Role of shelf morphology in grounding-line stability: a numerical approach

Rhonika Robinson

Louisiana State University and Agricultural and Mechanical College

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ROLE OF SHELF MORPHOLOGY IN GROUNDING-LINE STABILITY: A NUMERICAL APPROACH

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science

in

The Department of Geology and Geophysics

by

Rhonika Robinson
B.Sc. Dillard University, 2006
May 2009
Dedication

I can do all things through Christ which strengtheneth me. Philippians 4:13.
Acknowledgements

I would like to thank my advisor, Dr. Phil Bart, my committee members, Dr. Huming Bao and Dr. Annette Engel. Additionally, I think it is imperative to recognize the support received by Dr. Jonathan Tomkin, for his many words of advice, and Dr. James Fastook, whose model was used in this study. I would also like to the thank Dr. Ray Ferrel, who first exposed me to geology and changed the course of my life. To the faculty and staff of LSU Geology Department, thank you for all the support. Financial support was given in part by NSF - Office of Polar Programs to Philip Bart, Applied Depositional Geosystems (ADG) and Geoscience Alliance to Enhancement of Minority Participation (GAEMP).
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Abstract

The main concern of this study is to discover how the transition from a shallow to an overdeepened, foredeepened shelf might affect grounding-line translation of the West Antarctic Ice Sheet (WAIS). Deep shelves permit a larger influx of relatively warm Circumpolar Deep Water (CDW), which melts the ice at grounding lines, and thereby, create a potentially unstable situation in which ice retreat may accelerate. Numerical analysis of the responses of marine ice sheets on various shelf profiles confirmed that a change in shelf morphology changes ice sheet dynamics. Ice sheet retreat on an overdeepened, foredeepened shelf is, at least, 3 times faster than ice sheet retreat on a shallow shelf that deepens toward the basin. Therefore, we can conclude that as the shelf transformed from its previous shallow, slightly dipping configuration to the present overdeepened, foredeepened configuration the ice sheet, indeed, became more susceptible to rapid retreat.
Chapter 1
Introduction

Research involving grounding-line dynamics increased exponentially ever since Mercer (1978) asserted that a collapse of the West Antarctic Ice Sheet (WAIS) may be imminent due to the present issue of global warming. If collapse of WAIS were to occur, global sea level would rise by 5 to 6 meters (Bentley, 1997). The fact that WAIS is grounded below sea level, meaning it is a marine based system, has been indicated as one of the main reasons for it’s presumed instability (Shepherd et al., 2002). However, there is little to no published work confirming this supposition. This study endeavors to confirm or refute the proposition that the profile of the shelf, an ice sheet is grounded on, does indeed influence its stability.

The Antarctic shelf configuration has undergone alterations in the past resulting in the present day foredeepened profile. Anderson (1999) links the present morphology of the shelf to a combination of isostatic loading and glacial erosion. Numerous advances and retreats of the ice sheet, sculpted the shelf by transporting eroded sediment from one region to another (Figure 1.1). Accordingly, one can logically infer that past continental shelf configurations may have interacted differently with warm deep water.

As shown in Figure 1.2, Modified Circumpolar Deep Water (MCDW) intrudes onto the shelf. Mixing near the calving front forms High Salinity Shelf Water (HSSW) and Low Salinity Shelf Water (LSSW), which either moves landward below the ice shelf or seaward to become Antarctic Bottom Water (AABW). Melting at the grounding line freshens the
HSSW, compelling the HSSW upwards as it morphs into Ice Shelf Water (ISW). Finally, the ISW, a very cold brine, either rises to the surface and adds to the production of sea ice, or sinks to the bottom as AABW.

Figure 1.1: Evolution of continental shelf. Modified from Bart (2003). (A) Sediment is transported as the ice sheet advances. (B) Redistribution of sediment from interior to the shelf edge. (C) Decoupling of the ice sheet as it retreats resulting in a foredeepened profile.

