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Mapping the sensitivity of the Amundsen Sea Embayment to changes in external forcings using Automatic Differentiation

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Key Points:

- Future ice discharge is sensitive to basal conditions within 60 km of the grounding zone
- Pine Island Glacier’s projected mass balance is most sensitive to the strength of its shear margins
- The integrity of Thwaites’ ice shelf connecting to the Eastern ice rise is critical

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Abstract

Thwaites and Pine Island glaciers as well as other ice streams in West Antarctica have been changing dramatically over the past decades. Although changes in ocean conditions are likely the primary driver of these changes, it remains unclear *where* other processes could cause more mass loss. By employing automatic differentiation and two independent ice sheet models, we construct maps of the sensitivity of the volume above floatation to changes in ocean-induced melt rates, ice rigidity, basal friction, and surface mass balance. We find that changes in basal melt close to the grounding lines and along shear margins have a larger impact on the glaciers' final volume. The glaciers are sensitive to changes in basal friction on regions close to the grounding lines, while changes in ice rigidity has a larger impact along the shear margins of Pine Island. The sensitivity to surface mass balance is uniform over grounded ice.

Plain Language Summary

The Amundsen Sea Embayment is the region of Antarctica that is changing the fastest. Pine Island and Thwaites glaciers have been thinning and accelerating over the past three decades and it is not clear whether they are going to continue to do so over the coming years. Here, we use two models of ice sheet flow and employ a new tool that shows what physical process is the most critical, and where, if we are interested in the future contribution to sea level rise of this sector of Antarctica. We find that the basal friction close to the zone where the ice starts to float exerts a very strong control on the mass balance. We also find that the connection between grounded ice and pinning points under the ice shelf is key to keep the system stable. Increasing basal melting or weakening the ice in this sector would lead to significant acceleration and further mass loss.

1 Introduction

The Antarctic Ice Sheet has been losing mass over the past four decades (Rignot et al., 2019), primarily because of the increase in ice discharge in the Amundsen Sea. Thwaites and Pine Island glaciers alone are contributing almost 75% of the total mass loss of the Antarctic Ice Sheet (Rignot et al., 2019). While it is now accepted that this mass loss was caused by the intrusion of warm Circumpolar Deep Water spilling over the continental shelf and reaching ice shelf cavities (R. B. Alley et al., 2015; Jenkins et al., 2016), it is not clear how these glaciers are going to change over the coming decades. To address this question it is important to better understand ice-sheet response to changes in external forcings, such as ocean-induced melt rates or surface mass balance, or in boundary conditions, such as basal drag. These influencing factors are known to exhibit strong spatial variability (e.g., Dutrieux et al., 2013) and it is likely that any changes will be highly spatially variable as well. Thus, an important aspect of this question is to determine *where* changes in external forcings, like ocean-induced melt rates or surface mass balance, or in boundary conditions, such as basal drag, would have the largest effect on the mass balance of Thwaites and Pine Island glaciers.

Goldberg et al. (2019) investigated the impact on spatial patterns of sub-ice shelf melt on Smith Glacier, a small but strongly thinning ice stream in the Amundsen sector. We expand on this study in terms of both mechanistic and geographic scope. We investigate the role of four different factors that could enhance the ice discharge and hence the imbalance of the Amundsen Sea sector: ocean-induced melt rates under floating ice, a weakening of the ice (through a reduction of the ice rate-factor), changes in basal friction, and changes in surface mass balance. We use automatic differentiation to generate sensitivity maps of the volume above floatation, which directly contributes to sea level, to these four quantities. It has been shown, for example, that glaciers can respond very differently to different distributions of melt rates that have, overall, the same total integrated melt (Gagliardini et al., 2010). The precise location of where melt occurs has

a stronger impact than the area-averaged value of basal melt. It is therefore critical to determine precisely where changes in melt, or other external forcings or boundary conditions, would have the largest impact on the glaciers' mass balance.

Mapping the sensitivity of a glacier to a given external forcing can be done using ensemble methods (e.g., Reese et al., 2017). However, such methods require to run the model thousands of times, depending on the spatial resolution of the sensitivity desired – limiting the study to consideration of time-independent response only. Automatic Differentiation (AD) provides an efficient method to get these sensitivity maps at the scale of the model's mesh, as it only requires to perform one single backward propagation pass on the model (e.g., Heimbach & Bugnion, 2009).

