The Impact of Elevation-SMB Feedbacks on the Evolution of Thwaites Glacier, West Antarctica

Undergraduate Thesis

By

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Abstract

The Amundsen Region of the West Antarctic Ice Sheet is one of the major active contributors to global sea level rise. Thwaites Glacier is a large, fast-flowing glacier in this region which is experiencing mass loss, flow acceleration, and rapid grounding line retreat, indicative of the marine ice sheet instability. Although there are many factors that may influence the potential destabilization and collapse of Thwaites Glacier, surface mass balance is an important factor as the balance of precipitation and ablation change with changing glacier geometry. This study investigates a surface elevation-SMB relationship and its influence on projected future stability at Thwaites Glacier. Observational data and regional climate model outputs are used to identify a strong elevation-SMB relationship at Thwaites Glacier. The Ice-Sheet and Sea-Level System Model is then then used to simulate Thwaites Glacier's evolution with an added elevation-SMB feedback. Incorporating an elevation-SMB feedback increases the model prediction for ice mass loss by 5%-10% over a 200 year transient simulation.

Contents

1 Introduction

Sea level rise, driven in part by ice sheet and glacier melt, poses a threat to coastal communities throughout the world. Some of the most active glacial contributors to recent sea level rise are in the Amundsen Region of the West Antarctic Ice Sheet. In particular, Thwaites Glacier, a West Antarctic marine-terminating glacier, is rapidly thinning and retreating at its margin, due to increased ice discharge into the ocean (Rignot, 2008; Medley et al., 2014). The changes observed at Thwaites Glacier have been put forward as evidence of destabilization and collapse of this glacier, a process often called the "marine ice sheet instability", a runaway acceleration in ice flow to the ocean (Joughin et al., 2014). The changing geometry of Thwaites Glacier (i.e. its horizontal extent and vertical elevation) may affect the balance of precipitation and surface melting (or overall surface mass balance, hereafter SMB) of the glacier, which could prompt further ice loss in the future.

This study will investigate the connection between Thwaites Glacier's elevation-SMB relationship and the glacier's projected future stability as it relates to ice mass loss, and ice flow at the ice-ocean interface. This work represents a piece of an important effort to accurately simulate the coupled evolution of ice sheets and climate, as the relationships found here could potentially apply to other marine-terminating glaciers. If significant, the relationship found here can contribute to refining and improving ice sheet models, and in turn, provide a means for improving the accuracy of sea level projections.

Observational data and climate model outputs are commonly used as environmental inputs to numerical ice sheet models to simulate the projected response of glaciers to future climate change. In this project, I use observations of snowfall rate and regional climate model SMB outputs focused in the Amundsen Region to identify an elevation-SMB relationship at

Thwaites Glacier that may affect its vulnerability to future climate change. Initial tests of precipitation-geometry feedbacks are included in a simple mathematical model of marine-terminating glacier evolution to show how shifting glacier geometry may play a role in accelerated ice sheet collapse and sea level rise. The state-of-the-art Ice-Sheet and Sea-Level System Model (ISSM) is then used to simulate Thwaites Glacier as it responds to future climate change, incorporating the elevation-SMB feedback. This thesis ends by discussing how an elevation-SMB feedback changes the rate of retreat in a glacier undergoing the marine ice sheet instability. Particularly, this study is relevant in the context of Antarctic glacier evolution, which may include both an atmospheric feedback and marine ice sheet instability. This thesis provides important implications for future sea level projections, as most simulations of the evolution of ice sheets in Antarctica over long time scales do not include coupling to SMB models, thus do not include the possibility of an SMB feedback. Here, I discuss the implications of including such a feedback for glaciers that become unstable due to the marine ice sheet instability.

2 Literature Review

Marine-terminating glaciers have long been regarded as sensitive indicators of climate change (Nye, 1960). The total mass "balance" of marine-terminating glaciers is influenced by the accumulation and surface melt that make up the surface mass balance (SMB) along the length of the flowing glacier. Changes in SMB result in changes in ice flow, thickness, and length (Rignot, 2008; Gardner et al., 2018; Christian et al. 2020). SMB may vary as surface elevation changes along the length of a glacier. Surface melt rates increase with decreasing elevation as lower elevations on the glacier are subject to warmer temperatures and more variable weather conditions (Weertman, 1961; Oerlemans, 2003). At higher elevations on the glacier, snowfall decreases as elevations become too high for the cold atmosphere to retain moisture (Weertman, 1961).

Early work by Weertman (1961) simplified the elevation-surface mass balance relationship by assuming a constant average snow accumulation at higher elevations and a constant surface melt rate at lower elevations of the glacier. Because the snow accumulation and melt rates are slowly varying functions over the glacier's surface, Weertman held that the accuracy of ice sheet evolution calculations would be retained when using the simplified relationship. Using a simple model of ice sheet evolution, Weertman (and also Oerlemans (1981), using different assumptions) predicted that there is a minimum stable ice sheet size under the simplifying assumptions of the relationship between elevation and surface mass balance. More recent models of ice sheet evolution incorporate more realistic representations of the elevation-surface mass balance feedback, accounting for the continuous changes in surface mass balance rate across different elevations on the glacier surface (Oerlemans, 2003; Edwards et al., 2014). This allows scientists to identify how the presence of an elevation-surface mass balance feedback impacts sea level rise contributions and ice sheet sensitivity to climate change. Recent work by Edwards et al. (2014) found that incorporating a realistic elevation-surface mass balance feedback amplifies the Greenland Ice Sheet contribution to future sea level. Although implementing a realistic surface mass balance feedback may influence model predictions, the feedback itself and impacts on ice sheet sensitivity to climate change are yet to be fully understood. In particular, while the elevation-SMB feedback has been studied extensively in the context of Greenland, its influence on Antarctic Ice Sheet evolution has received less attention.

