Referee #1 we compare ice thickness results to observations instead of ice surface elevation.

As I said before, I also don't think that the authors can claim that the match between measured velocities and observed velocities provides any test of the model. Friction has been determined by tuning the model to match observed velocities so any match between observed and simulated velocities is partly a consequence of the tuning procedure. Here I think the authors might be able to narrate to readers a bit more thoroughly what they actually measured and what they predicted (without prescribing) and how the measurements can be used to test the things that the model predicted that weren't ingested in any tuning exercises.

As explained above, we invert for the relaxed velocity. Therefore, "tuning" is done for the initial state of the simulation, not for observed present day velocity. Furthermore, we compare observations to results after 160 years of simulation.

Some miscellaneous comments

Page line 13 extra space before

We could not find what you are referring to.

Don't capitalize Grounding line or Basal friction

Done.

Page 3 below 5: The ice temperature is determine by solving an advection-diffusion equation. The paper says the temperature field was initialized using surface air temperature. Does this mean the ice temperature was run to steady-state using the assumed surface air temperature?

We have divided up the explanation for ice viscosity, and have moved some parts of the explanation to section 3.1, Model Initialisation. The first part remains in the Introduction section in section 3:

"Ice viscosity follows Glen's Flow law (Glen, 1955). The initial viscosity is taken from Table 3.4 in Cuffey and Paterson (2010, p. 75), assuming ice temperature of -5°C and will be refined in section 3.1"

Further explanation is given in section 3.1 Model Initialisation:

"Given computed ice velocity and thickness from the first relaxation, ice viscosity and basal friction can be redefined. The ice viscosity is calculated by extruding the model with 15 layers and solving for the thermal steady state based on forcing the surface with 1854–1900 UI mean surface air temperature (Box, 2013)."

Page 3, line 10: The grounding line position is automatically calculated in each step implies that the terminus is at flotation. Why is this a good approximation and why is it forbidden for the terminus to have a thickness greater than flotation?

As explained above, the model includes a grounding line migration scheme. During the simulation, the glacier can evolve a terminus at flotation, but it is not forced to float. In most cases for our simulation, the grounding line is located directly at the terminus position.

I found a few other grammar mistakes throughout and I would urge the authors to give the manuscript one more proof read.

We improved the study regarding grammar and spelling.

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Simulating ice thickness and velocity evolution of Upernavik Isstrøm 1849–2012 by forcing prescribed terminus positions in ISSM

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Abstract. Tidewater glacier velocity and mass balance are ~~sensitive to terminus retreat~~known to be highly responsive to terminus position change. Yet, it remains challenging for ice flow models to reproduce observed ice ~~marginal~~ margin changes. Here, using the Ice Sheet System Model (ISSM; Larour et al., 2012) , we simulate the ~~1849–2012~~ ice velocity and thickness changes ~~on~~ of Upernavik Isstrøm ~~using the Ice Sheet System Model (ISSM; Larour et al., 2012) , by prescribing observed glacier terminus changes. We find that a realistic ISSM simulation of the past mass balance and velocity evolution of Upernavik Isstrøm is highly dependent on terminus retreat. At the end of the~~ (NW Greenland) by prescribing a collection of 27 observed terminus positions spanning 164 ~~year simulation, the 1990–2012 ice surface elevation and velocities are within ±20% of the observations. Thus, our model setup provides a realistic simulation of the~~ years (1849–2012~~evolution for Upernavik Isstrøm. Increased ice flow acceleration is simulated~~). The simulation shows increased ice velocity during the 1930s, the late 1970s and between 1995 and 2012 ~~, coinciding with increased prescribed~~ when terminus retreat was observed along with negative surface mass balance anomalies~~and terminus retreat. The simulation suggests three distinct periods of mass change~~. Three distinct mass balance states are evident in the reconstruction: (1849–1932) ~~having~~ with near zero mass balance, (1932–1992) with ice mass loss dominated by ice dynamical flow, and (1998–2012), ~~where~~ when increased retreat and negative surface mass balance anomalies lead to mass loss twice that of any earlier ~~year. The main products resulting from this study are~~ period. Over the multidecadal simulation, mass loss was dominated by thinning and acceleration responsible for 70 % of the total mass loss induced by prescribed change in terminus position. The remaining 30 % of the total ice mass loss resulted directly from prescribed terminus retreat and decreasing surface mass balance.
Although the method can not explain the cause of glacier retreat, it is a reconstruction of ice flow and geometry during 1849–2012 ~~reconstruction of surface elevation, velocity and grounding line position of Upernavik Isstrøm.~~ and can serve as a metric for evaluating simulations investigating the effect of calving laws.

1 Introduction

In recent decades, glaciers terminating into the ocean (tidewater glaciers) ~~show increasing melt rates and~~ have exhibited widespread thinning and velocity acceleration (e.g. Pritchard et al., 2009; Rignot et al., 2011; Velicogna et al., 2014; Khan et al., 2015). Increased air and ocean temperatures induce increased surface melt rates and frontal retreat (Podrasky et al., 2012; Rosenau et al., 2013; Moon et al., 2014), represented by submarine melt and iceberg ~~break-off (calving)~~calving. The Greenland ice sheet ~~consists of~~ has more than 240 tidewater ~~glaciers~~ glacier outlets (Rignot and Mouginot, 2012) and its mass balance is highly affected by changes in tidewater glacier discharge (van den Broeke et al., 2009; Bevan et al., 2012; McMillan et al., 2016). ~~Global sea level is influenced by~~ Greenland's ice mass changes ~~(e.g. Rignot et al., 2011; Gardner et al., 2013) and sea level~~ have dominated global sea level contributions of the past two decades (e.g. Rignot et al., 2011; Gardner et al., 2013) . Sea level projections rely on models to estimate discharge and Greenland's contribution to sea level that are coming more into line with observations (Shepherd and Nowicki, 2017) . However, ~~ice flow models still do not fully reproduce observed changes in calving front retreat and ice flow speed (Nick et al. (2009) , IPCC, 2013 chapter 13)~~accurate simulation of terminus position remains a major challenge (Nick et al., 2009, IPCC, 2013 chapter 13) .