We analyze the sensitivity of the ice volume above floatation, which is the quantity that controls the contribution to sea level rise, after a 20-year simulation. We derive, for each vertex or cell of the mesh, the sensitivity of the final volume above floatation to a perturbation in each of the four forcings at every single node or cell. We first describe the general method employed in this study, how it is implemented using two different approaches in two independent ice flow models, and then discuss the results. We conclude on the areas that are most at risk for changes in each of the four input parameters considered here. Our findings could have implications for guiding and focusing future geophysical exploration of the Amundsen sector.

2 Methods

We use two different ice sheet models: STREAMICE, which is a package of the MIT General Circulation Model (MITgcm, Goldberg & Heimbach, 2013), and the Ice-sheet and Sea-level System Model (ISSM, Larour et al., 2012). Both models are described in ample detail in Barnes et al. (2021). We only summarize here the most important characteristics of each model.

The model domains include both Pine Island Glacier and Thwaites Glacier and the Dotson and Crosson ice shelves (Fig. 1). The two models use the same initial geometry (ice thickness and surface) and bed elevation. The bed topography is based on Bed-Machine Antarctica v2 (Morlighem et al., 2020). The surface elevation is derived from radar altimetry (Bamber, 2000) and represents the state of this sector in 1995/1996. The ice surface velocity is derived from satellite interferometry (InSAR, Mouginot et al., 2014). STREAMICE relies on a uniform grid of 318×520 cells at a spatial resolution of 1.5 km, while the ISSM model uses a non-uniform mesh of 24,000 elements that have a resolution of 3 km in the vicinity of the grounding line and along the shear margins, and a coarser resolution in regions of slow flow. Here, both models use a 2-dimensional depth-integrated expressions of ice sheet flow: the Shelfy-Stream Approximation for ISSM (MacAyeal, 1989), and an L1L2 variant for STREAMICE (Goldberg, 2011).

In both models, ocean-induced melt is only applied to fully floating elements to avoid artificial grounding line retreat (Seroussi & Morlighem, 2018). ISSM employs a sub-element parameterization of the grounding line (Seroussi et al., 2014), while STREAMICE does not implement any sub-grid scaling of basal stress. Among all four forcings considered in this study, sensitivities to melt rates for marine ice stream models can be potentially problematic due to these differing treatments of the grounding line (see supplement).

In all simulations, the calving front is kept fixed, and basal friction, τ_b , is modeled using a Coulomb-limited sliding law (Gagliardini et al., 2007):

$$\tau_b = \frac{C_b u_b^{1/m} \alpha^2 N}{(C_b^m u_b + (\alpha^2 N)^m)^{1/m}}, \quad (1)$$

Figure 1. Initial ice surface velocity from STREAMICE (a), ISSM (b), and the 1995 InSAR-derived ice velocity (c).

where C_b is the friction coefficient, u_b is the basal velocity, N is the effective pressure at the ice base, $\alpha^2 = 1/2$ defines the maximum value of τ_b/N , and $m = 3$ is the friction exponent.

ISSM uses a thermal model to initialize the ice rigidity (B) over grounded ice, and an inversion based on InSAR-derived surface velocities for floating ice. The friction coefficient, C_b , is inverted for over grounded ice. For STREAMICE, C_b is set to 0 over floating ice, while B is inverted over the whole domain, with a cost term applied for grounded ice only that penalizes deviation from the initial guess (based on the temperature product of Pattyn, 2010). No such cost term is applied over floating ice (for details see Barnes et al., 2021).

The ocean-induced melt under floating ice is described by a depth-dependent parameterization:

$$\dot{m}(x, y) = m(x, y) + \begin{cases} 0 & \text{if } z \geq 0, \\ -\frac{1}{10}z & \text{if } 0 > z > -500, \\ 50 & \text{if } z \leq -500, \end{cases} \quad (2)$$

where z is the ice-shelf base depth (negative if below sea level), and $m(x, y)$ is a perturbation field taken initially equal to 0. This melt parameterization has been shown to be in good agreement with measured and modeled melting rate under Thwaites Glacier (Seroussi et al., 2017), but is smaller than observations for Pine Island Glacier’s ice shelf, especially close to the grounding line where melting rate can reach ~ 100 m/yr (Rignot et al., 2013; Adusumilli et al., 2020).

We then run the model forward for 20 years, from 1996 to 2016. The surface mass balance, $\dot{a}$, is derived from the Regional Climate Model, RACMO2.3 (van Wessem et al., 2014).