Recent climate conditions may be influencing many marine ice sheets to enter a regime of destabilization and collapse due to a runaway acceleration in ice flow to the ocean known as the Marine Ice Sheet Instability (Weertman 1968; Joughin et al., 2014), which is completely different from the instability arising from to the elevation-SMB feedback. The marine ice sheet instability can occur over various timescales differently depending on glacier size and influence from climate feedbacks (Robel et al., 2018). When the ice in the grounding zone, the region where ice from a glacier goes afloat in the ocean, is on a reverse-sloping bed (getting deeper towards the glacier interior), the glacier is at a greater risk of becoming unstable due to triggering the marine ice sheet instability. Depending on the severity of the bed slope and ice sheet interactions with the ocean and climate, the grounding line can begin to retreat quickly, leading to significant ice loss and contributing to sea level rise. The factors that influence the marine ice sheet instability can be explored through ice sheet models of varying complexity. Relationships between climate and ice sheet states can be represented through mathematical equations and implemented in ice sheet models to predict glacier responses to certain climate scenarios.

Ice sheet models have become more advanced as scientists seek to couple more processes within the Earth system. Outputs from high-resolution regional models of SMB, including the Regional Atmospheric Climate Model (RACMO) and Modèle Atmosphérique Régional (MAR) are often used to force ice sheet models when predicting future ice sheet evolution (Lenaerts et al., 2019). Although climate models simulate SMB with validation from sparse field measurements, RACMO and MAR have been shown to accurately represent climate conditions along all regions of Antarctica (van Wessem et al., 2018; Agosta et al., 2019; Mottram et al., 2020; Donat-Magnin et al., 2020). According to Antarctic observational data and climate model outputs, the relationship between surface mass balance and elevation of Thwaites Glacier may be strong enough to produce an atmospheric feedback under changing climate conditions (Pollard & DeConto, 2005; Favier et al., 2013; Shepherd et al., 2018, 2019; Medley et al., 2013, 2014).

In recent years, computationally expensive simulations of ice sheet evolution, using models such as the ISSM, have provided projections of sea level contributions from glacier melt (Schlegel et al., 2019). These more realistic models are useful for understanding how atmospheric feedbacks from the elevation-SMB relationship will impact glaciers experiencing the marine ice sheet instability over time, and in turn, their sea level contribution. However, these complex models have many parameters and it is difficult to extract understanding of the dynamics of the coupled ice sheet-climate system with them alone. In this study, I use both a simple two-equation model and a more complex numerical ice sheet model to provide a comprehensive look into how the elevation-SMB feedback impacts Thwaites Glacier's stability and future sea level contribution.

3 Observation and Model Descriptions

The first part of this study utilizes observations of snowfall accumulation rate gathered during past field missions to understand the trend of SMB over elevation on Thwaites Glacier. Further evidence for this atmospheric feedback on Thwaites Glacier is developed by analyzing output from regional climate models focused on Antarctica. Once a potential elevation-SMB feedback is confirmed using these observations and climate models, a simple ice sheet evolution model is tested with an atmospheric feedback. The Ice-Sheet and Sea-Level System Model is then used to simulate the evolution of Thwaites Glacier under the influence of the elevation-SMB feedback. In the following sections, descriptions of the various methods and models are provided.

3.1 Observational Data

Observational data for Thwaites Glacier used in this study were obtained through the use of airborne snow penetrating radar transects from Medley et al. (2014). These airborne radar missions collected elevation and accumulation rate measurements (in units of m w.e / yr) along the glacier. The along-track radar-derived average accumulation values used for this study is from the 2009-2011 Operation IceBridge (OIB) survey grid of accumulation values over Thwaites Glacier (as seen in Medley et al. 2013, 2014). The radar used to collect this data, referred to as the snow radar, resolves near-surface stratigraphy over hundreds of kilometers along aircraft flight paths. The Center for Remote Sensing of Ice Sheets (CReSIS) developed the frequency-modulated continuous wave system of the radar, operating under 4-6 GHz frequency (vertical resolution ~10 cm) in 2009 and 2-6.5 GHz frequency (vertical resolution ~5cm) in 2010 and 2011. The radar-derived measurements provide a dense, regional dataset of accumulation from 1980-2009 along each radar profile, which overcomes the disadvantages of sparse ground-based measurements which are difficult to gather and completely absent from low elevations. The accumulation rates determined over the Thwaites Glacier region are plotted against the elevations at those measurement locations to produce a scatter plot depicting the relationship between elevation and the accumulation rate of Thwaites Glacier. Because observational data is sparse and difficult to collect in harsh conditions, there were no data collected below the 800 m elevation, even using the airborne dataset. The elevations below 800 m on Thwaites Glacier are generally located nearest to the ocean, where ice dynamics and weather are more volatile and severe. This makes it difficult for data collection to occur, and thus makes the use of climate model outputs that predict the SMB conditions below the 800 m elevations extremely useful in determining SMB trends in locations which are difficult to sample.

3.2 Regional Climate Models

Regional atmospheric climate models run freely, but are tuned and validated by comparison to field observations. Parameters in these models are adjusted until the model output matches observations as closely as possible.

These regional climate models generally span the entire continent of Antarctica, and simulate a range of variables on the model grid, including SMB. Because of their continuous spatial coverage and validation against observations, regional climate models are increasingly being used to supplement observational data for scientific questions where observations are insufficient.

The two climate models used in this study are RACMO 2.3p2 (van Wessem et al. 2018) and MAR (Donat-Magnin et al. 2020). The models have been tuned and validated against observations, and compare well to observations of SMB at a range of elevations along Thwaites Glacier, even those few observations nearest to the terminus below 800 m elevation.

RACMO version 2.3p2 used for this study is at a 27 km resolution over the entire Antarctic continent. MAR outputs used for this study were focused over the Amundson region at a 17.5 km resolution.

For each climate model, I analyzed SMB and elevation data over various glaciers in Antarctica. SMB model outputs of surface mass balance were plotted at the corresponding elevations, visualizing the SMB-elevation feedback trend along the glaciers. Once evidence for a significant atmospheric feedback along Thwaites Glacier was identified, the effects of this trend were investigated.

3.3 Two-Stage Model

Numerical ice sheet models can be simplified to their essential components while still capturing many of the essential aspects of ice sheet behavior. Such simplified explorations of the influence on ice dynamic processes are important when investigating the conditions under which specific feedbacks may be important. Robel et al. (2018) developed a simple two-equation model that describes the response of marine-terminating glaciers to external forcing. The model incorporates a general formulation representing SMB, which can be modified to include atmospheric feedbacks such as the SMB-elevation relationship. Because there are many atmospheric feedbacks yet to be implemented and explored in ice sheet models, the two-stage model is a useful tool for quickly and accurately understanding the impacts of a specific feedback on glacier evolution.

