

1 Reviewer #1 (R. Gladstone)

Review of “Sensitivity of the dynamics of Pine Island Glacier, West Antarctica, to climate forcing for the next 50 years”.

The authors present a sensitivity study for short time scale (50 years) change in the Pine Island Glacier (PIG). This is not the first such study, but is novel in that a different ice sheet model is used, different forcings are used (in particular the ice shelf basal melt comes from a high resolution ocean model), and the experimental design is slightly different. This study is a useful contribution, and is clearly written. Their conclusions are qualitatively similar to previous studies in that the dynamic regime of PIG is most sensitive to basal melting due to ocean circulation patterns.

An important outstanding question in this area is whether positive feedbacks relating to marine ice sheet instability will cause rapid acceleration of PIG retreat, or whether PIG contribution to sea level rise will remain modest. This study supports the latter answer, and because of the importance of this question I suggest some additional simulations be shown to demonstrate the robustness of this interpretation.

My main concern is that the authors have not satisfactorily demonstrated the robustness of the insensitivity of PIG dynamics to basal melting under newly ungrounded regions as the grounding line retreats. They have carried out relevant simulations reported as “not shown”, but I feel these simulations really need to be presented in the main paper.

The authors also need to demonstrate that their results are not sensitive to changes in resolution, and that their region of high resolution is sufficient to capture grounding line retreat. I would suggest they show a plot of the model grid (with a colour scale for resolution if the resolution is too fine to show individual elements) with both the initial and final ($\alpha = 3$ scenario) grounding lines shown. I would suggest they also repeat their control and one of their sensitivity simulations with resolution in the vicinity of the grounding line either halved or doubled, to show that this does not impact on the results.

We thank R. Gladstone for his suggestions and addressed his remarks by including additional figures and running additional experiments with different mesh resolution. The manuscript now includes figures for the mesh resolution and grounding line retreat for the control run and $\alpha = 2$ melting scenario. We show the velocity and volume change for the experiments including melting under newly ungrounding areas that were not presented in the previous version of the manuscript to demonstrate that melting rate applied under newly ungrounded areas does not impact the results as the grounding line retreat is limited in all our experiments. We also run the control and $\alpha = 2$ melting scenarios with a resolution of 250 m in the grounding line area and show the results

in an appendix. Additionally, we run an experiment with basal melting parameterization similar to *Favier et al.* [2014] to demonstrate that the grounding line retreat strongly depends on the basal melting rate applied.

General comment on grammar: look up the use of the semi-colon. There are a few places where you should use a semi-colon rather than a comma (e.g. first line of conclusions).

Done

Line by line comments follow.

P1876 L9-15 Which satellite observations? Please expand. A list of references is not sufficient. Please provide at least one line summarising the data from this reference (e.g. obtained from satellite Joe using laser altimetry). The SMB reference is a Greenland one. Presumably you are using RACMO modelled SMB. State this explicitly and provide the correct reference for Antarctica. And are these data sets really ALL from 2008? If not, indicate which ones represent 2008 and which represent other periods. Later on you say The data used to initialize the model are acquired on different years so I am a bit confused about the significance of 2008.

The SMB reference was indeed a reference to Greenland instead of Antarctica. It has been corrected and details about all the satellite observations have been added, with appropriate acquisition times.

L16-17 Which year is this grounding line position?

The grounding line is from 2007.

P1877 L4 Please indicate the resolution in regions the grounding line retreats to during the sensitivity experiments. Does the grounding line remain in regions of 500m resolution for all simulations? Or does it retreat into coarser resolutions?

The grounding line only retreats in areas with fine mesh resolution (see figures 2 and 6).

P1878 L6 clarify that your ice front variations correspond to retreat not advance.

Done

L9 twice in terms of absolute change or a multiplication factor?

We clarified this sentence.

L16-25 any speculation on the cause of the floating adjustment? Is it purely due to interpolation of coarse data sets or is there a “real” signal in there?

I do not think that there is any real signal here; this is probably just caused by the combination of initial conditions and imposed forcings.

P1878 L26 onwards. Is this acceleration due to recent retreat of the g.l.? Perhaps if the g.l. was initialised slightly further ocean-wards the control simulation would show less change? This is not a criticism, I am just speculating.

The initial grounding line position indeed plays a role in the acceleration of the glacier observed in the simulations. However, if the grounding line was initialized slightly downstream, we would probably observe a large retreat during the simulation, which would also lead to an acceleration.

P1879 L11 Clarify that this -7 to 20 mm is over the 50 year period, not a change per year. P1880

Done

L22-24 This is a rather sweeping statement. Have you discussed which parts of PIG are “unconfined”? Certainly the largest front retreat simulation shows an impact on dynamics.

We clarified that large ice front retreats affect the glacier dynamics on the long term contrary to small ice front retreats.

P1881 L12-24 Why is the stress transferred further upstream in the current study? Which study is “right”? Did the other studies mentioned have more simplifications in their stress model?

It is difficult to figure out if one study is better than the other. This is a combination of the datasets and initial conditions applied as well as the stress balance model used in the simulation. Furthermore it remains difficult to compare the ice acceleration to previous studies, as the changes in velocities are rarely shown; only ice thinning rates are sometimes provided. We clarified this part.

P1883 L11-19 I think it would be good to show the “not shown” simulations here. I personally find it surprising that extending the melting beneath newly ungrounded ice doesnt affect your results. I would need to see some results from the relevant simulations to be fully convinced of this.

A figure has been added to show these results. As mentioned in the manuscript, the grounding line retreat over the 50 year simulation remains limited hence the

small impact of the melting beneath the newly ungrounded ice. If the grounding line were to retreat more significantly during the simulation, the melting beneath the ungrounded ice would have a much larger impact on our results.

P1884 L22 Pattern? You havent talked about the pattern much, but more about the magnitude. If, as you say, the omission of basal melt from newly ungrounded regions isnt important then perhaps the pattern of basal melt isnt important, only its magnitude is? Or maybe what you are working towards is this: buttressing is important in the portion of the floating shelf nearest the grounding line due to the geometry of the embayment, but is not so important near the ice front. In this case then any basal melting in the buttressed region would reduce buttressing, and any ice front retreat into this region would reduce buttressing, causing faster flow. But melting nearer the calving front, or modest retreat of the calving front, isnt going to impact much. This is also consistent with your front retreat sensitivity experiments.

We clarified the sentence.

L23-24 I dont quite follow this line. Ocean circulation changes and melting remains constant? Perhaps you need to omit the word changes? Changes cant remain constant! Or maybe I didnt understand what you wanted to say?

Thanks for pointing this ambiguity; we clarified the text.