We rely on Automatic Differentiation (AD) to generate the sensitivity maps of the final volume above floatation (V) at the end of the simulation to the four input parameters: the friction coefficient (C_b), the ice rigidity (B), basal melting (through m), and surface mass balance ($\dot{a}$). To calculate the derivatives, STREAMICE employs a source-to-source transformation of the FORTRAN code using OpenAD (Utke et al., 2008; Goldberg et al., 2016), while ISSM takes advantage of the C++ language to use an object-overloaded approach through the CoDiPack package (Sagebaum et al., 2019). With object-overloading, all “active variables” (i.e., the ones that connect the dependent to the in-

dependent variables) also carry their derivatives and the trace is kept in memory. We then perform a single reverse sweep and apply a chain rule to compute the sensitivity of the model output to the four input fields. These sensitivity maps are the gradients of our quantity of interest, the volume above floatation after 20 years of simulation (V) to perturbations in any of these four parameters. For example, the Gâteaux derivative of V , $\mathcal{D}V(C_b)$, with respect to the friction coefficient, C_b , is defined as:

$$\forall \delta C_b \in \mathcal{H}^1(\Omega) \quad \langle \mathcal{D}V(C_b), \delta C_b \rangle = \lim_{\epsilon \rightarrow 0} \frac{V(C_b + \epsilon \delta C_b) - V(C_b)}{\epsilon}, \quad (3)$$

where δC_b indicates a perturbation in C_b , $\langle \cdot, \cdot \rangle$ is the inner product, and $\mathcal{H}^1(\Omega)$ denotes the space of square-integrable functions whose first derivatives are also square integrable on the model domain, Ω . These sensitivity maps can therefore be used to determine the magnitude of change in V for any perturbation in C_b , or another model parameters considered here. In practice, AD provides the gradient of V with respect to each nodal or element value of C_b , and we recover $\mathcal{D}V(C_b)$ on the $\mathcal{H}^1(\Omega)$ space by multiplying this output by the mass matrix inverse. This procedure avoids mesh-dependency sensitivities.

ISSM and STREAMICE use two fundamentally different methods to retrieve these gradients. Not only do they differentiate the code through different mechanisms, but also they have different approaches to finding the derivatives of the fixed-point velocity solver (Goldberg et al., 2016). Still, they should theoretically provide the same results, which is one of the benefits of this exercise. Since the two models are also different, in the sense that they are based on different meshes, different initial conditions, different stress balance approximations, and different numerical methods, we do however expect to see some differences in the results. On the other hand, strong agreement between the results suggests that (a) both ice-sheet models have similar sensitivities, despite their independent approaches; and (b) features in the computed sensitivities are representative of actual system sensitivities, and not numerical artifacts.

Automatic Differentiation is known to be more computationally and memory intensive than the primal model (i.e., the forward run). One approach to alleviate this problem is to use a check-pointing strategy (e.g., Margossian, 2019). This strategy, implemented in both ISSM and STREAMICE, consists in stopping the transient model every n iterations and writing the state of the model on disk, which allows to break down the entire simulation into smaller intervals by restarting the model at intermediary steps. STREAMICE makes use of the Revolve algorithm (Griewank & Walther, 2000), which optimizes this balance between storage and recomputation.

3 Results

We first performed some validation tests on simpler geometries (see supplement), as well as finite difference tests to validate our independent implementations of AD. The agreement between the sensitivity maps from ISSM and STREAMICE with a Coulomb-limited law is excellent and we then applied the same methodology to the Amundsen Sea Embayment glaciers.

Figures 2a and 2b show the sensitivity maps of the final volume above floatation after 20 years of simulations, with respect to the basal friction coefficient, C_b . Over the vast majority of the model domain, the sensitivity is negligible. This means that changing the basal friction over $\sim 85\%$ of this region would have virtually no effect on the mass balance of this sector over 20 years. Two regions, however, stand out. The area within 50 km upstream of Pine Island’s grounding line, and, to a smaller extent, 60 km upstream of Thwaites grounding line. The sensitivity being positive means that increasing the friction coefficient in these areas would lead to an increase in ice volume above floatation after 20 years compared to a simulation where the friction would not be changed. The

Figure 2. Sensitivity maps of the model’s final volume above flotation to the basal friction coefficient, C_b , from STREAMICE (a) and ISSM (b), and sensitivity to the ice rigidity, B , from STREAMICE (c) and ISSM (d).

opposite is also true: reducing the basal friction in this sector would lead to a decrease in the volume above flotation after 20 years. These two regions are therefore highlighted as the places where changes in basal conditions would affect the mass balance of the Amundsen Sea Embayment the most.