The equations governing this simple two-stage model show the evolution of an ice sheet through changes in length (L) and thickness (H) over time (equations 1 and 2).

$$\frac{dL}{dt} = \frac{1}{h_g}\left(Q - Q_g\right) \tag{1}$$

$$\frac{dH}{dt} = P - \frac{Q_g}{L} - \frac{H}{h_g L}\left(Q - Q_g\right) \tag{2}$$

The change in the glacier's length over time (dL/dt) depends on the thickness of the glacier at the grounding line (h_g) and the ice flux through the grounding line (Q_g). Once the rate of change of glacier length is determined, the values can be incorporated into the equation defining the change in glacier thickness over time ($\frac{dH}{dt}$). The change in glacier thickness is strongly related to the precipitation parameter, P, which is a constant value in this equation.

In the appendix, initial tests of a precipitation-glacier geometry feedback are run with a simple model to determine the potential conditions under which the elevation-SMB feedback will influence the evolution of unstable marine-terminating glaciers. These tests ensure the elevation-SMB relationship is worth investigating in a more realistic numerical ice sheet model to specifically simulate the evolution of Thwaites Glacier.

3.4 ISSM

The Ice-Sheet and Sea-Level System Model (ISSM) is a numerical model of ice sheet and glacier evolution that has been developed at the NASA Jet Propulsion Laboratory since 2012. We base our simulations with ISSM on a model configuration developed by Seroussi et al. (2017) to simulate the catchment basin of Thwaites Glacier, including the basal topography, SMB, ocean forcing, and ice flow. In this configuration, the equations of ice flow and mass conservations are solved on a mesh made of 44,500 anisotropic triangular elements corresponding to horizontal resolutions near the grounding line of 500 meters, and 15 km near the ice divide. Over each 2-week time step, ice velocities, ice thicknesses, and grounding line positions in the model are updated using a higher-order model to determine the transient shallow shelf approximation.

The configuration of ISSM from Seroussi et al. (2017), is forced by averaged SMB over the 1979-2010 period from RACMO2 over Thwaites Glacier. We modify this constant SMB input to update periodically and reflect a more realistic representation of the elevation-SMB feedback. With the new SMB feedback implemented in an offline fashion, I will run ISSM simulations that can shed light on how this atmospheric feedback may be influencing Thwaites Glacier evolution over coming centuries.

4 Results

4.1 Observational Data

Data from the Operation IceBridge airborne snow radar (Medley et al. 2014) is used as the initial determinant of the relationship between glacier surface elevation and SMB in the Amundsen region. Flight tracks from the airborne radar (Fig. 1) show the spatial distribution of the observations.

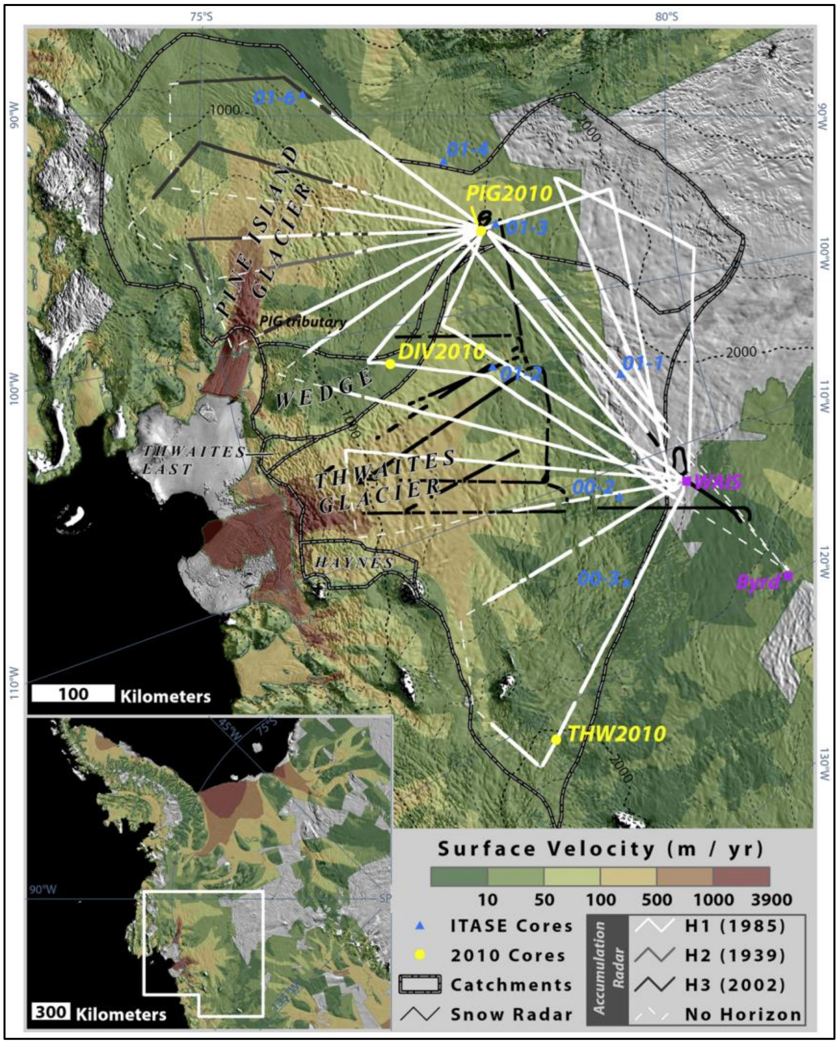

Figure 1: Radar tracks of the Medley et al. (2014) field campaign. The figure shows the accumulation radar tracks as solid white and grey lines spanning the Amundsen region, including Thwaites Glacier. The solid black lines are from the Medley et al. (2013) radar survey campaign. The dashed white lines indicate no horizon was mapped.

From the airborne field survey, accumulation data and surface elevation measured by the radar were plotted against each other to provide an initial visualization of the relationship between elevation and SMB in the entire Amundsen region (Fig. 2).