Figure 4: the text in the figures is very small and hard to read. Colour looks the same for alpha 2.5 and 3 (b). Dashed lines not explained in caption (c). Perhaps dashed lines are for start of simulations and solid lines are for end of simulations? Best to make this clear in the caption. Would be good to see control simulation in each subplot. E.g. alpha =1 is control for top panels. Is front 1 already a retreat in middle panels? If so please add control to middle plots. At bottom beta = 1 would be the control I think.

We improved the figure and clarified the captions.

2 Reviewer #2 (Anonymous)

Authors, using the Ice Sheet System Model (ISSM), propose a sensitivity analysis of the dynamics of Pine Island Glacier following surface mass balance, melting and calving perturbations. This is a well written manuscript, with results apparently in line with most recent published work. This is original in the sense that this is the first time ISSM model is used with a mobile grounding line on an actual glacier and presented work may confirm or infirm precedent results. With that respect, this paper would clearly deserve publication as more studies on Pine Island Glacier must be done to better apprehend its forthcoming future. I however have one essential criticism detailed below that must be answered before publication could be envisaged.

As mentioned, this to is my knowledge the first time a dynamic grounding line is used in ISSM on an actual drainage basin. However, very (too) few details are given to be fully confident that the grounding line dynamics is modeled with enough accuracy. And estimating the contribution of PIG to SLR in the future is essentially a question of grounding line dynamics. In particular, I find astonishing to not see any figure showing grounding line positions during and at the end of at least one simulation! Regarding this issue, I think that the discussion on two specific points must be considered:

Are the results robust against the resolution (500 m) used in vicinity of the grounding line? A sensitivity analysis on the mesh size should be presented. In particular, it should be shown that a smaller grid size will not lead to a more extended retreat of the grounding line retreat and a larger ice discharge. Showing the region where mesh is refined sounds also important to me (i.e. show that the retreat is not limited because elements are becoming too coarse).

Authors mention a 10-km retreat. Please show it! And preferably with the elevation of the bedrock in background. How does this compare with recent results published by Favier et al. (2014) who claimed that no stable position could be found in the retrograde bed slope region? This also would require some discussion and positioning with/against Favier's results.

We thank the reviewer for his/her comments and suggestions to improve the paper. First, we would like to highlight the fact that we participated to the MIS3D and the implementation of the Grounding line migration has been validated [Pattyn et al., 2013].

In our simulations, the grounding line does not retreat over the main trunk. Favier et al. obtain similar results for the control run and m1 experiments. None of our simulations show that the grounding line is unstable. This is explained by the difference between the basal melting rates that we are applying (based on high-resolution MITgcm simulations), that are significantly lower than the ones used in Favier et al. [2014]. In one additional experiment, we use a similar parameterization of basal melting rates as the ones used in [Favier et al., 2014], and the grounding line retreats far upstream. We therefore argue that basal melting rates under floating ice are critical and precise estimates are needed in order to provide better projections of future ice sheet behavior.

Furthermore, in order to have consistent datasets with similar acquisition time, the bathymetry was slightly adjusted so that the initial grounding line position matches the observed 2007 position. Recent results show that the bedrock of Pine Island Glacier is likely to be 200 to 300 m deeper than provided in previous datasets [Rignot et al., 2014], which might also explain the limited grounding line retreat over the 50-year simulations.

Some other technical or more minor comments. p.1876, l. 24. Authors affect the bedrock elevation to ensure that the physics of the model is compatible with the geometry. I did not clearly understand whether the change has been

done below the ocean or below the grounded part. They mentioned that it impacts the bedrock elevation over 10km upstream the grounding line. Isn't it downstream? So, to my understanding, they modified the bedrock below the grounded part. How much does it affect the bedrock elevation? 10m, 500m? We know that the bedrock slope is crucial for the dynamics of the grounding line in this region, details should be given on the procedure and the impact on the elevation. Furthermore, there is a striking agreement between the 10 km where the bedrock may have been modified and the extension of the grounding line retreat. I guess it is a coincidence? Or is it an artifact? This must be clarified.

We thank the reviewer for pointing out this error, it has been clarified in the manuscript. The bathymetry is modified downstream of the grounding line, so there is no link between the grounding line retreat and the modified bathymetry.

p. 1877, l. 20. Authors have to relax the surface to avoid flux divergence anomalies. It is not clear to me whether the grounding line is allowed to move during this relaxation or not. If it is free to move, then does it move a lot? If the grounding line stays at its initial position during the relaxation, as the thickness is changing (figure 3), is there any problem when starting the projection (hydrostatic equilibrium not respected anymore)? This should be clarified.

The grounding line position is kept fixed during the relaxation period. We ensured that all previously floating ice still had a thickness smaller than the hydrostatic equilibrium thickness.

p. 1880, l. 2. "the time series diverge ... mass balance is affected both by changes in ice dynamics and enhanced basal melting". I agree because, as I understand, this is the change in volume that is plotted in figure 4. I would strongly suggest to not present the results in terms of total volume change but in terms of change in volume above floatation. This is the quantity which is meaningful in terms of sea-level rise equivalent (as the ice below the floatation surface will be replaced by water once melted or grounding line retreated) ... And in that case, only the dynamics or SMB over grounded ice shelf would affect the contribution.

Done

p. 1883, l. 24. "We choose not to change the pattern of basal melting, as we do not know how changes in ice shelf cavity will impact oceanic circulation and basal melting rates, and our results are therefore conservative estimates of changes". Saying that the estimations are conservative make the implicit assumption that the melt will somehow increase and amplify the dynamic response of the glacier. If we do not know how change in the cavity will affect the melt rate, it assumes that we do not know the trend. Therefore pretending that

it is a conservative estimate sounds as a strong hypothesis; melt may decrease. This should be reformulated.

We agree that it is very difficult to predict the impact of changes in the sub-ice shelf cavity on the circulation of the ocean, and therefore basal melting rate under floating ice. However, if the grounding line retreats, more ice is exposed to the ocean, it seems very likely that the total ocean induced melting will increase hence the mention of “conservative estimates”.

p. 1884, l. 2. ”Our results show that precise estimates of basal melting under floating ice are required and essential for constraining the evolution of the glacier dynamics”. In the previous paragraph (p. 1883, l. 11-19) the authors say ”Additional experiments (not shown here) show that introducing moderate melting rates under ungrounding ice does not affect our results”. So, affecting the melt distribution seems to not have a strong impact. Why accurate estimation of melt rate should be done? This sounds very contradictory to me.

We make a distinction between:

- melting rates beneath the ice shelf (which is critical)
- melt rates applied to the regions where the grounding line retreats (which is not essential since the grounding line retreat is limited in our simulations).

We clarified this sentence.

References

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- Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith and Kohler glaciers, West Antarctica from 1992 to 2011, *Geophys. Res. Lett.*, *in press*, 2014.