Tidewater glacier retreat occurs due to calving (Benn et al., 2007; Nick et al., 2010) and submarine ~~frontal~~ melt (Motyka et al., 2011; O'Leary and Christoffersen, 2013; Morlighem et al., 2016a; Rignot et al., 2016). Yet, no universal calving law exists (Benn et al., 2007) and model approaches either (1) focus on the development and performance of a particular calving law (e.g. Cook et al., 2014; Todd and Christoffersen, 2014); (2)~~simplify the glacier simulation~~ simplify glacier simulations using flow line or flow band models (e.g. Nick et al., 2013; Lea et al., 2014), neglecting e.g. across-flow stresses or (3)~~are too complex and~~ determine glacier terminus changes on ice particle scale and are thereby not well suited for long-term studies (Åström et al., 2013, 2014).

Upernavik Isstrøm (UI), a set of West Greenland tidewater glaciers, has been the focus of several observational studies. Weidick (1958) compiled historical records of UI terminus positions between 1849 and 1953, concluding that terminus retreat had increased starting in the 1930s. Observed periods of increased UI terminus retreat in 1931 to 1946, in the late 1990s and in 2005–2009 correlate with elevated air temperatures (Andresen et al., 2014). Two ~~dynamic ice loss events~~ periods of increased dynamically driven ice loss took place on UI between 1985–2010 (Kjær et al., 2012) and were responsible for 80 % of the ice mass loss during 1985–2012 (Khan et al., 2013).~~Hence, previous~~

Previous studies either simulate tidewater glacier retreat with ice flow models or discuss observed terminus changes and its implications for tidewater glaciers. In this study, we combine observations and ice flow models by using observed terminus positions in the Ice Sheet System Model (ISSM; Larour et al., 2012) to simulate Upernavik's glacial system evolution from 1849, near the end of the Little Ice Age, to 2012. We reconstruct the 1849 ice surface elevation and force ISSM glacier terminus retreat with 27 observed terminus positions.

This study does not aim to simulate physically caused retreat, instead we evaluate the effects of changing termini on UI's ice surface elevation and velocity. We (1) investigate whether prescribed terminus change produces a realistic thinning and velocity history; (2) compare simulated mass loss, surface elevation and velocity changes with 1985–2012 observations; and

(3) correlate the calculated dynamic ice loss with observational studies. ISSM produces a ~~monthly~~ weekly reconstruction of UI ice ~~elevation, grounding line position,~~ thickness and surface velocity from 1849–2012.

2 Area and ~~Data~~data

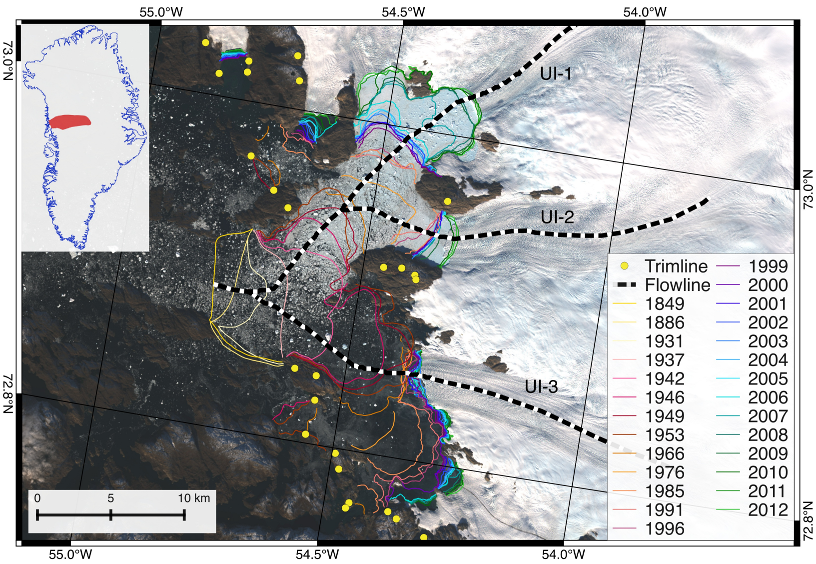

Figure 1. Upernavik Isstrøm's observed margin front positions between 1849 and 2012 (lines) and trimline positions (yellow dots; Kjeldsen et al., 2015). The background image is from Landsat 8 (September 2013). Inset is the location and shape of the Upernavik catchment (red area), ~~defined~~ determined by 2008/09 surface velocity from Rignot and Mouginot (2012), which define the model domain.

UI has a catchment area of ~~64,667~~ ~64,700 km^2, terminating into several tidewater glaciers. We ~~denote~~ focus on the three main glaciers ~~by~~ and denote them UI-1, UI-2 and UI-3 from north to south (Fig. 1). Historically, the three glaciers shared the same terminus between 1849 and 1931 ~~(Fig. 1; Weidick (1958)).~~ (Fig. 1; Weidick, 1958) . In the 1930s the glaciers separated in two, UI-1/UI-2 and UI-3. UI-1 and UI-2 decoupled after 1966. Historical front positions (Fig. 1) were collected from several sources: 1849–1953 (historical records; Weidick, 1958), 1966–1975 (satellite images; Andresen et al., 2014), 1985–1996 ~~(aerial photographies (1985) and satellite images; Khan et al., 2013)~~ (aerial photographs (1985) and satellite images; Khan et al., 2013) , 1999 to 2012 (satellite images; Jensen et al., 2016).

For initialisation and evaluation of the model we use data from different studies, described in Table 1.