The airborne radar survey only captures accumulation measurements above 800m in surface elevation. The lower 800m in surface elevation, located from

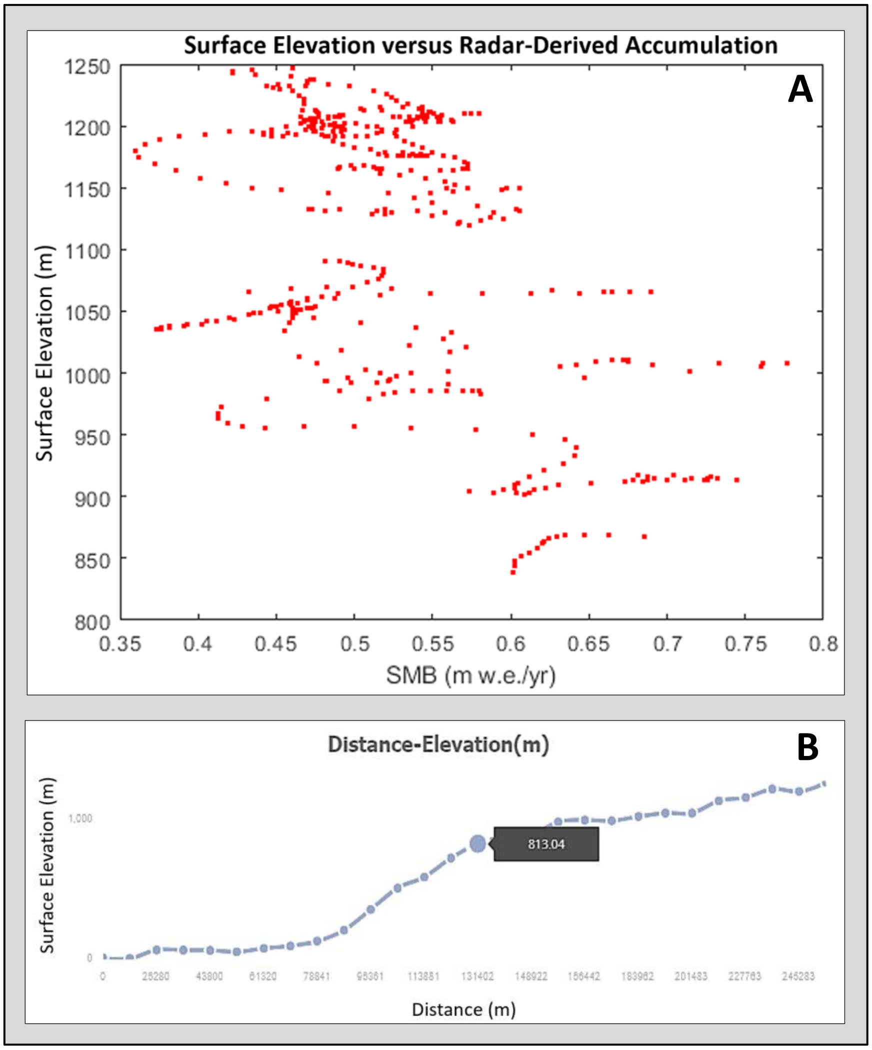

Figure 2: A) Airborne radar-derived accumulation at elevations across the Amundsen region from the Medley et al. (2014) field survey. Surface elevation is measured in meters and accumulation representing SMB is measured in meter water equivalent per year. **B)** The surface elevation profile of Thwiates Glacier shown with distance from coast in meters from the Antarctic Reference Elevation Model of Antarctica Explorer tool, developed by Howat et al. (2019).

the terminus of the glaciers at the ocean to approximately 131km inland is not measured in this survey and is not represented in Figure 2A. The Medley et al. (2014) survey considered the lower elevations as a relatively small area of the glacier basins, and thus do not contribute substantially to the spread of accumulation rates in their study. The surface elevation profile of Thwaites Glacier is shown in Figure 2B.

Because it is not known how important the measurements of SMB in the lower 800m of surface elevation in this region are in determining the overall relationship between elevation and SMB, we need to use a more complete dataset of surface mass balance including lower elevations of Thwaites Glacier.

4.2 Climate Model Reconstructions

To compensate for the lack of SMB data at low elevations provided by observational measurements, regional climate models are used to determine SMB values over the entire surface area of the Antarctic ice sheet, including below 800 meters in surface elevation. Though numerical models lack many of the processes that occur in the real glacier-atmosphere system, they are validated sufficiently against observations of surface mass balance to be confident that they are capturing many of the large-scale trends in SMB, including those investigated here. Climate model outputs of certain regions are selected to examine the elevation-SMB relationship unique to each glacier, allowing the determination of which glaciers may be more susceptible to an atmospheric feedback. Two climate models were used in this part of the study for the purposes of comparing model outputs and determining if common elevation-SMB trends exist between the models, which use a range of different model physics and numerics.

4.2.1 RACMO

The initial determination of elevation-SMB relationships was done using RACMO2.3p2, targeting individual glaciers of potential interest. Two glaciers were analyzed in the Amundsen region of the West Antarctic (Thwaites Glacier and Pine Island Glacier), and two glaciers were analyzed from the East Antarctic (Totten Glacier and Lambert Glacier). Figure 3 depicts the analyzed area over Thwaites Glacier as an example (with red dots showing

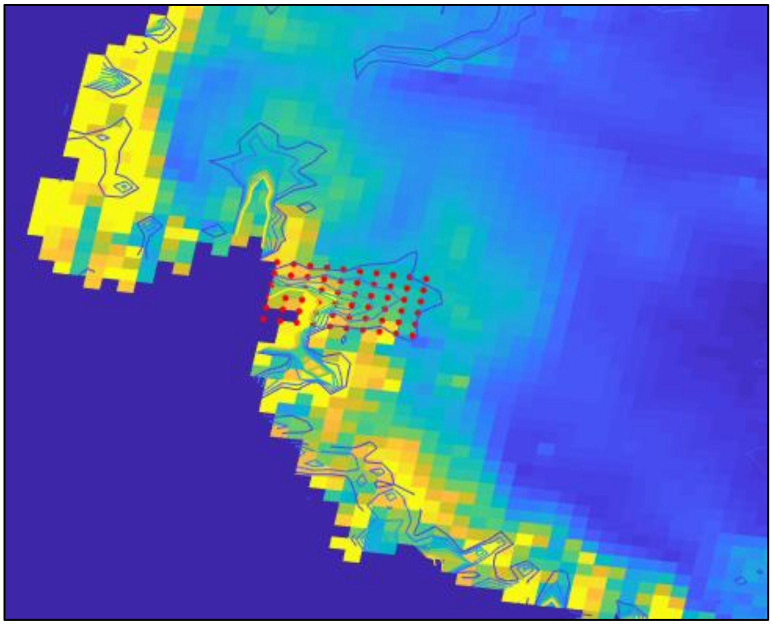

Figure 3: Targeted area over Thwaites Glacier is shown by the grid of red dots. Color variations represent RACMO-simulated SMB values. Lines show ice flow velocity values of glaciers local to the region.

the RACMO model grid points included in our analysis). The climate model outputs for SMB used in determining the elevation-SMB relationship at each glacier are encapsulated by the grid assigned.