Rignot and Jacobs (2002) propose that the continental shelf physiography plays a significant role in permitting Circumpolar Deep Water (CDW) onto the shelf, exposing the grounding line to changes in the temperature and ocean circulation of ocean. They asserted that variations in the thermohaline circulation have a considerable impact on basal melting rates under the ice shelf that may alter the distribution of ice thickness, retreat grounding
Figure 1.2: CDW intruding on shelf. Taken from Smethie and Jacobs (2005). Cartoon displaying circumpolar Deep Water intruding onto the shelf and mixing with Ice Shelf Water to form Bottom Water on the Ross Ice Front. AASW = Antarctic Surface Water, CDW = Circumpolar Deep Water, WRSSW = Western Ross Sea Surface Water, ISW = Ice Shelf Water, HSSW = High Salinity Shelf Water, LSSW = Low Salinity Shelf Water, AABW = Antarctic Bottom Water.

lines, and thus increase the velocity of ice flow, destabilizing the ice sheet. In agreement, Bart and Iwai (submitted) also stipulated that the Antarctic Peninsula outer continental shelf experienced augmented glacial erosion for a brief period in the early Pliocene which resulted in an overdeepened and foredeepened shelf that allowed CDW to intrude the shelf and melt the ice at the grounding line (Figure 1.3).

Although considerable progress has been made on the history of the Antarctic Ice Sheet, the dynamics of grounding-line migration is still poorly constrained (Parizek and Alley, 2004). This is attributable to the lack of understanding of the many mechanisms accountable for the behavior of an ice sheet. The purpose of this study is to confirm quantitatively that shelf morphology is indeed one of the many mechanisms responsible for ice-sheet dynamics.
Figure 1.3: Encroachment of CDW as the continental shelf evolves. Taken from Bart and Iwai (submitted). The encroachment of Circumpolar Deep Water as the shelf transitions from previous configuration to present day overdeepened and foredeepened profile.
and hence, WAIS is inherently instable because of the modern overdeepened, foredeepened shelf.

This study attempts to link ice-sheet stability and shelf morphology by conducting a comparative, numerical analysis. The study utilizes five disparate shelf profiles, subjecting them to identical conditions and evaluating the responses of the ice sheet. The Ross Sea Embayment region, home to largest Antarctic ice shelf, was chosen as the site for modeling experiments. It is bounded by the Transantarctic Mountains of Victoria Land to the west and Marie Byrd Land to the east. The broad continental shelf measures an average of 500 meters below sea level at the edge, and slopes landward to approximately 1000 meters (Mosola and Anderson, 2006). The selected forcing, ocean temperature, is considered suitable for the experiments because the ice sheet is grounded out onto the continental shelf and susceptible to changes in ocean properties.

The experiments, using The University of Maine Ice Sheet Model (UMISM), involve five configurations of the Ross Sea continental shelf (shallow-dipping, shallow-flat, deep-dipping, deep-flat and foredeepened), as well as increasing increments in ocean temperature ranging from 0.5°C to 4°C. These experiments test the sensitivity of the ice sheet on each of the shelf configurations to changes in ocean temperature. The results provide the opportunity to evaluate the degree to which the depth and shape of the shelf affect ice-sheet stability.
Chapter 2
Methods

2.1 Model Description

The advent of numerical ice sheet models transformed the field of glaciology into a more quantitative science Hughes (1995). Numerical modeling can be used as a tool to quantify qualitative observations of a particular physical system as it responds to various factors Holmulnd and Fastook, 1993).

Hughes (1995), asserts that ice sheet models are developed for two main reasons; predictive purposes, and interpreting and understanding previous ice sheets. All ice sheet models attempt to approximate physical processes by estimating mass balance, internal temperatures, parameters for ice flow and bed settings etc. There are a number of ice sheet models used to reconstruct geological events and processes of the Antarctic Ice Sheet (Oerlemans, 1982; Huybrechts, 1990; Hughes, 1992; Schoof, 2003; Parizek and Alley, 2004).

The University of Maine Ice Sheet Model (UMISM) was used in this study (Fastook, 1990; Fastook and Prentice, 1994). UMISM is a time-dependent, two-dimensional model that solves the mass-continuity equation (2.1) using the finite-element method.

\[ \nabla \cdot \sigma(x, y) = \dot{a}(x, y) - \frac{\partial h}{\partial t} \]  

(2.1)

Previous Antarctic applications of UMISM include determining the response of the Antarctic Ice Sheet (AIS) to different climates (Fastook and Prentice, 1994), ascertaining past ice
sheet elevations in interior West Antarctica (Ackert et al., 1999) and establishing the influence of sea-level on WAIS instability (Fastook, 1984).

The model is a component of ice sheet physics including, mass and momentum conservation for ice dynamics, energy conservation for temperatures within the ice sheet, a hydrostatically supported visco-elastic plate which accounts for isostasy, distribution and movement of water produced by basal melting, and a simple climatology for surface temperatures and mass balance.

Below is a brief summary of the main components of the model. This is taken from a more detailed description of the model, which is available for the reader (Fastook, unpublished; http://tulip.umcs.maine.edu/shamis/umism/umism.html).