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Sensitivity of the dynamics of Pine Island Glacier, West Antarctica to climate forcing for the next 50 years

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Abstract

Pine Island Glacier, a major contributor to sea level rise in West Antarctica, has been undergoing significant changes over the last few decades. Here, we employ a three-dimensional, higher-order model to simulate its evolution over the next fifty years in response to changes in its surface mass balance, the position of its calving front and ocean-induced ice shelf melting. Simulations show that the largest climatic impact on ice dynamics is the rate of ice shelf melting, which rapidly affects the glacier speed over several hundreds of kilometers upstream of the grounding line. Our simulations show that the ~~speed-up~~ speedup observed in the 1990s and 2000s is consistent with an increase in sub-ice-shelf melting. According to our modeling results, even if the grounding line stabilizes for a few decades, we find that the glacier reaction can continue for several decades longer. Furthermore, Pine Island Glacier will continue to change rapidly over the coming decades and remain a major contributor to sea level rise, even if ocean-induced melting is reduced.

1 Introduction

Pine Island Glacier is one of the most active glaciers in Antarctica, with an ice discharge of more than 130 Gt/yr in 2013 (Mouginot et al., 2014; Medley et al., 2014). It has experienced dramatic changes over the past decades: its velocity has increased by more than 40% between 1996 and 2007 and its grounding line has been retreating at a rate of about 1 km/yr between 1992 and 2011, which resulted in the progressive ungrounding of its ice plain (Corr et al., 2001; Mouginot et al., 2014; Rignot et al., 2014). Satellite observations reveal an average rate of mass loss multiplied by 4 between 1995 and 2006 on the main trunk (Wingham et al., 2009). The changes in ice dynamics have been attributed to the presence of warm, subsurface water in the ocean (Rignot, 1998; Payne et al., 2004), which was observed for the first time in the 1990s (Jacobs et al., 1996). The recent increase in speed was attributed to the intrusion of warm water through a widening gap in the ice shelf cavity resulting from ice shelf thinning (Jacobs et al., 2011). It was however noted that since 2009 the glacier speed at the grounding line has reached a steady

value (Mouginot et al., 2014), which has been suggested to indicate a temporary stabilization of the glacier [grounding line](#) based on a two-dimensional model simulation (Joughin et al., 2010).

Earlier simulations with a two-dimensional model indicated a 10% increase in velocity from a 13% reduction in ice shelf extent, and a 70% speed up from the collapse of the entire ice shelf (Schmeltz et al., 2002). Thomas et al. (2004b) studied the impact of grounding line migration using a flow line (1-dimensional) model. They found that the grounding line retreat of Pine Island Glacier reduced the buttressing force on the grounded part of the glacier and had a stronger effect on glacier flow than changes in ice shelf extent or thickness. They showed that grounding line perturbations were transmitted almost instantaneously over long distances inland. Their model correctly predicted that the entire ice plain would unground in the following years if ice thinning rates remain unchanged and that the ice shelf would reach a flow speed of 4 km/yr. Using a 2D/3D mixed model, Payne et al. (2004) showed that the increase in ice shelf melting would reduce basal friction at the grounding line and changes would be transmitted upstream, more than 200 km inland, on a decadal timescale, by a diffusive process. More recently, Joughin et al. (2010) used a [simplified](#) 2D planview model with constrained grounding line dynamics and ice shelf margins to conclude that the grounding line retreat will be reduced [in the future for several decades](#) and the mass loss should remain steady. Using a volume continuity model, however, Thomas et al. (2011) found that grounding line retreat will be maintained and yield glacier speeds in excess of 10 km/yr within a few decades. Williams et al. (2012) concluded from a model study that high frequency forcings (decadal to sub-decadal) are transmitted by membrane stress and not by driving stress, and propagate rapidly several tens of kilometers inland. Favier et al. (2014) used a three-dimensional (3D) Full-Stokes (FS) model and parameterization of the ocean-induced melting rate to study the grounding line retreat of Pine Island Glacier. They showed that the grounding line of Pine Island Glacier is likely to have started an irreversible retreat on the downward sloping bed of the main trunk and that its contribution to sea level rise could reach 100 Gt/yr in the next 20 years.

Here, we use a 3D model that includes grounding line dynamics, data assimilation for basal friction and a high-resolution mesh to analyze the impact of external forcings on the ice flow dynamics of Pine Island Glacier. These external forcings are: (1) surface mass balance (SMB),

(2) calving front position and (3) ice-shelf melting. We discuss the impact of each external forcing on ice dynamics, i.e., on the velocity pattern over the entire basin. We compare our results with observations and conclude on the possible evolution of the glacier over the next 50 years.

2 Data and Methods

We initialize our numerical model to match ~~the satellite observations of satellite observations centered around~~ 2008. The surface elevation is a combination of satellite radar and laser altimetry from ICESat and ERS-1 (Bamber et al., 2009). The bed topography is from, ~~the bed topography from~~ ALBMAP (Le Brocq et al., 2010), ~~the ice-shelf thickness from derived from ground-penetrating radar measurements~~ (Lythe and Vaughan, 2001). Ice shelf thickness is retrieved from satellite radar altimetry from ERS-1 (Griggs and Bamber, 2011) and the sea-floor bathymetry under the floating part of Pine Island Glacier is from NASA's Operation IceBridge (OIB) gravimetry (Studinger et al., 2012). We employ surface temperature and SMB forcings (ice accumulation) from the regional atmospheric model RACMO2 (Lenaerts et al., 2012) and the geothermal heat flux ~~from~~ is inferred from satellite magnetic data (Maule et al., 2005). The model domain corresponds to the extent of Pine Island Glacier catchment basin, which is constrained by topography and ~~flow vector direction, with velocity data~~. The grounding line position from corresponds to the 2007 grounding line position derived from differential satellite synthetic-aperture radar interferometry (DInSAR) from ERS-1 and 2, RADARSAT-1 and 2 and ALOS PALSAR (Rignot et al., 2011b, 2014). We rely on melting rates reconstructions from the MITgcm using the OIB bathymetry (Schodlok et al., 2012). The melting rate is an average over a year and is kept constant throughout the simulation, so no additional melting is introduced if ice starts floating. Fig. 3 shows the basal melt rate distribution under the floating ice of Pine Island Glacier as well as its distribution with depth. As bathymetric and bed data remain sparse and do not match at the grounding line, we lower the bathymetry in the first 10 km upstream downstream of the grounding line so that hydrostatic equilibrium is consistent with the grounding line position. ~~This adjustment~~ The correction applied to the bathymetry lowers its elevation

up to 100 m over a spatially limited area. It restrains grounding line advance, which is consistent with recent observations (Rignot et al., 2011a).