After determining the location of grid points corresponding to each glacier of interest (by masking out grid points with velocity below XX m/yr), the elevation used as a boundary condition for RACMO was plotted against RACMO-simulated SMB for those grid points (Fig. 4). The strength of the relationships between surface elevation and SMB at each targeted glacier can be assessed based on the scatter of the data. Because the elevation-SMB relationship is substantially stronger at Thwaites Glacier than at the other glaciers tested, further investigation using other reliable climate models is necessary to confirm the robustness of the relationship.

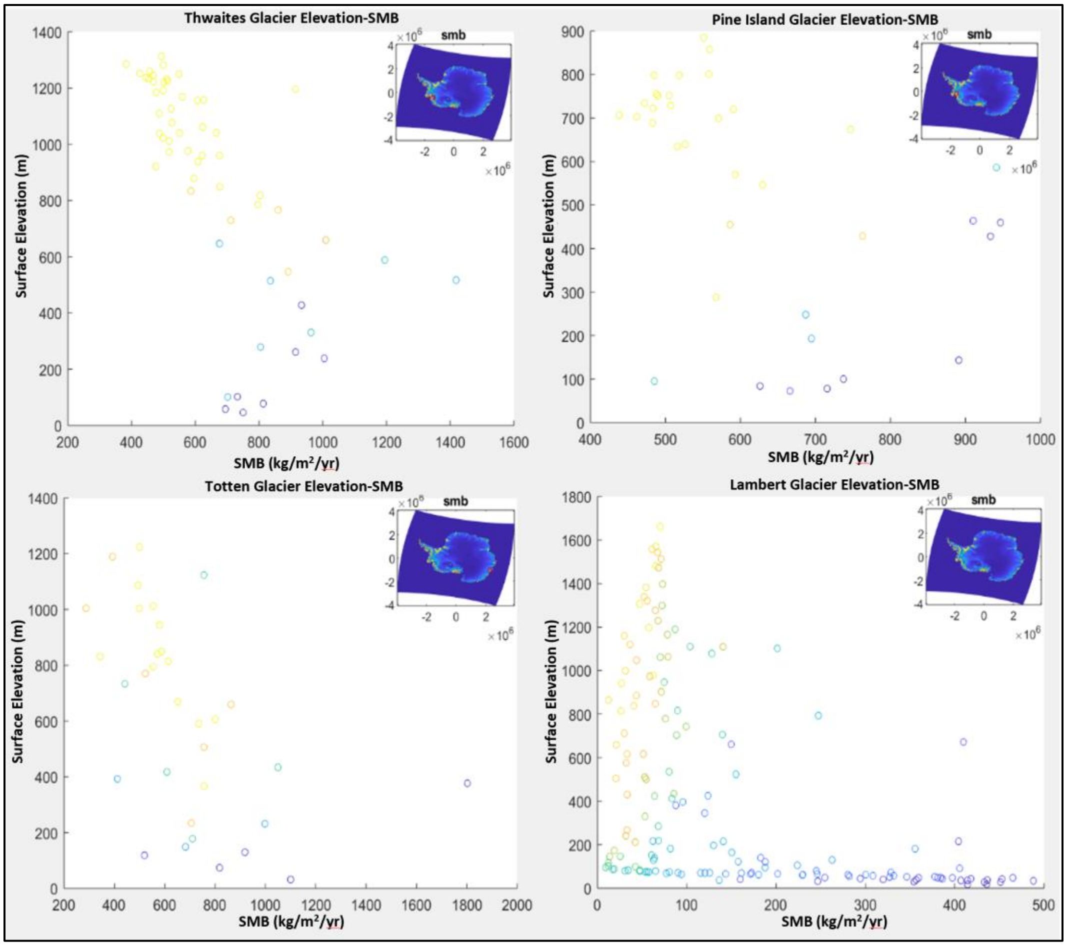

Figure 4: Elevation plotted against a 27 km resolution RACMO2.3p2-simulated SMB output for Thwaites Glacier (A), Pine Island Glacier (B), Totten Glacier (C), and Lambert Glacier (D). Color indicates distance from coast with dark purple indicating the coast and yellow indicating inland.

4.2.2 MAR

The same coordinates (and masking criteria) were used from the RACMO test to identify the Thwaites Glacier region in MAR output. Elevations were plotted against the MAR-simulated SMB values in order to verify their relationship with the RACMO-derived outputs (Fig. 5). The clear elevation-SMB relationship at Thwaites Glacier also exists in MAR. This increases confidence that there is a real relationship between elevation and SMB at Thwaites Glacier.