Table 1. Data for ~~initializing~~ initialising and evaluating the simulation

Datum	Source	Description
Bed topography	~~Morlighem et al. (2016b)~~ Morlighem et al. (2017)	~~derived~~ Derived with mass conservation approach, extended with bathymetry measurements
Bathymetry measurement		2012 NASA project, led by Eric Rignot and Todd Dupont
Bathymetry measurement	Fenty et al. (2016); OMG Mission. (2016)	NASA project Oceans Melting Greenland OMG
Bathymetry measurement	Andresen et al. (2014)	~~ship-based~~ Ship-based single point echo sounders
~~Trim line~~ Trimline points	Kjeldsen et al. (2015)	Little Ice Age maximum extent (Fig. 1)
Surface mass balance (SMB)	Box (2013)	~~monthly~~ Monthly data, covering 1840–2012
1985 Digital elevation model (DEM)	Korsgaard et al. (2016)	~~based~~ Based on aerial photographs, 25 m resolution
2005 DEM	Howat and Eddy (2011)	Greenland Ice Sheet Mapping Project (GIMP), 30 m resolution
2012 DEM	Noh and Howat (2015)	ArcticDEM, 2–10 m resolution
Ice surface velocity	Rignot and Mouginot (2012)	~~winter~~ Winter 2008/09
Ice surface velocity	~~Nagler et al. (2017)~~ http://esa-icesheets-greenland.org/ (described in Nagler et al. (2017))	~~provided~~ Provided by ESA project Climate Change Initiative (CCI) Greenland Ice Sheet in winters between 1991/92 and 2008/09
Ice surface velocity	Howat (2016)	~~provided~~ Provided by MEaSUREs, in the winters 2000/01, 2007/08 and 2009/10
Ice surface elevation	Thomas and Studinger (2010); Krabill (2010, updated 2016)	~~from~~ IceBridge ATM; UI-1 in 2009–2012 and UI-3 in 1994, 1999, 2002, 2009, 2010, 2012
Mass change	Wiese et al. (2015); Watkins et al. (2015)	~~provided~~ Provided by the Jet Propulsion Laboratory (version: JPL RL05M GRACE mascon solution); suitable for regional (300 km scale) ice sheet mass change comparisons (Schlegel et al., 2016)

3 Ice ~~Flow Model~~flow model

We use the Ice Sheet System Model (ISSM; Larour et al., 2012), a finite-element thermomechanical ice flow model. Ice flow is calculated applying the Shelfy Stream Approximation (SSA; MacAyeal, 1989), ~~using~~ that integrates vertically averaged ice properties (e.g. ice rheology, thickness, velocity) and neglects vertical shear stresses. The SSA is well suited for fast-flowing glaciers like Upernavik, where the ice flow is primarily driven by basal sliding.~~SSA is a 2-D approximation of the 3-D Stokes equation with the ability of upstream ice pushing downstream by including the effects of longitudinal stress and neglecting lateral drag.~~

Ice viscosity ~~is given by~~ follows Glen's Flow law ~~(Cuffey and Paterson, 2010) , with temperature dependent, spatially varying ice viscosity parameter B, calculated by applying the 1964–1990 UI mean surface air temperature (Box, 2013) to table~~ (Glen, 1955) . The initial viscosity is taken from Table 3.4 in Cuffey and Paterson (2010, p. 75)~~. The mean time period is chosen, since surface air temperature and SMB are stable on UI during 1964–1990.The mesh~~ , assuming ice temperature of $-5°$C and will be refined in section 3.1.

A Coulomb-like friction law is applied on grounded ice:

$$\tau_b = -C^2 N v_b \tag{1}$$

where v_b is the basal velocity, N the effective pressure on the glacier base and C is the friction coefficient (Fig 1, supplementary). Friction is not applied on floating ice.

The model domain is set to the Upernavik catchment, which is defined by the flow direction given by the 2008/09 surface velocity from Rignot and Mouginot (2012) (red area in Fig. 1). We use an adaptive mesh that has a resolution ~~that varies~~ varying between 300–800 m in the area of observed terminus changes and 12 km near the ice divide, resulting in about 17,000 mesh elements. Resolution increases with larger changes in ice velocity (Rignot and Mouginot, 2012) or bedrock topography ~~(Morlighem et al., 2016b)~~ (Morlighem et al., 2017) and decreases stepwise with distance from the front.

~~The Grounding line position is automatically calculated in each simulation time step (Seroussi et al., 2014) .~~ We impose hydrostatic pressure at the terminus and keep the ice velocity and surface elevation constant at the inland boundary~~, setting ice surface velocity to the 2008/09 observed velocity (Rignot and Mouginot, 2012) and setting ice surface elevation to the GIMP DEM (Howat et al., 2014)~~ . No submarine frontal melt or calving rates are applied, since the study aims to simulate ice velocity and thickness changes caused by observational prescribed terminus changes. The ice is allowed to float depending on a hydrostatic criterion (Seroussi et al., 2014) .

3.1 Model ~~Initialisation~~initialisation

Since starting the simulation in 1849 extends the present day ice extent by 356 km^2, model initialisation requires reconstruction of ~~both~~ the ice surface elevation ~~and ice velocities~~ in the extended area. To initialise the model we thus reconstruct the 1849 ice surface elevation~~and velocity,~~ , as described in the following. Over the present day ice covered area, ~~ISSM is initialised with 2008/09 ice surface velocity (Rignot and Mouginot, 2012) and~~ the initial ice surface is given 2005 ice surface elevation

(GIMP; Howat et al., 2014). The present day ice surface velocity is extended to the 1849 ice extent along the flow lines, following fjord bathymetry. Away from the flow lines, missing velocity values are extrapolated. At the 1849 terminusmarine terminus (given by Weidick, 1958) , the ice surface elevation is set to 70 m a.s.l. consistent with marine termini in the area, based on IceBridge data (Krabill, 2010, updated 2016). Trimline data points (Fig. 1; Kjeldsen et al., 2015) mark the 1849 surface elevation and ice extent on the bedrock along the fjords. In the remaining area the ice surface elevation is interpolated. Given the new ice surface and the floatation criterion (Cuffey and Paterson, 2010) :

$$h_{float} = \frac{\rho_{water}}{\rho_{ice}} h_{water},$$

with ocean water density $\rho_{water} = 1,023 \mathrm{kgm}^{-3}$, ice density $\rho_{ice} = 917 \mathrm{kgm}^{-3}$ and the water depth h_{water}, we calculate the ice shelf floatation height h_{float}. Thus, the ice The ice thickness is set to h_{float} floatation height or to the maximum thickness, defined through the initialized initialised ice surface elevation and bed topography. The ice surface velocity is resolved performing a stress balance solution.