We use the Ice Sheet System Model (ISSM) to perform our numerical experiments (Larour et al., 2012). A 3D higher-order approximation (Blatter, 1995) of the full-Stokes equations is applied to a 225,000 element mesh. The mesh horizontal resolution varies from 500 m near the grounding line to 10 km in the mountainous regions (see Fig. 2) and is vertically extruded in 14 non-uniform layers (thinner layers at the base). To initialize the model, the coefficient of basal friction is inferred using assimilation of InSAR derived surface velocity data of 2008 (Rignot et al., 2011a; Mougintot et al., 2012) on grounded ice, as described in Morlighem et al. (2010) (Fig. 1a). Basal friction is assumed to follow a linear viscous law. Ice rigidity is based on the values provided in (Cuffey and Paterson, 2010) assuming thermal steady-state on grounded ice and is inferred using data assimilation of surface velocity on floating ice. Ice temperature and hardness are updated at each step during data assimilation of basal friction for consistency (Morlighem et al., 2010). No additional tuning, such as melting rate correction or ad-hoc time dependent friction coefficient, is applied.

The data used to initialize the model are acquired on different years, with different instruments and at resolutions that range from 300 m for observed surface velocities (Rignot et al., 2011a) to several kilometers for bedrock topography (Le Brocq et al., 2010). These data are not always consistent and lead to large ice flux divergence anomalies in ice flow simulations (Seroussi et al., 2011). We therefore relax the model for 10 years with a fixed grounding line and using present-day forcings in order to reduce the spurious oscillations in ice thickness that exhibit large anomalies in the first years caused by the uncontrolled interpolation of ice thickness data on regular grids. An alternative would be to use mass continuity to improve the bedrock topography of the grounded part of Pine Island Glacier (Morlighem et al., 2011, 2013) but is beyond the scope of this study.

Simulations are run forward for 50 years with time steps of three weeks to satisfy the CFL condition (Courant et al., 1967). At each time step, the ice velocity, topography and grounding line position are updated. We use a floatation criterion for grounding line retreat: ice starts floating if it becomes thinner than the floatation thickness. Ice temperature is kept constant

during the simulation and ice thickness change is computed with a mass transport equation, stabilized with the streamline upwinding finite-element method.

We investigate the influence of external forcings through three model parameters. In the first set of experiments, we multiply the SMB (accumulation of ice) by a coefficient α varying between 0 and 3. In a second set of experiments, we ~~vary the~~ simulate the retreat of the ice front position from 0 to 40 km (Fig.1b); this is twice the distance between the 2011 ice front and the position of the current rift that calved in November 2013 (Howat et al., 2012). In a final experiment, we multiply the ocean induced melting rate pattern from the MITgcm by a coefficient β that varies between 1 and ~~2, which is twice the estimated increase in~~ 2. A study by Jacobs et al. (2011) estimated that the ocean induced melt water under Pine Island ice shelf between 1994 and 2009 increase by 50%, so our multiplication factor is twice the observed increase rate over this period. In the SMB experiments, we chose a range of α such that the volume change is larger than the melting experiments. SMB, front position and melting rates are then kept constant during all the simulations. These experiments simulate changes that are twice as large as what have been recently observed.

3 Results

Model initialization is in good agreement with observations, with an average velocity difference of about 13 m/yr between modeled (Fig.1a) and observed velocities from 2008. During the 10 years of relaxation, the ice thickness mainly adjusts on the floating part of the glacier, with about 100 m of thickening downstream of the grounding line along the main trunk and thinning up to 150 m on the rest of the floating ice. Changes on grounded ice are more local and of smaller amplitude (Fig. 4a). Velocity is also mainly changing over the floating part of the glacier, with a speed up of 300 m/yr along the shear margins and slowdown of about 150 m/yr at the grounding line of the main trunk (Fig. 4b). A small acceleration of the main trunk and the main tributaries is also observed.

The glacier evolution during the 50 years of the simulation under present day conditions shows an increase in velocity over the ice shelf, from 3.7 km/yr in its initial state to 4.5 km/yr

after 50 years of evolution. This change in speed propagates several hundreds of kilometers inland: the model shows an increase in speed of 200 m/yr, or 20%, 100 km upstream of the grounding line, in areas where initial speed is 1.0 km/yr. Changes in flow speed are detected all the way to the flanks of the glacier topographic divides; most of the glacier speeds up by 20%. Ice thinning is equivalent to a total of 11 mm of sea level rise after 50 years, or 78 Gt/yr.

The first sensitivity experiments (Fig.5a) show that changes in SMB do not affect the ice dynamics over 50-year simulations: ice speed changes by less than 0.1% when SMB is multiplied by a factor 3 compared to current values. Changes in SMB, however, lead to variations in glacier volume above floatation (Fig.5b) equivalent to a sea level variation between -7 mm and +20 mm. ~~The glacier volume over 50 years. The volume above floatation~~ remains constant when SMB is doubled. Time series of ~~glacier volume~~ volume change are quasi linear because ~~the volume changes~~ changes in volume above floatation do not involve any change in ice dynamics.

Changes in ice front position have an immediate effect on ice velocity (Fig.5c), and make the ice front velocity vary from 3.7 to 5.4 km/yr. After 50 years, the ice front velocities stabilize at the same speed, except in the case of very large retreats (> 25 km, with more than half of the ice shelf being removed). Hence, changes in ice front position have only a moderate impact on long-term glacier speed. Changes in ice front position, however, ~~are immediately followed by a reduction in ice volume~~ do not impact the volume above floatation of the glacier (Fig.5d). ~~After the initial response,~~ The rate of volume change is similar for all front retreat except for ~~very large~~ the most extreme retreat as all experiments lead to a similar discharge after 50 years as noted above. The perturbations introduced here do not destabilize the glacier, ~~so the ice front is likely to readvance again and the volume change between the different scenarios to be reduced. However, the model used in this study does not allow evolution and do not affect its dynamic on the long except when very large ice front retreats are introduced, as areas of the ice front, so it remains fixed after the initial perturbations~~ shelf actively buttressing the ice stream are removed in this case.

Sensitivity to basal melting under floating ice is shown in Fig.5e,f. A doubling of the basal melting rate leads to a velocity increased of 800 m/yr on the floating part of the glacier (Fig.5e). Acceleration is not limited to the floating part but propagates hundreds of kilometers inland in 1

to 5 years. Increased melting also leads to ~~ice volume decrease~~ a decrease in ice volume above floatation (Fig.5f). The time series of ~~ice volume diverges with time~~, because the glacier mass balance is affected by both changes in ice dynamics and enhanced basal melting volume above floatation show an increased contribution with time as the glacier is accelerating in response to changes in basal melting rate. Multiplying the basal melting by a factor of two leads to an additional ice volume loss of 5.4 mm of sea level equivalent.

Fig.7a-c and g show the pattern of velocity change in the first 15 years of simulation in the case of a basal melting rate increase by 50%. The acceleration has the same pattern as the velocity and is not limited to the main trunk of Pine Island Glacier but affects almost its entire drainage system: a velocity increase of more than 200 m/yr in the first 15 years affects all tributaries flowing above 500 m/yr.