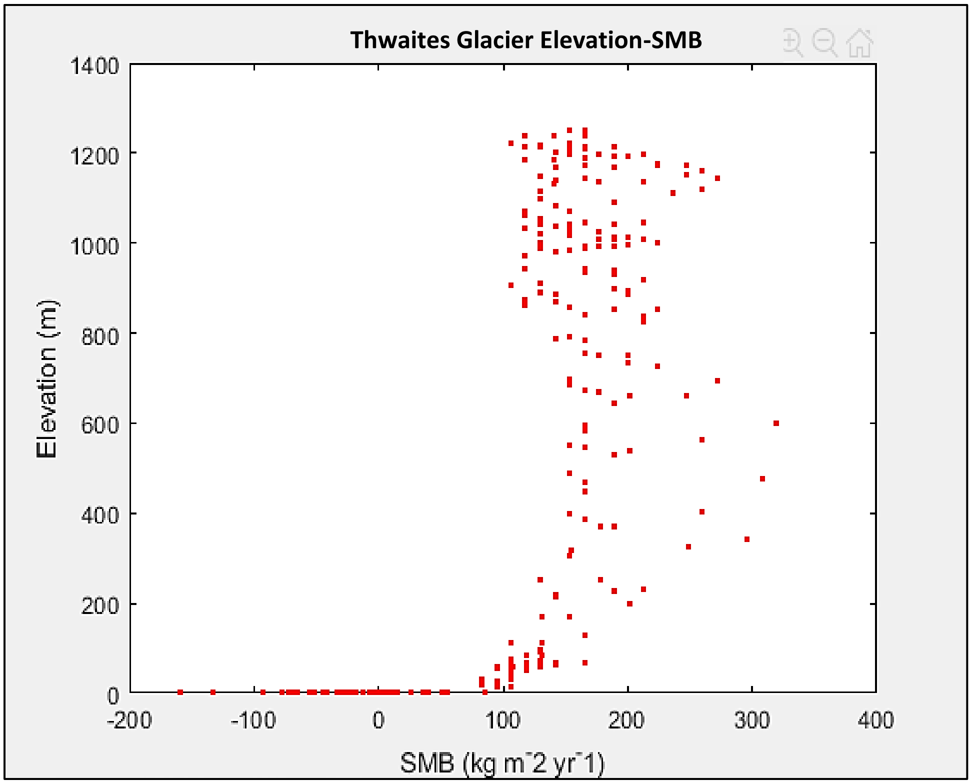

Figure 5: Elevations plotted against a 17.5 km resolution MAR-simulated SMB output for Thwaites Glacier.

4.3 ISSM

Initial tests of precipitation-glacier geometry feedbacks using simple 1-stage equation models (see Appendix) showed that there is a plausible feedback strength range that may influence the transient evolution of a glacier. These initial proof of concept simulations with a simple model gave us confidence that the surface elevation-SMB feedback found in observations and climate model outputs is worth investigating further using a more realistic and complex model such as ISSM, to investigate how precipitation-glacier geometry feedbacks may influence the future evolution of Thwaites Glacier.

Two transient simulations were run using ISSM with the shallow shelf approximation, and a domain encompassing the Thwaites Glacier catchment (model configuration adapted from Seroussi et al. 2017): a simulation with the originally implemented averaged SMB derived from RACMO (and not changing in time with glacier evolution) and a simulation with SMB changing according to a simple positive elevation-SMB feedback. This feedback is implemented as an asynchronous offline coupling to the model which pauses the ISSM simulation, updates the SMB according to the evolution of glacier thickness, and then resumes the simulation. The positive feedback we included in ISSM has the form:

$$P(x) = P_0 + \beta h \quad (3)$$

Where $\beta = 10^{-3}$captures the strength of the elevation-SMB feedback. Ultimately, we made considerable effort to configure and run this model and add the SMB-elevation feedback in an offline fashion (since ISSM does not include any built-in SMB feedbacks), so we focus on a pair of proof-of-concept simulations and what they reveal about the influence of SMB-elevation feedbacks on marine-terminating glacier evolution.

The SMB of Thwaites Glacier in a 200-year transient run involving the elevation-SMB feedback from Equation 3 is pictured in Figure 6. The entire catchment basin is shown as a fixed region, with color changes denoting changes in SMB values (in m/yr). The lower elevations of Thwaites Glacier closest to the coast show concentrated regions of decreased SMB throughout the simulation in places where Thwaites Glacier things and retreats the most rapidly in the simulation. The entire catchment shows an overall decrease in SMB by many 10’s cm/yr.