As we are interested in determining how the model geometry and velocity react to the prescribed terminus change and not internal model instability, we relax the model prior to the transient run, bringing ice surface elevation and velocity into equilibrium (following Schlegel et al. (2016)). Equilibrating model geometry and velocity requires constant forcing, i.e. a stable SMB. The SMB at Upernavik is found to be stable in 1854–1900 and 1964–1990. The mean 1854–1900 SMB value is used for equilibrating the model for 1849 conditions and 1964–1990 is set as the SMB reference period to evaluate simulated mass balance.

We perform two successive relaxations to equilibrate the model stepwise , each relaxation starting from previous relaxed model

Table 2. Steps for model initialisation

Step	Input	Output
Relaxation 1	GIMP extended to 1849 terminus position, Ice viscosity (initial guess), Basal friction (initial guess)	Reconstructed 1849 ice thickness and velocity
Thermal	Ice thickness and velocity from relaxation 1	Improved ice viscosity
Inversion	Surface velocity from relaxation 1, Ice viscosity from thermal	Inverted basal friction
Relaxation 2	Ice thickness from relaxation 1, Ice viscosity from thermal, Basal friction from inversion	Steady state ice thickness and velocity

applying relaxation runs stepwise (Table 2), keeping SMB constant to the 1854–1900 mean SMBvalue (Box, 2013) . The first relaxation recalculates ice surface elevation and velocity constrained by ice flow equations implemented in ISSM, to minimise inconsistencies between reconstructed ice surface elevation and velocity, resulting from data interpolation onto the mesh and

~~extrapolation. The basal friction coefficient for~~ provides reconstructed 1849 ice thickness, given the GIMP surface elevation extended to the 1849 terminus. Thus, in the first relaxation ~~is chosen so that the~~ basal friction is based on the assumption that driving stress is ~~balanced by basal drag~~ equal to basal stress at any given point ~~.~~using the initial geometry. ~~The first relaxation is stopped after 125years simulation and provides ice thickness and velocity for the second relaxation.~~Given computed ice velocity and thickness from the first relaxation, ice viscosity and basal friction can be redefined. The ~~Basal~~ ice viscosity is calculated by extruding the model with 15 layers and solving for the thermal steady state based on forcing the surface with 1854–1900 UI mean surface air temperature (Box, 2013) . The basal friction coefficient is constant in time, but varies in space, and is calculated by an adjoint-based inversion, following Morlighem et al. (2010) and MacAyeal (1993), ~~minimising the error between the observed velocity and the simulated velocity~~given the updated ice viscosity from the thermal steady state simulation.

The second relaxation runs for 5,000 years until ice velocity and thickness are equilibrated, provided with ice thickness from the first initialisation, simulated ice viscosity and inverted basal fricition. The end state of this relaxation provides the initial values of simulated ice ~~thickness, surface velocity and pressure at the bed~~ surface elevation and surface velocity for the 1849–2012 simulations.

3.2 Simulation ~~Setup~~setup

We run two different model simulations: (1) a control run $ISSM_{control}$, forced only by monthly SMB (Box, 2013) using a fixed terminus at the observed 1849 ice margin and (2) a prescribed terminus change simulation $ISSM_{PT}$, forced by monthly SMB and observed calving front positions. $ISSM_{control}$ serves to estimate the ice mass, velocity and ~~surface elevation~~ thickness changes that are simulated without prescribed terminus change.

The prescribed terminus position change in $ISSM_{PT}$ is implemented through a ~~levelset based~~ levelset-based method (Bondzio et al., 2016, 2017) and performed in July of the observation year, according to observed terminus positions (Fig. 1). The highest surface air temperatures and melt rates on UI are observed in July, increasing the likelihood of terminus retreat (van As et al., 2016). We introduce 20 additional calving front positions, ~~linearly interpolated~~ created through linear interpolation between the observed termini positions and constrained by the mesh resolution~~to reduce induced~~ . The additional calving fronts aim to improve realistic simulation behavior by splitting large ice area changes ~~that are causing numerical instabilities in the ice flow equations~~induced by the prescribed terminus changes into smaller areas within shorter time periods.

Within the prescribed ice area, the grounding line is evolving freely and floating tongue formation is thereby allowed.

The simulation evaluation time step is set to 73 h, constrained by the CFL condition (Courant et al., 1967), ensuring the numerical stability solving the ice flow equations at each time step.

4 Results and ~~Comparison~~comparison

During the simulation, most of the ice ~~surface elevation~~ thickness and velocity changes occur near the central flow lines of UI-1, UI-2 and UI-3. ~~Elevation and velocity changes~~ Simulated changes in ice thickness and velocity in the majority of the model domain (more than 70 km inland from the 2012 terminus or 5 km away form from the central flow lines of the three glaciers) are below 25 %, corresponding to below changes of 20 m and 10 m y^{-1} changesover 164 simulation years. Hence, in the following we present relative and absolute changes in ice velocity and surface elevation thickness along the central flow lines of UI-1, UI-2 and UI-3 (from the 2012 terminus reaching 30 km upstream ; (Fig. 1).