In all the above scenarios, variations in the grounding line position are small ~~, which is~~ and grounding line positions remain in areas with a fine mesh resolution. Fig. 6a shows the grounding line position at the beginning of the simulations and at the end of the melting scenarios for $\beta = 1$ and $\beta = 2$. The grounding line retreats by no more than 10 km during the 50-year simulations and is very limited over the main trunk. Using a finer mesh resolution did not change the results, proving that grounding line retreat is not limited by a too coarse mesh resolution (see appendix and fig. 6b) but by the glacier topography and basal melting rate values applied here. This retreat is consistent with Joughin et al. (2010) and follows one of the two retreat modes modeled in the ensemble runs of Gladstone et al. (2012), ~~the~~. The other mode of retreat being grounding line retreat ~~rates~~ of several hundreds of kilometers per century. ~~In our simulations, grounding line position retreats by no more than 10 km during the 50-year simulations, experiments with increased basal melting lead to the largest grounding line retreat~~ This mode is consistent with control run and m1 scenarios of Favier et al. (2014), but does not agree with the other scenarios: none of our simulations show that the grounding line is unstable. This is explained by the difference between the basal melting rates that we are applying (based on high-resolution MITgcm simulations), which are significantly lower than the ones used in Favier et al. (2014).

4 Discussion

~~Both changes in~~ Changes in both SMB and basal melting affect Pine Island Glacier's volume, but basal melting under floating ice is the only modeled forcing that affects the glacier's dynamics on the timescales under study here. Increased basal melting causes thinning of floating ice that leads both to a reduction in buttressing from the ice shelf and a grounding line retreat. Experiments focusing on ice front retreat also confirm that limited ice front retreat over an unconfined part of the ice shelf, due to calving events for example, have no long-term effect on the glacier's dynamics.

In their study of Pine Island Glacier, Favier et al. (2014) show that the grounding line of Pine Island Glacier is engaged on an unstable 40 km retreat and that the glacier is controlled by marine ice sheet instability. Their results also show that limited ice front retreats do not affect grounding line dynamics while changes in basal melting rates under floating ice strongly impact grounding line motion. In their control experiment, the basal melting is parameterized to match certain recent observations (Dutrieux et al., 2013). A small reduction in grounded ice area is observed in this case, which is similar to the results reported here. Their simulations show that if basal melting increases and extends to a larger portion of the ice shelf, the grounding line starts an unstable retreat along the 40 km retrograde slope. In our simulations, even in the case of doubled melting rate, the grounding line position does not retreat more than 10 km. This is probably caused by the different patterns of melting rates: basal melting rates in Favier et al. (2014) are as high as 100 m/yr over large areas, while only a few points have melting rates above 50 m/yr in our study. In an additional experiment, we use a similar parameterization of basal melting rates as the ones used in Favier et al. (2014) (no melting the for ice shelf base above -200 m, melting linearly increasing with depth until it reaches 200 m/yr at -800 m and equal to 200 m/yr for elevations lower than -800 m). The grounding line retreats over 30 km upstream, which is similar to the results of Favier et al. (2014) (fig. 10)). This confirms that the applied basal melting rate is critical for simulations of ice stream dynamics and grounding line retreat.

Our simulations reveal that even if increased basal melting causes limited grounding line

retreats, it reduces the buttressing from the ice shelf as the ice is thinning, which leads to a speed up of Pine Island Glacier. A change in basal melting not only affects ice velocity in the floating part of the glacier: acceleration propagates inland, and reaches the flanks of the ice divide, as predicted by Williams et al. (2012) for decadal forcings. Our simulated accelerations are difficult to compare with previous results as acceleration is rarely provided. However, they propagate further inland than in ~~prior studies:~~ most prior studies; we obtain a velocity increase of about 100 m/yr up to 200 km upstream of the grounding line, through ~~the~~ a combination of transmission of membrane stress and ~~not by~~ driving stress or diffusive processes. In previous studies, a similar speed up is confined to the first 70 km upstream of the grounding line in Payne et al. (2004) and to the first 120 km in Thomas et al. (2004a). In Joughin et al. (2010), the ~~acceleration is confined to the floating area, except in the case of a plastic bed for which it propagates over the first 50~~ thinning rate propagates inland and reaches 1 m/yr 100 km upstream of the grounding line after a decade.

Comparison of the first 15 years of simulation with satellite observations of previous acceleration of Pine Island Glacier in the 1990s and 2000s (Mouginot et al., 2014) (Fig.7d-f) provides qualitative estimates as model and observations are from different years. It shows that the patterns of modeled acceleration due to enhanced sub-ice-shelf melting ($\alpha = 1.5$) are in agreement with the observed glacier acceleration, with similar patterns after 10 and 15 years. Modeled velocities differ from observations along the side margins of the ice shelf: in this region, ice accelerates more in the model than in the observations (1000 m/yr in the first ten years of simulation vs 800 m/yr between the 1996 and 2006 observations). Our simulation shows an acceleration of the main trunk and most of its tributaries (Fig.7b,e) similar to previous changes observed in the past decades. Acceleration in the area just upstream of the grounding line is smaller in our simulations than in the observations (700 m/yr on average in the ice plain after 15 years of simulations vs 900 m/yr in the observations, fig.7g), suggesting that our results underestimate the actual speed up of Pine Island Glacier. This acceleration is difficult to compare to that inferred in prior studies, which mainly focused on the glacier centerline.

In an additional experiment (fig. 8a) we increase sub-ice-shelf melting for a limited time. In this simulation, basal melting from the MITgcm is multiplied by 1.5 for the first five or fifteen

years and then switched back to its initial value. The ice shelf velocity increases and reaches ~ 4.9 km/yr in both cases after 50 years compared with 5.0 km/yr when increased basal melting (also multiplied by 1.5) is kept constant over the entire 50 year simulation. In the control run where basal melting from MITgcm is directly used, the ice shelf velocity after 50 years is 4.5 km/yr. This indicates that a temporary increase in basal melting rates has a long-term impact on ice dynamics and that Pine Island Glacier will not slow down and stabilize even if ocean conditions were to return to what they were a few decades ago. This conclusion is consistent with the marine instability hypothesis that states that glaciers on downward sloping bed inland are intrinsically unstable (Weertman, 1974; Schoof, 2007) and with recent studies of Pine Island Glacier (Favier et al., 2014). Change in glacier volume [above floatation](#) after 50 years is almost identical if basal melting rate is increased for 5 or 15 years (fig.8b) and about 0.4 mm of sea level equivalent lower than if increased melting is kept constant for 50 years.

Our study provides estimates of climate sensitivity of Pine Island Glacier based on a 3D higher-order formulation, with a high resolution in the grounding line area. No melting rate or surface accumulation correction is introduced to start with a model in steady-state condition (Joughin et al., 2010; Cornford et al., 2013), and no additional parameterization is needed to include buttressing, reduction of basal friction, contrary to most of the studies performed with flowband models. We have shown in another study that errors in ice rigidity and basal friction do not affect the results significantly for these short-term simulations (Seroussi et al., 2013). Our model has however some limitations, such as a fixed ice front that can only be changed manually, no rheological weakening of the floating ice and a grounding line that is not based on contact mechanics, which would be too computationally intensive for this kind of sensitivity experiments.