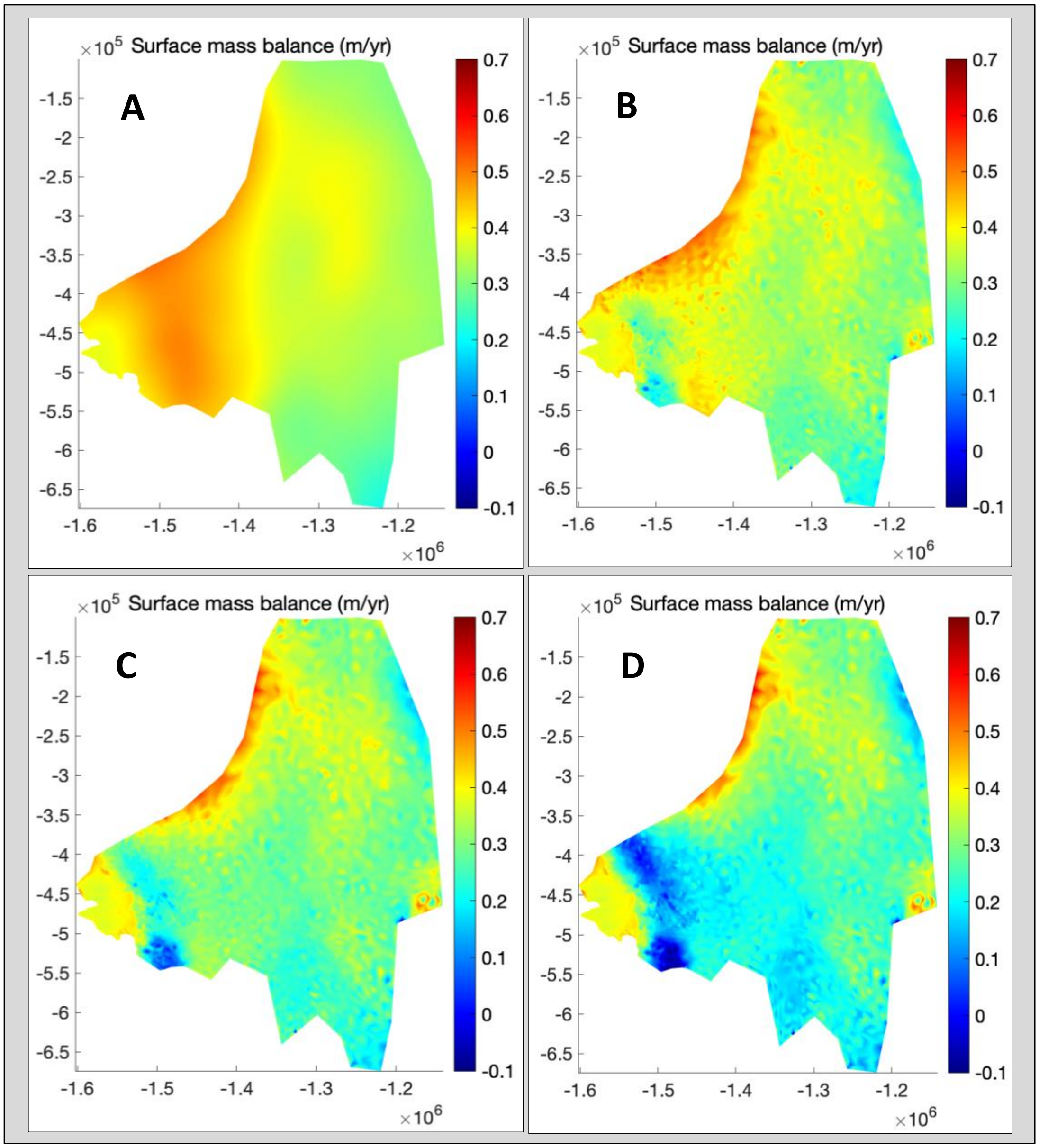

Figure 6: ISSM outputs of SMB in m/yr. Each plot represents the ISSM output after a 50 year transient run in succession (A-D) including the feedback equation. A) The initial SMB values in years 1-50 with regular (no feedback) SMB conditions. B) SMB values in years 51-100 with SMB feedback. C) SMB values in years 101-150 with SMB feedback. D) SMB values in years 151-200 with SMB feedback. Color bars signify SMB in m/yr.

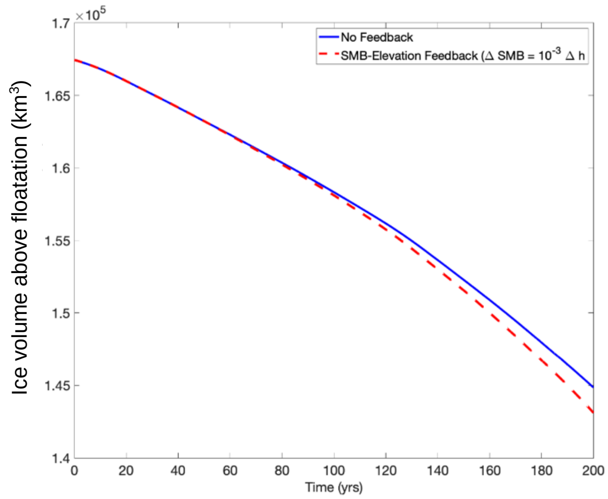

Figure 7: Comparison of ISSM ice volume above floatation measurements in km^3 between runs with no feedback and runs with feedback over a 200 year transient run. The no feedback run is shown by the blue solid line, and the run with the added SMB-elevation feedback is shown by the red dashed line.

To determine how drastic the ice mass changes between the non-feedback runs and the feedback runs were, ice volume above floatation for each simulation was plotted in Figure 7. At the end of the 200-year transient simulations, there is a ~5%-10% greater decrease in ice volume when the SMB feedback is included in the model.

5 Discussion

5.1 Observational Data

Observational data on SMB can be used to determine if there is a significant atmospheric feedback between surface elevation and SMB in the Amundsen region of Antarctica. The radar-derived accumulation measurements from Medley et al. (2014) capture spatial variability better than widely spaced point measurements from the ground (i.e. ice cores, ground radar). The region where accumulation was derived from the radar is relatively dry (i.e. not subject to significant melting) because it is at high elevation, and thus provided an effectively equivalent surface mass balance measurement for this study.

The airborne accumulation and elevation measurements in Figure 2A show a general trend of decreasing SMB with increasing surface elevation. This relationship is expected at high elevations due to the elevation-desert effect, where less moisture is contained in the atmosphere as elevation increases. The radar survey incorporates many glaciers in the Amundsen region, including Pine Island and Thwaites Glaciers, which may complicate the determination of the elevation-SMB relationship at any one glacier. With the large spatial footprint of these measurements, it is difficult to determine whether there is a strong relationship between elevation and SMB at a specific glacier. Separating these data by glacier would leave very little data since only two flight lines were flown over Thwaites Glacier (with just a few data points at the lowest elevation where data is available).

The cause of the relationship between SMB and elevation at Thwaites Glacier is that it is oriented North-South, where low-pressure systems, which travel primarily North-South in this region, bring moisture to the terminus of the glacier and work their way up along the length of the glacier, precipitating at decreasing rates as they travel to higher elevations (Parish & Bromwich, 1986; Nicolas and Bromwich, 2011). Pine Island Glacier is oriented East-West, so low-pressure systems do not advance directly along the length of the glacier. The northern boundary of Pine Island Glacier is situated along the Eights Coast Mountains where it is drier, and the southern boundary is located towards the much wetter windward side. Therefore, due to the different orientations of major glaciers in the Amundsen region, the elevation-SMB feedback may be vastly different and complicated when observed as a composite over the entire region.

An additional limiting factor of the measurements from accumulation radar is the lack of data below 800m of surface elevation. This excludes the wetter, more variable atmosphere near the glacier terminus, where the ice meets the ocean. The elevation profile of Thwaites Glacier in Figure 2B shows a large glacier area not observed in the airborne radar data. This low elevation area is also some of the most dynamically changing ice at Thwaites Glacier. Gathering measurements below the 800m elevation point would be beneficial in determining a relationship between elevation and SMB as it represents more variant atmospheric conditions, but comprehensive observational accumulation data below 800m in the Amundsen region does not currently exist.

5.2 Climate Model Reconstructions

Regional climate models provide spatially comprehensive information on the surface elevation-SMB feedback in different regions in Antarctica. Upon comparison of the four targeted glaciers in Figure 4, the relationship between elevation and SMB is strongest and most obvious at Thwaites Glacier. While the relationship appears less strong in the Eastern Antarctic and Pine Island glaciers, there is a visible shape to the relationship at Thwaites Glacier.

The differences between the surface elevation-SMB relationships at each glacier are likely due to variations in glacier geometry. For instance, Thwaites Glacier is oriented North-South, so low-pressure storm systems move along the length of glacier starting from the glacier mouth. As the storm systems advance inland at Thwaites, the moisture in the air causes precipitation to fall along the glacier length. Pine Island Glacier, although located adjacent to Thwaites Glacier, consists of an East-West orientation and the Eights Coast Mountain Range on the northern side. This causes the interactions between storm systems and elevation to be much more complicated than at Thwaites Glacier.