4.1 Model comparison

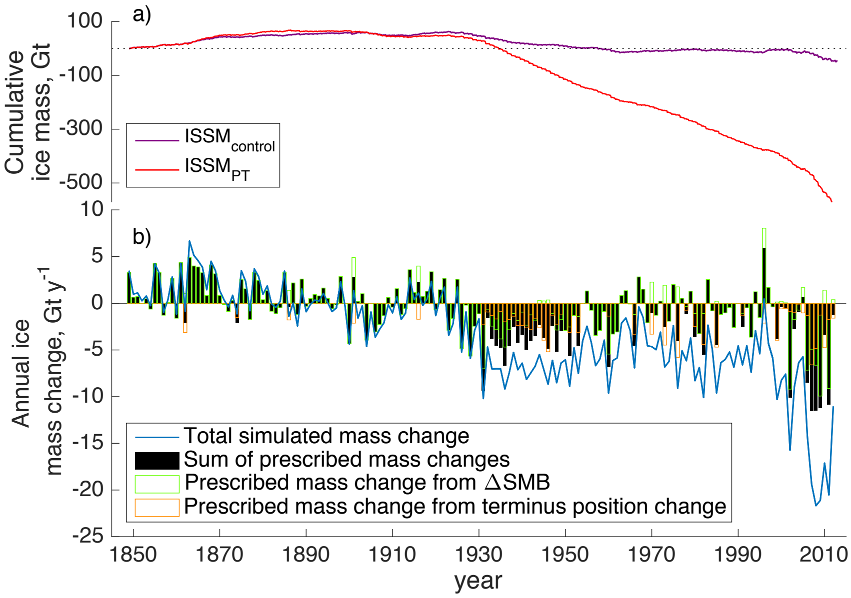

Figure 2. a) Simulated cumulative ice mass in Gt. ISSM$_{PT}$ changes are shown in red; control run changes in purple. b) The blue curve illustrates simulated annual change in ice loss mass for ISSM$_{PT}$. The black bars indicate the ice mass that is removed due to ΔSMB and prescribed change changes of the terminus position. The green outline marks the portion of mass change due to ΔSMB, and the orange outline the share of prescribed terminus change respectively.

Between 1849 and 2012, ISSM$_{control}$ shows less than 7 % surface elevation lowering and 6thinning and 5 % acceleration, simulating a change in velocity less than 120 m y^{-1} and a surface elevation lowering less than 10thinning less than 30 m along the central flow lines for the entire period. In contrast, ISSM$_{PT}$ produces on average 36a thinning between 20 % elevation lowering in 1849–2012, reaching up to 84along the flow lines and up to 60 % at the in the area between 2012UI-2 terminus terminus and 70 km upstream in 1849–2012, corresponding to thinning between 100 and 450 m along the flow lines. The average ice surface velocity increase along UI-1 and UI-2 is 180 % and on UI-3 is 47 % on UI-3. Cumulative ice mass loss over the simulation period of the entire model domain (converted from modelled water equivalent assuming 917 kg m^{-3} ice density) was by the end of the model simulation −4550 Gt for ISSM$_{control}$ and −585 Gt for ISSM$_{PT}$ (Fig. 2). The following section focuses on presenting 99 % of simulated ISSM$_{control}$ mass loss was prescribed by ΔSMB while 30 % of total ice mass loss simulated by

ISSM$_{PT}$ was prescribed, with ΔSMB accounting for 9 % (−50 Gt) and prescribed terminus position change contributed 21 % (−121 Gt). Thus, 70 % of by ISSM$_{PT}$ simulated mass loss is caused by thinning and acceleration. The succeeding subsections describe ISSM$_{PT}$ results in more detail.

4.2 Mass balance

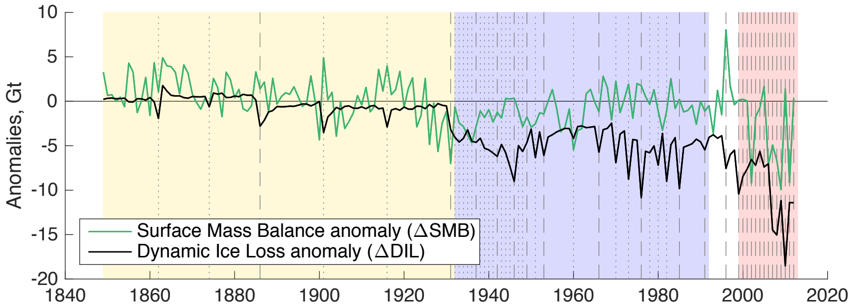

Figure 3. Simulated ice mass changes from anomalies (relative to 1964–1990 mean values) for the simulation ISSM$_{PT}$. The background is highlighted in yellow for periods of time where ΔSMB controlled MB, blue is where ice mass loss is driven by Δ~~SID~~ DIL and red, where ΔSMB and Δ~~SID~~ DIL have equally increased influence on the MB. Prescribed termini changes are marked with dashed (observations) and dotted (interpolation) lines.

In the following section we focus on the simulated mass balance (MB) through the model runs (see cumulated mass change in Fig. 2). For ~~tidewater~~ marine terminating glaciers, mass balance can be attributed to either changes in SMB or changes in dynamic ice loss (DIL). A tidewater glacier is in equilibrium, when SMB and DIL are in balance. Deviations in SMB and DIL change the glacier and its stability ~~, hereafter~~ hereafter referred to as anomalies ΔSMB and ΔDIL. SMB is a model input and ΔSMB are calculated relative to the mean value of the stable UI period 1964–1990 SMB. ΔDIL is calculated as the residual between the simulated MB and ΔSMB.

The simulated annual MB for the UI catchment (Fig. 2) is positive from 1849 to 1920. In this period, the MB from the ISSM$_{PT}$ and ISSM$_{control}$ are similar due to very few and small terminus changes (Fig. 2) and MB is thus dominated by ΔSMB. Anomalies in DIL (Fig. 3) are evident by small (−0.5 to −4 Gt) peaks that coincide with prescribed terminus retreat. After 1920, the MB becomes negative, except in 1996, when ΔSMB has a peak (8 Gt), which is attributed to a high winter accumulation (McConnell et al., 2001; Box et al., 2006). Figure 3 highlights three periods in MB trends: (1) 1849–1932, when MB is ~~close to zero~~near equilibrium, (2) from 1932 to 1992, when the negative ~~total~~ MB is driven by ΔDIL, and (3) 1998–2012, when SMB and DIL both have high negative anomalies and the total mass loss each year ~~is~~ was twice as high as any year before.