In all our simulations, the pattern of basal melting is kept constant with time. Additional experiments ~~(not shown here)~~ show that introducing moderate melting rates under ungrounding ice does not affect our results, ~~as~~ [Fig. 9 shows the ice velocity and ice volume above floatation if we apply in the areas that unground either the average basal melting rate under floating ice or the highest value of melting rate. Results show that applying the average basal melting rate value has a small impact on the simulations while extreme melting leads to variations comparable to](#)

a doubling of the basal melting rate over the floating area. This result is not surprising, as the grounding line retreat remains limited in our 50-year simulations all our experiments. This is also confirmed by results of Favier et al. (2014):; they run two experiments with similar basal melting parameterization. In the first one, basal melting is turned on as grounded ice starts floating, while in the second one, basal melting is limited to the initial floating part of the glacier. Results of these two experiments are very similar in terms of both grounded area and sea level rise. ~~The assumption made in our experiments should therefore not affect our,~~ confirming our results.

Melting rates are kept constant throughout the simulations, while we know that changes in ice shelf cavity will affect their amplitude and spatial distribution (Schodlok et al., 2012). We choose not to change the pattern of basal melting, as we do not know how changes in ice shelf cavity will impact oceanic circulation and basal melting rates, and our results are therefore conservative estimates of changes. Melting rate parameterizations (Pollard and DeConto, 2009; Little et al., 2009) provide a first estimate but do not include specifics for each glacier. Results from the MITgcm highlight that no simple parameterization of basal melting rate based on ice shelf depth for example can be derived (fig. 3). Recent observations in the bay adjacent to Pine Island glacier also report the large temporal variability of ocean heat and oceanic induced melting in this area (Dutrieux et al., 2014). Our results show that precise estimates of basal melting under floating ice are required and essential for constraining the evolution of ~~the glacier dynamics~~ glacier dynamics, as a modest increase of 10% in basal melting rates impacts ice sheet dynamics. To achieve this goal, however, progress is necessary in the modeling of ice-ocean interactions beneath the ice shelves with coupled ice-sheet/ocean/atmosphere models (Schodlok et al., 2012). Finally, our simulations suggest that the ~~mass loss from~~ acceleration of Pine Island Glacier will continue to propagate inland and its mass loss will continue for decades to come, even if the oceanic conditions return to their state prior to the 1990s and the grounding line position remains stable for a few decades. Similarly, if more ocean heat reaches the grounding line area, the mass loss will continue to increase for decades to come, with no sign of stabilization.

5 Conclusions

Our study shows that Pine Island Glacier is highly sensitive to basal melting under its floating extension; this parameter controls most of the dynamics of this glacier, even if grounding line retreat remains limited. ~~Changes~~The effect of changes in sub-ice-shelf melting ~~not only affect are not limited to~~ the floating tongue and grounding line area but are rapidly transmitted hundreds of kilometers inland. Increase in sub-ice-shelf melting for only five ~~year~~years destabilizes the glacier for several decades and has a long-term impact on its dynamics. A qualitative comparison of our model results with satellite observations of the 1990s and 2000s shows the good qualitative agreement between modeled and observed accelerations and suggests that the glacier speed-up is consistent with increased basal melting under the ice shelf, although not exactly from the same time period. Coupling of ~~the~~ice sheet with ocean circulation models is therefore desired for future studies to conduct more accurate simulations, as the glacier is controlled by ~~the pattern of~~ ocean induced melting rates. Overall, Pine Island Glacier is likely to keep accelerating over the coming decades, even if ocean circulation ~~changes and melting remains constant~~and melting remain unchanged and the grounding line temporarily stabilizes over a local feature in the bedrock topography.

Appendix A Sensitivity to mesh resolution

To show that our results are not sensitive to the mesh resolution and that the grounding line retreat is not affected by the size of the elements, we performed two experiments with a mesh resolution divided by two (a resolution of 250 m in the grounding line area): the control experiment with the initial basal melting under floating ice from the ocean model ($\beta = 1$) and the extreme melt experiment with a basal melting multiplied by $\beta = 2$.

The grounding line positions at the beginning and the end of the simulations are shown on fig. 6b. The results are in excellent agreement with the initial mesh that has a resolution of 500 m in the grounding line area (fig. 6a), demonstrating that the mesh resolution is not a limiting factor for the grounding line retreat in our experiments.

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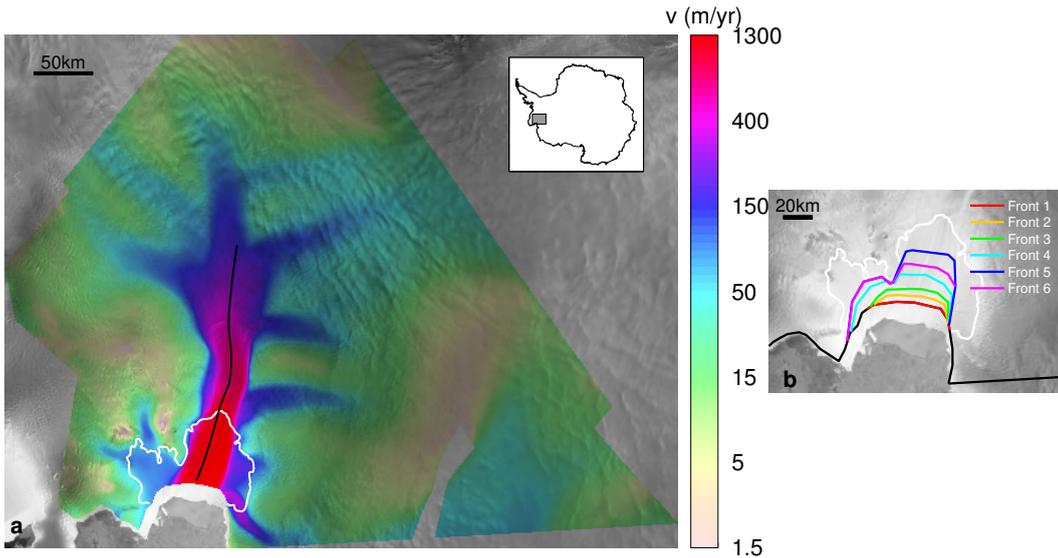


Fig. 1. (a) Initial modeled 2008 velocity of Pine Island Glacier, overlain on a MODIS Mosaic of Antarctica with initial grounding line (white) and centerline (black). (b) Ice front positions used in the sensitivity study.