Figures 2c and 2d show the sensitivity maps with respect to the ice rigidity, B . Again, over the vast majority of the model domain, the sensitivity remains negligible. The regions that show a particularly high sensitivity are the shear margins of Pine Island glacier over the ice shelf, and also up to about 50 km upstream of the grounding line. A small band of about 20 km of high sensitivity is also visible along the grounding line of Thwaites, but also Dotson and Crosson. Again, a positive sensitivity means that increasing the ice rigidity, B , would increase the final volume above flotation, and also that a decrease in B would induce a decrease in the final volume above flotation.

The second set of figures (Fig. 3) shows the sensitivity maps of the model with respect to external forcings: surface mass balance (Fig. 3a and 3b), and basal melting (Fig. 3c and 3d).

In the sensitivity map related to the surface mass balance, most of the grounded ice has a clear positive sensitivity, that gradually decreases to 0 as the grounding lines and floating ice are reached. We also notice that the transition zone between high sensitivity and low sensitivity is wider in regions of fast flow compared to regions of slower flow.

In the maps showing the sensitivity to perturbations in basal melt, we have no sensitivity over grounded ice, as expected, but we have a highly spatially variable pattern over the floating ice shelves of this sector. The maps consistently show a high sensitivity along the shear margins of Pine Island, the grounding lines of Dotson and Crosson, and the ice that connects Thwaites to the Eastern Ice Rise. These sensitivities are now negative, meaning that an increase in basal melt in these regions would lead to a decrease in the final volume above flotation. Note that the central parts of Pine Island Ice Shelf and the majority of Thwaites’ ice tongue have very low sensitivities to basal melt.

Figure 3. Sensitivity maps of the model’s final volume above flotation to the local surface mass balance, SMB, from STREAMICE (a) and ISSM (b), and sensitivity to ocean melting, m , from STREAMICE (c) and ISSM (d).

4 Discussion

The agreement between the sensitivity maps produced by the two ice sheet models that are completely independent indicates the robustness of the results. The two models are written in different languages, and rely on different stress balance equations, meshes, discretization methods, AD tools, and different initialization procedures (Barnes et al., 2021). This remarkable agreement validates the approaches implemented in ISSM and STREAMICE, and provides confidence in the maps obtained from each one.

In terms of basal friction, the zone upstream of grounding lines for both Pine Island and Thwaites is clearly highlighted as an area where changes in basal friction (e.g. due to grounding line retreat or changes in the subglacial hydrological system) would lead to strong changes in the rate of mass loss of this region. The interior of the ice sheet, where the ice is slower, does not seem to have much impact. This could be due to the time interval that we considered here: 20 years. If the ice flow becomes faster (or slower) upstream, it will take some time before it has any impact on the ice discharge and, consequently, on the glaciers’ mass balance. While the region of fast flow close to the grounding zone is clearly the most important in terms of rapid mass loss, we cannot exclude that changes in basal friction in the interior would have an impact on the ice discharge but probably over longer time scales (i.e., >20 years).

The sensitivity maps with respect to the ice rigidity show that the weakening of the ice shelf along the shear margin of Pine Island would accelerate the mass loss of this glacier, which is consistent with previous studies (e.g., Lhermitte et al., 2020). These shear margins buttress the flow of the main trunk of Pine Island and any change, due to increased fracturing (Lhermitte et al., 2020) or to the development of sub-ice-shelf channels (K. Alley et al., 2019), will lead to a reduction of its buttressing effect, which will ultimately increase the ice discharge. Our sensitivity maps show that this effect would be at least an order of magnitude stronger than a weakening of other regions of the Amundsen Sea Sector, including the shear margins of Thwaites Glacier. Another sector that is highlighted in these maps is a region ~ 20 km upstream of Thwaites grounding line. It is interesting to note that the sensitivity map with respect to basal friction in this same sector (i.e., over the eastern part of Thwaites) is lower. This counter-intuitive result could be explained by the fact that this region is close to flotation and so our effective pressure, N , is small. Increasing the friction coefficient, C_b , would have a limited impact on the overall basal stress, whereas decreasing the ice rigidity would instantaneously lead

to flow acceleration and enhanced discharge. The models do not show a strong sensitivity to margin weakening along the grounded margin of Thwaites Glacier, suggesting that a possible migration of the Eastern margin of Thwaites would not have a strong impact on the mass balance as weakening on other regions closer to the grounding line, at least over a 20-year period. The sensitivity to changes in ice rigidity on Thwaites' ice tongue is negligible. This suggests that recent changes in this region (i.e., "crumbling" of the ice shelf) did not have any significant impact on Thwaites mass balance.