~~Simulated~~ Khan et al. (2013) and Larsen et al. (2016) measure surface elevation changes from aerial photographs, satellites and digital elevation models between 1985 and 2010. These yield a total mass change during different time periods and congruent to our calculations ΔDIL is estimated as the residual of mass change and ΔSMB. Both studies refer to different areas

Table 3. Observed vs. simulated ice mass changes (with $ISSM_{PT}$).

	Khan et al. (2013)[a]		Larsen et al. (2016)		
	1985 – 2002/05	2002/05 – 2010	2000 – 2005	2006 – 2008	2009 – 2011
Observed Total observed ice mass changes, Gt	-32 ± 9	-17 ± 10	-6 ± 20	-25 ± 14	-39 ± 17
Simulated Total simulated ice mass changes, Gt	-37 [b]	-32 [b]	-48	-41	-44
Observed dynamic ice loss, Gt	29 ± 9	12 ± 11	5 ± 10	16 ± 4	27 ± 4
Simulated dynamic ice loss, Gt	32 [b]	26 [b]	40	24	28

[a] converted from km^3 to Gt ice equivalent

[b]results from 2002/05 as mean values of that time

within the UI catchment. Table 3 presents a comparison of the observed mass changes and our simulation results, recalculated for the particular areas. Due to sparse data coverage Khan et al. (2013) combine surface elevation measurements acquired between 2002 and 2005 to quantify elevation changes and refer to this period as 2002/2005. The average of simulated ice mass loss between 2002 and 2005 is taken for comparison with the 2002/2005 observations from Khan et al. (2013) . Simulated total ice mass changes in 1985–2002/05 and 2009–2011 2005 and 2006–2011 correspond with observed ice mass changes from Kjær et al. (2012); Khan et al. (2013) Khan et al. (2013) and Larsen et al. (2016) (Table 3). In 2002/05–2010 and 2000–2005, simulated mass changes are 85% larger than the maximum of what is observed. DIL is 85% the mass change from 1985–2010. During Additionally, the DIL during 2000 to 2005 DIL is 85makes up 83 % of the mass change and in 2006–2011 the DIL is 60this percentage is reduced to 64 %of mass changes, in agreement with Khan et al. (2013) and Larsen et al. (2016). In 2000–2005, however, simulated total mass changes are 81 % larger than the maximum of what is observed.

A comparison with GRACE, that measures gravity field variations from which mass change is computed, shows equivalent seasonal mass loss fluctuations in summer and mass gain in winter with an overall negative trend. The simulated mass change rates resemble 98 % of GRACE's rate (see supplementary).

4.3 Ice surface elevationthickness

$ISSM_{PT}$ simulates 20–10010–80 % ice surface lowering thinning from 1849 to 2012 over an area reaching 5070 km upstream from the 2012 terminus (see supplementary). Transient surface elevation changes along the central flow lines of UI-1, UI-2 and UI-3 are visualised in movie01 (supplementary). The model simulation shows increased surface lowering in the time periods 1930/40, 1970/80 and from 2000 onwards.

Simulated surface elevation in To evaluate simulated ice thickness, we compare simulation results with the residual ice thickness obtained from observed surface elevation data and the bed topography from Morlighem et al. (2017) , that is used in the simulation setup. We refer to the supplementary for illustrations of spatial comparisons between simulation results and observations. Simulated thickness in 2005 lies within $\pm$2030 % of the observed surface elevation observed thickness (GIMP)and in 2012 it lies within −20 and −10, except in the shear margin regions of UI-1, where simulated ice thickness is too high by up to 160 % of observations. A comparison of absolute ice thickness in 2005 shows up to 200 m lower simulated thickness than observed, apart from the shear zones of UI-1, where the ice is up to 200 m thicker than observed. Differences between the simulated 2012 ice thickness and observations (ArcticDEM) show the same pattern with less difference in the UI-1 shear zone. The 1985 DEM based on aerial photographs (Korsgaard et al., 2016) ~~reaches~~ covers only the UI coastal area, reaching at most 40 km inland ~~. Simulated surface elevation is 60~~ and covering primarily the UI-3 area. Simulated ice is 20 to 100 % ~~higher~~ thicker around UI-1 and UI-2 than the 1985~~reconstruction~~ observations and 10 % ~~lower~~ thinner on average along UI-3.

NASA Operation IceBridge (Thomas and Studinger, 2010; Krabill, 2010, updated 2016) provides ice surface elevation along UI-1 (2009–2012) and UI-3 (1994, 1999, 2002, 2009, 2010, 2012). A mean value comparison along the UI-3 flow ~~lines~~ line illustrates that the simulated ice thickness is on average 10 % less than observations (Fig. 4)~~, illustrate that the simulated surface elevation is two third of that observed 0–5~~. The same comparison on UI-1 shows simulated ice thickness being 104 ~~km upstream of the 2012 terminus and 56-62~~% of observations close to the UI-1 terminus and 93 % of ~~that observed 5–10~~observed thickness 5 to 10 km upstream ~~of~~ the 2012~~terminus. Simulated surface elevations close to the UI-1 terminus resemble IceBridge observations to 90–100%. Further upstream, UI-1 simulation results are 70–80% of observed ice surface elevation.~~ terminus. Observed IceBridge and simulated surface elevation along flow lines 5 km downstream and 20 km upstream of the 2012 terminus have high correlation with R-squared values of ~~0.93~~ 0.80 for UI-1 and ~~0.97~~ 0.95 for UI-3.

$ISSM_{PT}$ simulates ~~trends in elevation that are equivalent to those of~~ the major thinning trends as described by Kjær et al.