The general rule of mass balance states that mass, which enters a system must either leave the system or accumulate within the system. Thus, flux of ice into an area must be balanced by alterations in the thickness of ice in that area. The continuity equation (2.1) is used to govern the balancing of fluxes in and out of a region, where \( \sigma \), is the flux of ice, \( \dot{a} \), is the accumulation rate and \( \partial h/\partial t \), is the change in ice elevation surface.

To attain ice-surface elevations, one must find a relation to flux (\( \sigma \)) in equation (2.1), which depends on ice density, gravity, a flow-law constant, velocity due to sliding (that is dependent on ice temperatures and basal water production), ice thickness and surface slope.

The net accumulation rate is derived by mass balance and uses average annual surface temperatures obtained from a simple climate model (discussed below). Accumulation rates are acquired for each node in the model domain based on the saturation vapor pressure and surface gradient. Ablation rates are computed using the number of positive degree days founded on a latitudinal-adjusted seasonality. Lastly, net accumulation is simply the difference between accumulation and ablation at each node.
Internal temperature values are calculated using equation (2.2),

$$\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} - w \frac{\partial T}{\partial z} + \frac{Q}{\rho c}$$

(2.2)

where \(k\) is the thermal diffusivity and is the coefficient in the term describing the diffusion of heat; \(w\), is the velocity of the advection of heat in the vertical direction; \(Q\), is the applied or external heat, \(\rho\), is the ice density and \(c\), specific heat. Temperatures are computed in only one-dimension, the vertical (\(z\)), therefore, horizontal diffusion and advection are neglected. Of the two, only horizontal diffusion is of any significance. However, its importance is restricted to areas of fast flowing streaming ice.

The flux of water beneath the ice is also governed by conservation laws. The thickness of water, \(w\), under the ice is determined by equation (2.3).

$$\frac{\partial w}{\partial t} = -\nabla \cdot \bar{\sigma} + \frac{\partial S}{\partial t}$$

(2.3)

The left-hand side of the equation represents the change in water thickness with time. On the right-hand side, the first term expresses the velocity of the flux of water and the last term represents external sources and sinks of water.

One of the primary inputs to UMISM is the bedmap data, derived from Lythe et al. (2001). The model also takes into consideration isostasy because it is vital to determining bed topography as ice is accumulated and ablated on the bed’s surface. Depression of the bed is calculated by assuming a visco-elastic, hydrostatically supported plate. The model uses the Reissner-Mindlin Plate Theory to approximate the response of a deforming bed beneath an ice-sheet.

Apart from bedrock topography, mass balance at each grid point, is a primary input and is derived from the climate model. The climate is regulated by modifying the annual average air temperature, which is obtained from the Greenland Ice Core Project (GRIP) core
\( \delta^{18} \text{O} \) record, at sea level. This temperature is used as the initial value for all calculations involving surface temperatures. Surface temperatures are determined from an atmospheric lapse rate that is adjusted for surface elevation and distance from the pole. The limitations of this simplified climate model, implemented by UMISM, are noted but it is an appropriate approximation for real temperatures.

All the various above-mentioned physical processes jointly determine the ice surface elevation at each grid node in the model. Other output consists of isostatically adjusted bedrock elevation, column-integrated ice velocities, and internal temperatures within the ice column.

### 2.2 Model Domain

The whole Antarctic Ice Sheet is modeled by UMISM. However, for the purpose of this study, only a limited region is needed. A section of Antarctica can be modeled either as embedded or not embedded. The key difference is in the treatment of boundary conditions. Embedded ice sheet modeling, includes running the whole ice sheet at a low resolution, while running the designated area at a higher resolution. This allows the boundary conditions for the smaller domain to be informed by the developments occurring on the larger domain. This type of modeling is pertinent to studies determining ice-flow patterns and positions of ice divides. For non-embedded modeling, a value for ice-surface elevation at the boundary (Dirichlet Boundary Condition) or flux of ice across the boundary (Neumann Boundary Condition) must be specified. For this study, non-embedded modeling is used and the boundary values are fixed. Although this is not the ideal situation, it ensures that there is no influence from processes occurring in other sections of Antarctica, where the continental shelf isn’t altered. It is vital that the response of the ice sheet is due to only changes in ocean temperature and Ross Sea continental shelf morphology.