The sensitivity maps with respect to surface mass balance show a clearer pattern: changing the surface mass balance over floating ice would have no effect on the final volume above floatation, precisely because ice shelves maintain floatation, whereas increasing the surface mass balance over grounded ice directly contributes to the volume above floatation. The transition between the high sensitivity, upstream, and the low sensitivity, downstream of the grounding line, is a function of ice speed. For instance, increasing the surface mass balance 3 km upstream of the grounding line of Pine Island would only increase the volume above floatation over a 1-year period. It happens because, over the course of one year and at a speed of ~ 3 km/yr, any change at this distance would be advected downstream of the grounding line, from which its contribution would be canceled as the ice becomes afloat. The longer the ice remains grounded over this 20-year period, the larger the sensitivity to changes in surface mass balance.

Finally, the sensitivity maps with respect to an increase in basal melt shows a complex pattern that is consistent across the two models. The shear margins of Pine Island stand out again, for the same reasons as above: a weakening or thinning of the ice margins leads to ice speed-up and increased mass loss. We now also see a strong sensitivity along the grounding lines of Dotson and Crosson, a region ~ 20 km upstream of Thwaites Glacier's grounding line over which the grounding line retreats during the simulation, as well as the region that connects Thwaites Eastern Ice Rise to Thwaites tongue. This ice rise provides critical buttressing to upstream flow and the integrity of the ice connecting grounded ice to this ice rise has a strong impact on future ice discharge. Increasing the melt in this region would reduce the buttressing force exerted by this ice rise and result in more mass loss. It is also interesting to note that both models highlight a region to the east of this sector that has a positive sensitivity to increased melt. In other words, if ocean melting increased in this region, the final volume above floatation would increase. We hypothesize that this region is actually mechanically connecting Thwaites' ice tongue and the Eastern ice shelf, and that the ice tongue is "pulling" the eastern side. Increasing the basal melt in this region would reduce the shear stresses exerted by Thwaites' ice tongue and reduce the ice velocity of the Eastern ice shelf. This is however an exception in this sensitivity map as the vast majority shows a negative sensitivity to enhanced melt. Note, however, that most of Thwaites tongue is "passive", i.e., changes in melt over the ice tongue do not impact the final volume above floatation of Thwaites. This is in line with the sensitivity map to ice rigidity. These results suggest that the calving of Thwaites' tongue over the last decades had a negligible impact on the glacier's dynamics compared to changes over the Eastern ice shelf.

A limitation of these results are that they are linear in nature. That is, Eq. 3 represents a linearization of a nonlinear model, and as such is not necessarily quantitatively accurate when considering large perturbations. However, previous application to Crosson and Dotson ice shelves suggest that linear sensitivities are a strong indication of sensitivities to large changes in forcing (Goldberg et al., 2019). A Weertman friction law was employed in an earlier version of this work, and the results were very comparable to the ones presented here, further suggesting that our results are not specific to the friction law used, at least qualitatively. We performed additional experiments to test the sensitivity of our results to the length of the transient simulation (Figures S7 and S8) and to the applied melting rate (Figure S6) and the sensitivity maps are qualitatively similar, again suggesting that the areas highlighted here are robust features. The consistency

of these sensitivities across different models demonstrates that our conclusions are related to the physics of the system, and not due to specific modeling approaches or model parameters.

These maps could be used to inform future field campaigns. We see, for example, that changes over Thwaites' ice tongue have virtually no effect on the glacier's mass balance, which is expected as the ice tongue is mostly unconfined. The fine scale details in these sensitivity maps, however, highlight regions that, if they were to change even over a limited area, would affect the mass balance of this sector and should therefore be closely monitored. These maps indicate not only which factor but also *where* changes would have the greatest impact on the mass balance of the glaciers of this sector. We see that in most sensitivity maps, changes in the grounding line region will have the greatest impact.

5 Conclusions

We compared the sensitivity maps of the volume above floatation after a simulation of 20 years from two ice sheet models with respect to four different forcings. These experiments show, at a high resolution, *where* changes in any of these forcings would have the largest effect on the glacier mass balance. Overall, we find that, while the surface mass balance controls the sensitivity of the mass balance over the grounded portion of the domain, changes in basal friction, ice rigidity or ocean-induced melt in the vicinity of the grounding lines have a strong effect on the dynamics of the glaciers of the Amundsen Sea Sector. The shear margins of Pine Island are also particularly sensitive to changes in ice rigidity and melting. More work on ice-ocean interactions and damage mechanics is therefore particularly important in order to reduce uncertainties of predictive ice sheet models.

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