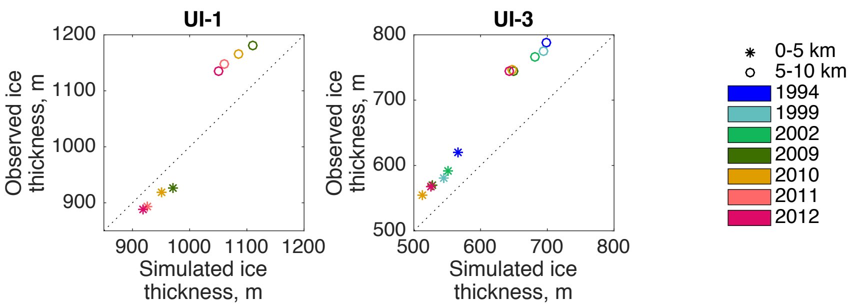

Figure 4. Observed vs. simulated ice ~~surface elevation~~ thickness along flight lines (IceBridge surface elevation data; Thomas and Studinger, 2010; Krabill, 2010, updated 2016) over UI-1 and UI-3. Stars mark mean values between 0 and 5 km from the 2012 terminus, dots refer to mean values 5–10 km upstream. Flight lines over UI-1 are available for the years 2009, 2010, 2011, 2012 and over UI-3 in the years 1994, 1999, 2002, 2009, 2010, 2012.

(2012) and Khan et al. (2013) between 1985 and 2010 on UI-1 and UI-3, though not on UI-2. Note that the observed thinning south of UI-3 between 1985 and 1991 (Khan et al., 2013) is not reproduced in $ISSM_{PT}$.

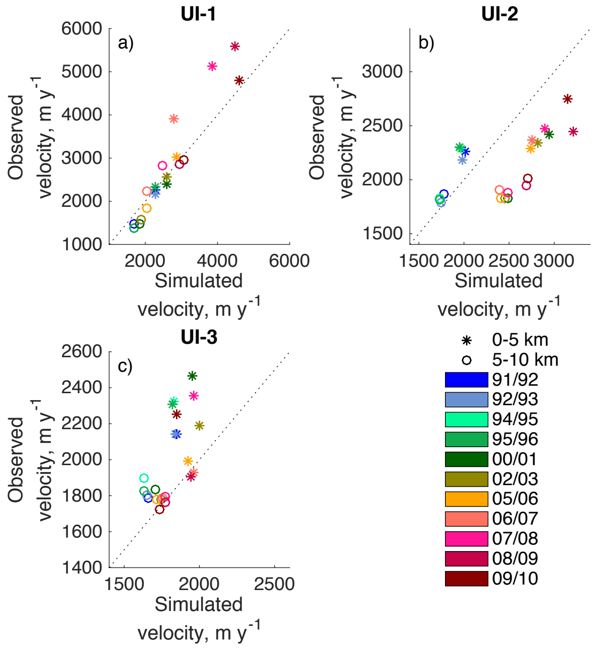

Figure 5. Observed vs. simulated ice surface ~~velocities~~ velocity along the central flow lines of UI-1, UI-2 and UI-3. Stars mark mean ~~velocities~~ velocity between 0 and 5 km from the 2012 terminus, dots refer to mean values 5–10 km upstream. ~~Velocity data in the winters of~~ Winter velocity maps for 1991/92, 1992/93, 1994/95, ~~1995/96,~~ 2002/03, 2005/06 ~~, 2006/07~~ and 2008/09 are ~~provided by CCI (Nagler et al., 2017)~~ produced from data available from http://esa-icesheets-greenland-cci.org/ and described in Nagler et al. (2017) . Winter velocity maps from 2000/01, 2007/08 and 2009/10 are given by MEaSUREs (Howat, 2016).

4.4 Ice surface velocity

By the end of the ISSM$_{PT}$ simulation, ice flow ~~velocities doubles~~ velocity has doubled at UI-1 and UI-2 and ~~accelerates~~ increased by 55 % at UI-3 compared to 1849. The simulated ice surface velocity evolution in plane view over the study period can be viewed in movie02 (supplementary). Short-term accelerations coincide with the induced ice mass change due to the prescribed terminus change (see movie01, supplementary). The simulation reproduces seasonal and annual velocity variations due to the SMB forcing in the model. Small (20 m y^{-1}) annual velocity fluctuations are forced by seasonal SMB fluctuations. Each retreat from the prescribed terminus change is followed by ~~an~~ acceleration between 1 and 70 % and 5–30 % surface lowering, lasting 0.5 to 6 months.

Simulated 2009 ice surface velocity is within ±20 % of observations from Rignot and Mouginot (2012), except in the shear margins, where simulated velocities are up to ~~200~~250 % ~~of~~ higher than observations. Winter velocity maps between 1991 and 2010 (Table 1) are used to evaluate recent changes in simulated velocity. Observed and simulated winter ice surface velocity averaged between 0 and 5 km and 5 to 10 km upstream of 2012 terminus (Fig. 5) have R-squared values of 0.90 on UI-1, 0.88

on UI-2 and 0.92 on UI-3. Observations show 20 % velocity increase on UI-1 from 07/08 to 08/09, however, this is not captured in $ISSM_{PT}$.

5 Discussion

The comparison of $ISSM_{PT}$ and $ISSM_{control}$ shows that the ice surface velocity and elevation thickness are significantly affected by the prescribed marginal changes. After each prescribed terminus change, $ISSM_{PT}$ simulates short (0.5 to 6 months) periods of faster flow (1–70 % acceleration), and the surface elevation lowers up to 30 % at the new terminus in response to the ice flow acceleration. These are dynamic readjustments to the instantly reduced terminal flow resistance from the prescribed retreat, which is induced in discrete time steps.

While $ISSM_{PT}$ produces maximum velocity and surface elevation changes of 275 % and 84 % respectively over the simulation period, $ISSM_{control}$ simulates minor changes (maximum ± 7 %) in ice velocity and surface elevation, describing only changes in thickness and velocity, representing sole mass changes prescribed by ΔSMB. This highlights the importance of simulated terminus retreat in order to reproduce a UI glacial system evolution. In 1985–2012, $ISSM_{PT}$ simulates mass changes similar to observations (Kjær et al., 2012; Khan et al., 2013; Larsen et al., 2016)and ice surface elevation being within 20% of GIMP or ArcticDEM and CCI or MEaSUREs velocity observations.