The model domain is located in the region comprising of the Ross Sea Embayment (consisting of continental shelf to shelf edge), a section of East Antarctica and the Transantarctic Mountains and most of West Antarctica (Figure 2.1). It covers an area of approximately 3.6
Table 2.1: Shelf Morphologies

<table>
<thead>
<tr>
<th>Shelf Morphologies</th>
<th>Coast(m)</th>
<th>Shelf Edge(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow dipping</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Shallow flat</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Deep dipping</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Deep flat</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Foredeepened</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>

x 10^6 km² and is composed of 16113 nodes spaced 15km apart. Data between the grid nodes were interpolated using a smoothing algorithm.

The shelf configurations used in the study replicates the various stages of the Antarctic continental shelf as it transitioned from a shallow, fairly flat morphology to its present overdeepened, foredeepened morphology (Table 2.1). The bed topography in the model domain had to be edited to reflect the various shelf morphologies. To facilitate this requirement MATLAB was employed. MATLAB is a high-level language as well as an interactive numerical computing environment (www.mathworks.com). The bed data, in the form of an array, was ‘looped’ through and modifications were made when needed. A simple algorithm was utilized to convert the present shelf to the required shelf profiles consisting of identifying the nodes which represented the coast and shelf edge for each column. The values between these nodes were populated incrementally from the coast value to the shelf edge value. For example, the shallow dipping shelf had values of 0 at every node identified as coast, and 100 at every shelf node. If the number of elements from the coast to the shelf nodes, in a particular column is 20, then the values would be, 0, 5, 10, 15.....100. The resulting ‘modeled’ shelves possessed smooth surfaces with either deep or shallow, dipping or flat, configurations (Figure 2.2).

2.3 Experimental Design

The approach of sensitivity testing is applied to determine the degree of influence that the shape of the shelf has on the stability of its ice sheet. If the ice sheets on all the shelves
Figure 2.1: Model domain. The model domain is highlighted. It includes the Ross Sea Sector of WAIS and EAIS, as well as the Ross Sea continental shelf. Modified from www.map-of-antarctica.us
Figure 2.2: Modeled Shelves. Matlab was used to edit present shelf (a) to create the various shelf morphologies used in this study.
produce similar results, then one can conclude that their stability is not affected by the shape of the shelf. However, the greater the disparity in their results, the more sensitive the ice sheets are to their shelf morphology. For this experiment, every shelf configuration is subjected to identical conditions and an analysis of the responses of the ice sheet is examined. Responses include inflation (thickening of the ice sheet), deflation (thinning of the ice sheet), and advance and retreat of the grounding line. The amplitude of the response indicates the sensitivity of the ice sheet on the shelf. Therefore, larger rates of retreat in the grounding line imply a more unstable ice sheet. With this methodology we are able to deduce which morphology(ies) create the most unstable ice sheet.

The model was initialized with a ‘calving factor’ of 0 and allowed to run for 10,000 years (Figure 2.3). A ‘calving factor’ of 0 simply means ice is not losing mass. The ice sheet expanded and terminated near the shelf edge at the end of the 10,000 year run. Subsequent to permitting the ice sheet to grow out to the shelf edge for the range shelf morphologies, warming of the ocean at varying degrees was initiated and the model was permitted to run for another 10,000 years, with all other factors remaining constant (Figure 2.4). Snap shots of the ice sheet were taken at every 1000 years (Figures 2.3 and 2.4). The ocean temperature in the model was increased according to the following sequence: 0.5 °C, 1.0 °C, 1.5 °C, 2 °C, 2.5 °C, 3 °C, 3.5 °C, 4 °C.

There is no dynamic ocean model, hence, ocean temperatures are imposed. Rignot and Jacobs (2002) conducted a study calculating 23 basal melt rates at remote regions around Antarctica. They used satellite radar interferometry to make observations on grounding-line locations, ice velocities and surface topography of outlet glaciers. These variables were included in their calculations of sub-ice-shelf melting rates. A basal melt rate of 1/0.1(m/°C) was established after incorporating all 23 data points (Figure 2.5). They stated that this rate is comparable to relations derived for icebergs thawing in warmer ocean water, as well
as a laboratory experiment conducted by Russell-Head (1980). Therefore, an increase of 0.1°C was converted to a melt rate of 1m/yr and was used in this study.

2.4 Assumptions

As with all experiments, certain assumptions are necessary. Limitations of the model led to two major assumptions, which are discussed below.