As indicated by the climate model outputs at Thwaites Glacier in Figure 4A and Figure 5, the SMB increases with increasing elevation until a certain point (400m-600m elevation), and then begins to show a decreasing SMB with increasing elevation. This trend of increasing SMB at low elevations and decreasing (towards zero) SMB at high elevations is in line with the SMB-elevation effect observed and simulated at North Hemisphere glaciers and ice sheets (Cutler et al. 2000). Both RACMO and MAR outputs support the same elevation-SMB relationship. The results here could indicate that there may be an important atmospheric influence in the observed marine ice sheet instability behavior at Thwaites Glacier. This result gives further reasoning to test the influence of an atmospheric feedback against existing ice sheet evolution models to see if there is any effect on glacier evolution predictions.

5.3 ISSM

The SMB distributions depicted in Figure 6 offer a useful visualization of the distribution of decreases in SMB over time at Thwaites Glacier when the elevation-SMB feedback in Equation 3 is implemented in the simulation. The highest decreases in SMB are focused in the lower elevations of the glacier near the coast, with some negative SMB values (indicating annually-averaged surface melting) appearing in the latter half of the 200-year run. Increased thinning near the coast may influence the ice-ocean interactions at the grounding line and could cause increased ice flow towards the ocean. Overall, the glacier thins over time, which impacts how the climate feedback interacts with the ice. If the height of the glacier decreases, the path of the low-pressure storm systems could change and potentially shift the distribution of SMB over the length of the glacier. The combination of changed system interactions could increase the speed of the marine ice sheet instability at Thwaites Glacier.

Figure 7 shows a comparison between ice mass loss (represented by the ice volume above floatation) between cases with no feedback and with the feedback included in transient ISSM simulations. The simulations show a 5%-10% increase in ice mass loss when the feedback in Equation 3 is included.

Though the difference between the simulations is relatively small at the end of the transient runs, further tests are needed using stronger feedbacks and longer transient runs to assess the full range of possible effects of the elevation-SMB feedback. A stronger elevation-SMB feedback could yield a larger difference in ice mass loss when incorporated into the model, and a longer transient run may show significantly increased ice mass loss rates at Thwaites Glacier.

6 Conclusion

This study has investigated the surface elevation-SMB relationship at Thwaites Glacier, Antarctica. Thwaites Glacier is an important case study for examining influences on ice sheet evolution and glacier stability, especially as related to the marine ice sheet instability. Understanding the elevation-SMB relationship here could indicate links between glacier and climate interactions at marine-terminating glaciers in Antarctica. This study contributes to the important effort of improving coupled models of ice sheets and climate.

At the beginning of this study, observational airborne radar data from the Medley et al. (2014) field campaign was used to investigate a potential surface elevation-SMB relationship over the Amundsen Region in West Antarctica. A loose relationship between elevation and SMB was found, potentially due to the large geographical region covered by the survey and the lack of data below 800m in elevation. Because Thwaites Glacier covers a smaller geographical region and has a significant portion below 800m in elevation, the use of regional climate models to determine a more refined relationship between elevation and SMB was necessary.

The regional climate models RACMO and MAR were used to target the elevation-SMB relationships at specific glaciers across Antarctica. Initially, RACMO was used to determine the elevation-SMB relationship for Thwaites Glacier, Pine Island Glacier, Totten Glacier, and Lambert Glacier. The outputs for Thwaites Glacier showed a much stronger relationship than the other glaciers, representing the elevation desert effect much more common in glaciers in the Northern Hemisphere. The other glaciers investigated in this part of the study showed loose relationships between elevation and SMB, potentially due to how storm paths interact with the different glacier geometries. Once the relationship at Thwaites had been found, MAR was used to verify the results from the RACMO tests. The outputs from the MAR runs closely resemble those of the RACMO runs for Thwaites Glacier.

In the final part of the study, ISSM was used to investigate the surface elevation-SMB relationship at Thwaites Glacier in further detail. With ISSM, two transient simulations of Thwaites Glacier's evolution were run using the ISSM configuration found in Seroussi et al (2017). One simulation contained no alterations to the original configuration from their study, using averaged SMB and simulating the evolution of Thwaites Glacier over the next 200 years. The other simulation used an asynchronously modified SMB that represented the general elevation-SMB feedback seen from the regional climate models. The distribution of decreasing SMB on Thwaites Glacier in the feedback-included simulations provide evidence for continued changing interactions between the ice-climate-ocean systems as geometry changes at Thwaites Glacier. We found a small increase in ice mass loss at Thwaites Glacier when the elevation-SMB feedback is included in the ISSM simulations. Although the exact effect of the elevation-SMB feedback on Thwaites Glacier is still uncertain, there is evidence that there could be a significant impact amplifying ice-climate-ocean interactions and accelerated ice mass loss in the future. Further tests of stronger elevation-SMB feedbacks and longer transient runs are necessary to make a more certain determination of what effects this climate feedback may have on Thwaites Glacier.

7 References

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8 Appendix

8.1 Two-Stage Model Tests

The use of a simple, accurate two-stage model is a computationally inexpensive method to determine potential effects of an elevation-SMB feedback on the overall behavior of Thwaites glacier. The feedback can be included in the model by changing the term corresponding to accumulation from snowfall in the model. The accumulation term, P(x), is usually set as a constant in the two-stage model. The addition of the atmospheric feedback changes the accumulation, to have a feedback, αh, over the glacier. The final accumulation term, which accounts for a precipitation-glacier geometry feedback is denoted by:

$$P(x) = P_0 + \alpha h \quad (4)$$

The two-stage ice sheet model used in Robel et al. (2018) incorporates the role of different physical processes in the glacier response to general forcing. In the case of this study, the atmospheric feedback related to the elevation-SMB relationship deduced from observations were incorporated to show the effects on the evolution of a marine-terminating glacier over time.

Tests of precipitation-glacier geometry feedbacks were run with the model in Equation 3 to provide an initial range of feedback strengths in which the precipitation-glacier geometry feedback becomes important for glacier evolution.