Recent studies suggest dividing mass balance into atmospheric and dynamically driven processes (Nick et al., 2009; Howat and Eddy, 2011; Kjær et al., 2012; Enderlin and Howat, 2013). Our simulation indicates three distinct MB periods when considering ΔSMB and ΔDIL. From the simulation start in 1849 to 1932, the total UI MB is the same for $ISSM_{control}$ and $ISSM_{PT}$, only diverging five times by one to four Gt y^{-1} when prescribed retreat is enforced. The increasing ΔSMB trend leads to a positive MB and thus mass gain. $ISSM_{PT}$ velocities start velocity starts to differ from $ISSM_{control}$ following the first prescribed retreat in 1862, showing a short (< 1 month) acceleration. The simulation indicates stable glacier behaviour without dynamically caused acceleration or thinning.

From 1925 onwards, ΔSMB reveals a negative trend, initiating the negative MB trend that lasts until the simulation end in 2012. Between 1931 and 1992, in two instances (1931–1960 and 1960–1992), 5–7 year periods of sustained less-positive SMB are followed by approximately 20 year long periods of elevated ΔDIL.

Within this these 60 years of simulation 31 terminus changes are prescribed, each removing 0.4–5 Gt of ice, which is as much as each of the five terminus changes the preceding 82 years (Fig. 2). The simulated mass loss in this period is therefore highly controlled by the prescribed retreat. ΔDIL consists of the removed ice mass at a prescribed retreat and of changes in ice mass flux caused by the acceleration of the glacier. We simulate two increased ΔDIL periods preceded by low ΔSMB as the result of observed terminus retreat. Induced by the prescribed terminus change in 1960 and 1966, a new period with increased ΔDIL lasts until 1992. UI's glaciers aim again for equilibrium, interrupted by seven prescribed terminus changes.

From 1999 onwards, ΔDIL and ΔSMB are roughly equivalent in contribution to the elevated negative MB. The simulation computes elevated dynamic ice loss due to 5.5 km terminus retreat on UI-1 within 12 years. We can not resolve, whether the increased retreat of UI-1 is due to (1) the change in ΔSMB from positive to negative values (+7 Gt to −7 Gt) or whether the glacier itself reaches an unstable position. However, as a result the retreat causes increased simulated ΔDIL adding up to the same amount as the increased negative ΔSMB. UI-2 shows similar behaviour. The result is a negative MB twice as negative as in any year before. In contrast, UI-3 is nearly stable, retreating ~~0.53~~ ~0.5 km between 1999 and 2012 and even advances in some years. It cannot be determined, whether UI-1 and UI-2 also will reach a stable position soon or whether they will continue to retreat and accelerate.

~~The simulation reproduces not only the retreat, but also the observed terminus advances~~ Although we primarily discuss prescribed ice margin retreat, it is worth mentioning that our method also includes advancing observed terminus position changes at UI-1 and UI-2 in summer 2012 and at UI-3 in the summers 2001, 2003 and 2007.~~However,~~

MEaSUREs data indicate 20 % speed-up on UI-1 from 2007–2008 to 2008–2009, when a large floating ice tongue breaks off (Larsen et al., 2016). ~~The~~ Yet, the observed acceleration is not captured by the simulation and may be related to unresolved loss ~~in~~ of buttressing in the simulation.

6 Conclusions

Our study shows that ~~glacier front changes are necessary for ice model simulations to reach realistic present day ice surface velocity and elevation. Prescribed~~ prescribing glacier front positions and surface mass balance are necessary to realistically simulate the multidecadal evolution of ice velocity and thickness at Upernavik Isstrøm. Our simulation suggests that dynamic response caused by prescribed terminus position change ~~avoids calving and melt rate estimations and reduces simulated retreat uncertainty. Dynamic ice discharge~~ is responsible for ~~80~~70 % ~~mass change in the 1985–2005 period and thereby plays~~ of the total simulated mass change. Thus, moving terminus positions play an important role for UI's acceleration and thinning. ~~$ISSM_{PT}$ captures~~ The simulation with prescribed terminus changes reproduces distinct mass loss periods of dynamically driven ice mass loss and extends the periods discussed in Kjær et al. (2012) and Khan et al. (2013) from 1985 to 1932.~~The method is applicable to different glaciers and time periods, since we realistically reconstruct the 164year UI glacial evolution matching observed velocity, surface elevation and mass changes within ±20% of observations, without any further assumptions.~~

~~Our approach is limited, since it needs defined terminus position changes throughout the simulation period, and it cannot be used~~ Prescribed terminus position change avoids calving and melt rate estimations and reduces simulated retreat uncertainty. Yet, our approach requires knowlegde about terminus positions and thus cannot be applied in future projections. However, the simulation results show the importance of ~~including calving into ice sheet models~~ calving in order to ~~capture~~ produce velocity and thickness ~~changes of a glacier~~change of tidewater glaciers. Better physically based calving laws are needed to understand and predict future glacier behaviour and glacier contribution to sea level rise. ~~Our method can help~~ The method of prescribed terminus change is a usefull tool evaluating calving laws ~~during past simulations before applying them in~~ or determining calving law parameters for hindcast simulations before they are applied to future simulations. Short-term simulations with prescribed terminus position ~~change might help answer the question,~~ changes can determine what observations are needed to evaluate and construct new calving laws, by establishing if seasonal terminus position variations are necessary to capture long-term glacier behaviour, to determine what data is needed to evaluate and construct new calving laws. Future work could include comparisons with the simulations using physically based calving laws (e.g. Bondzio et al., 2016; Morlighem et al., 2016a) and as well as the application of our method to other tidewater glaciers.

Author contributions. KH, NJS, EYL, JEB, KHK, KKK and SHL designed the study and setup the model. KH performed the study and data comparison and led the writing of the manuscript, in which she received input and feedback from all authors. MM created the bed geometry from bathymetry data, supoorted with data from ER and TKD. KKK provided trimline data and observed terminus positions. AMS processed winter ice surface velocity maps from ESA, CCI Greenland.

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

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