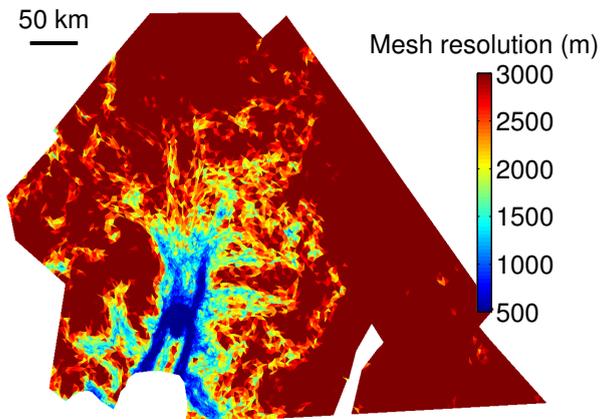


Fig. 2. Mesh resolution (in m) used in the simulations.

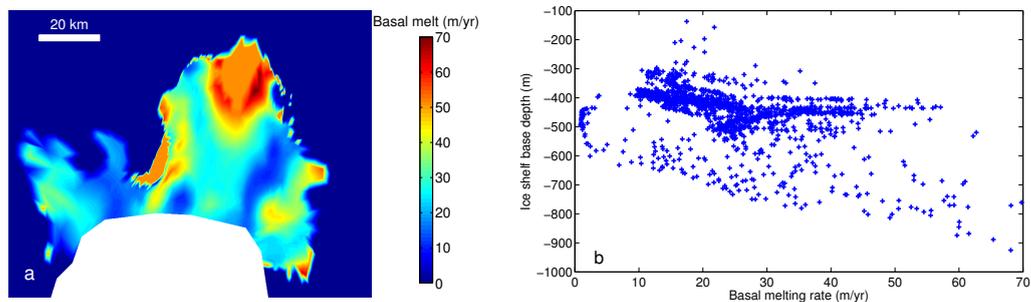


Fig. 3. (a) Basal melting rate (in m/yr) from the MITgcm filled with constants values (50 m/yr) over areas not covered but by the MITgcm. (b) Basal melting rate values (in m/yr) from the MITgcm represented as a function of ice shelf base depth.

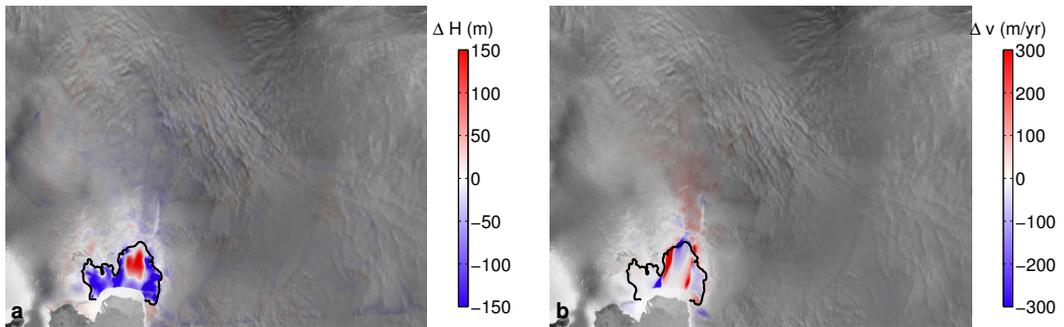


Fig. 4. (a) Thickness change (in m) and (b) velocity change (in m/yr) during the 10-year relaxation period overlain on a MODIS Mosaic of Antarctica. Black line represents the grounding line.

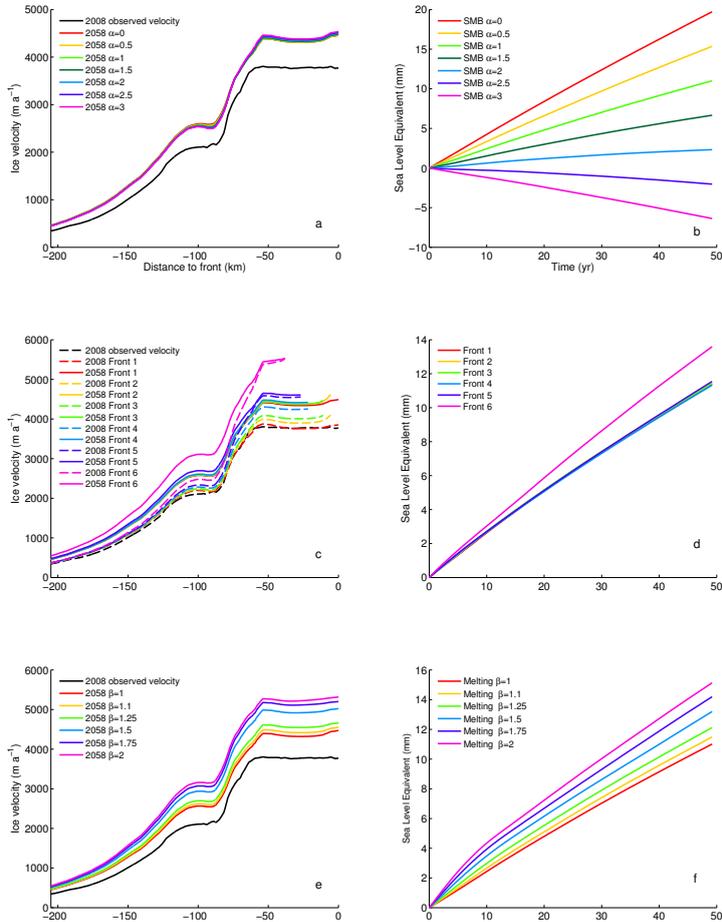


Fig. 5. Modeled velocity sensitivity (left column) and volume [above flotation](#) sensitivity (right column) to (a-b) surface mass balance; (c-d) ice front position and (e-f) ice shelf melting. [Solid lines on the left column represent the ice velocity at the end of the simulation and dashed line the initial velocity after ice front retreat when ice front position is changed.](#)

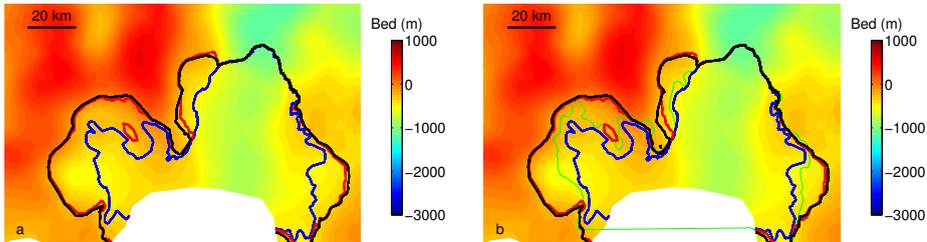


Fig. 6. Grounding line position at the beginning of the experiments (blue line), and at the end of the melting experiments in the case of $\beta = 1$ (red line) and $\beta = 2$ (black line) overlain on the bedrock elevation. The mesh resolution is 500 m (a) and 250 m (b) in the grounding line area.

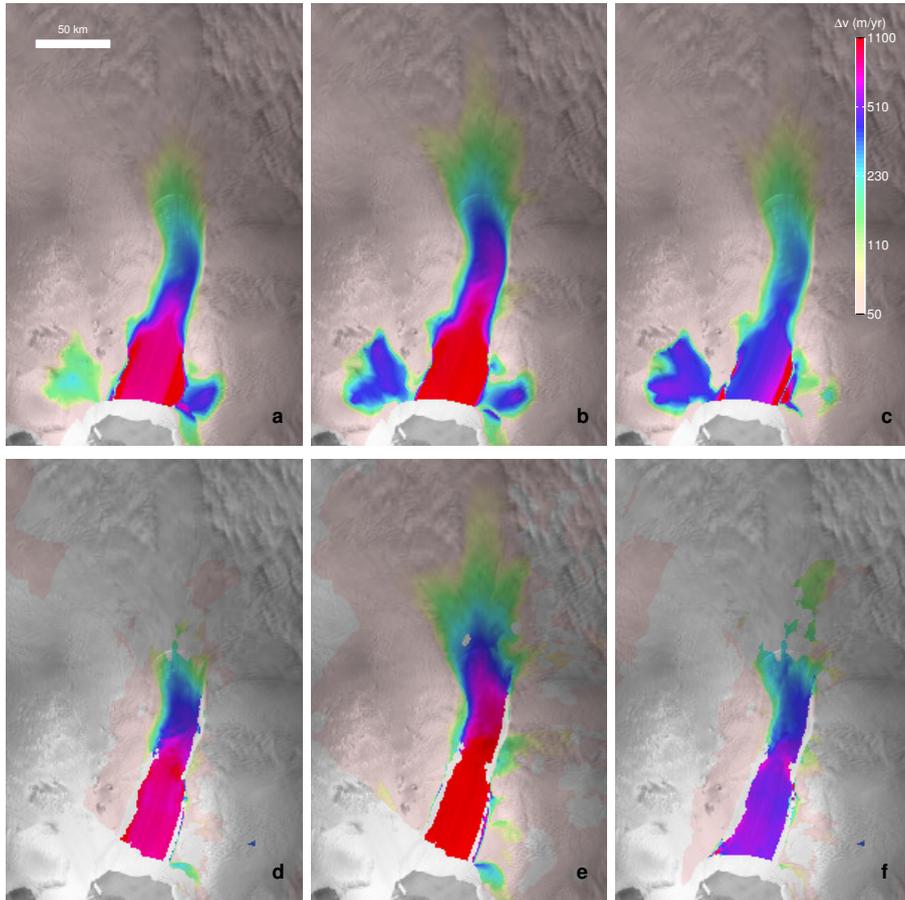


Fig. 7. Changes in observed and modeled velocities in m/yr on a logarithmic scale. (a) Modeled Year 11 - Year 1, (b) Modeled Year 15 - Year 1, (c) Modeled Year 15 - Year 11, (d), Observed 2006 - 1996, (e) Observed 2010 - 1996, (f) Observed 2011 - 2006. Modeled velocities are from the increased basal melting experiment (melting multiplied by 1.5). 20

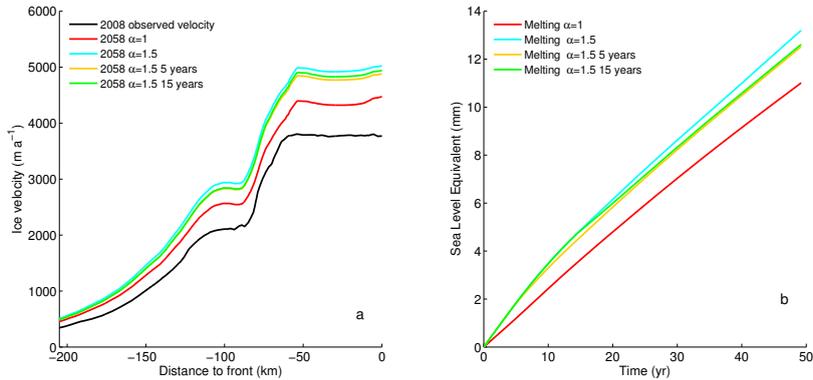


Fig. 8. Modeled velocity sensitivity (a) and volume [above floatation](#) sensitivity (b) to increased ice shelf melting over a limited time. Ice shelf melting is multiplied by 1.5 during the first 0 (red), 5 (yellow), 15 (green) and 50 (blue) years of the simulation.

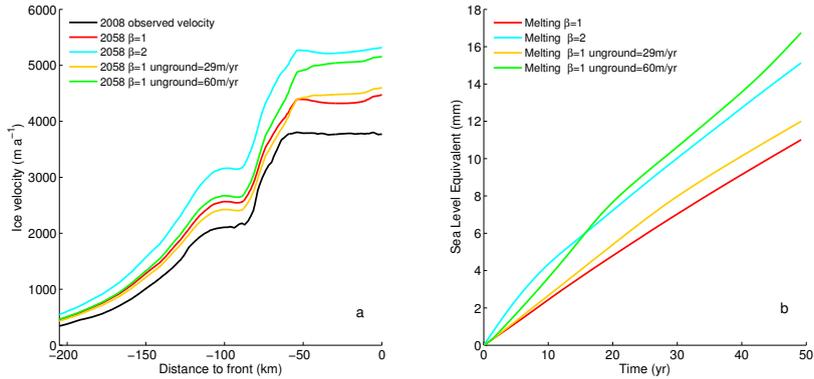


Fig. 9. [Modeled velocity sensitivity \(a\)](#) and [volume above flotation sensitivity \(b\)](#) to ice shelf melting applied over newly ungrounded areas.

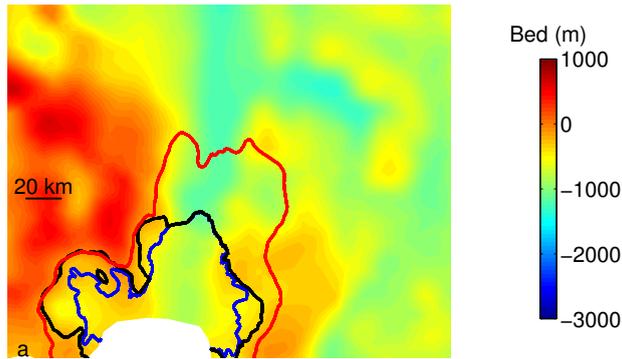


Fig. 10. Grounding line position at the beginning of the experiments (blue line), and at the end of the melting experiments in the case of $\beta = 1$ (red line) and for a basal melting rate parameterization based on the ice shelf base elevation similar to Favier et al. (2014), overlain on the bedrock elevation.

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