2.4.1 Ice Shelf

One of the limitations of the model is that it does not contain any ice shelf physics. In other words, there is no ice shelf represented in the model. An ice shelf is a floating sheet of ice that is nourished mainly by glaciers and snowfall (Fahnestock, 1996). Ice shelves act as buffers to an ice sheet. According to Alley and Whillians (1991), there exist longitudinal compressive stresses in ice shelves that act as a buttress. It is argued that due to the lack of an ice shelf in the model, the ice sheet is intrinsically more unstable. Although, it is a valid argument, the forcing used in this study, basal melting, affects the grounding line regardless of the presence of an ice shelf (Smedsrud et al., 2006). Additionally, Lingle et al. (1991) stated that the degree of buffering is negatively correlated to the increases in basal melt rates (ocean warming). They stated that the Ross Ice Shelf will thin by as much as 40% in 50 years in response to an increase in basal melt rate of only 2 m/yr. The significance of the buttressing effect of the ice shelf decreases as ocean temperature increases. Therefore, given the forcing and time scales used in this study, the presence of an ice shelf is not vital.

2.4.2 Basal Melting

Ocean temperatures are not derived from an ocean model but imposed. Therefore, any feedback mechanisms that occur beneath the ice shelf are not included. Empirical evidence for processes occurring at the grounding line is very limited. It is not certain what occurs as the ‘warm’ Deep Water (WDW) travels under the ice shelf and interacts with the ice at the grounding line. Modeling of these processes by Smedsrud et al. (2006), and Smethie
Figure 2.3: Advance of ice sheet. ‘Spin up’ of ice sheet for 10,000 years. The ice was allowed to advance out onto the shelf. The shallow-flat shelf is used in this figure. The colors indicate thickness of ice in meters.
Figure 2.4: Retreat of ice sheet. Following the ‘spin up’, an increase in ocean temperature was initiated, resulting in retreat of the grounding line. In this figure the temperature increase used was 3.5°C.
and Jacobs (2005) shows that the WDW melts the ice at the grounding line, freshens and ascends making space available for additional WDW to invade the cavity. This process can be compared to a constant flow of warm water accessible to melt the ice and is applied in the design of this experiment. However, future work on this subject matter should include a coupled ocean-ice-sheet model and results compared. On another note, every node at the grounding line is affected by the change in ocean temperature. In reality, WDW does not interact with the grounding-line ice everywhere simultaneously (Thoma et al., 2008). These issues were not resolved in this study.
Chapter 3
Results

Preliminary results confirmed that, with the same forcing (in this scenario sea level), deep grounding lines respond very differently to shallow grounding lines supporting the basic hypothesis and allowed for continued investigation on this topic (Figure 3.1).

(a) Shallow grounding line  (b) Deep grounding line
Figure 3.1: Preliminary results: Shallow versus Deep grounding line. Preliminary results confirmed the significant difference in response, to the same degree of forcing, of a grounding line shoaled by 100 meters (a) and one deepened by 100 meters (b). The red line in both panels is the “reference” grounding line and marks the location of the grounding line prior to the onset of forcing.
To determine ice-sheet instability certain aspects of the response of the ice sheet to ocean warming were analyzed. The amount of forcing required to produce a collapse is one extreme indicator of the stability of an ice sheet. Shelf profiles with ice sheets that collapse with smaller increases in ocean temperature are deemed more unstable than ice sheets that necessitate larger increases in ocean temperature. The timing of the collapse is another important factor in accessing ice sheet stability. Ice sheets with grounding lines that retreat more rapidly are also perceived to be less stable.

An assessment of threshold temperatures was also conducted to give insight on the warming necessary to produce an inevitable collapse. Lastly, results on the comparison between the modeled foredeepened shelf and the present shelf was conveyed.

The results presented in this section focus on the responses of the ice sheet to forcing. This comprises the last 10,000 years of the simulated runs. Ice-surface elevations at each node, generated every 100 years by the model, were analyzed every thousand years.

### 3.1 Collapse

The phrase ‘ice-sheet collapse’ suggests a sudden and grand event that entails huge masses of ice breaking apart into pieces and drifting into the open ocean. In reality, the collapse of an ice sheet may take thousands of years before it is completely gone (Vaughn and Spouge, 2002). In this study, a collapse is defined as the loss of most or all of the West Antarctic Ice Sheet grounded ice (Figure 3.2).

The shallow-dipping and shallow-flat shelves responded similarly to various degrees of forcing. Both shelves required a warming of 3.5°C in ocean temperature to instigate a collapse (Table 3.1). The ice sheets on each shelf were completely gone by 19000 years, 9000 years after the introduction of warm water on the shelf. They collapsed 2000 years earlier (17000 years) with a 4°C change in sea temperature.

Unlike the shallow shelves, the deep shelves possessed ice sheets that behaved very differently to the temperature changes. The foredeepened shelf required the least change in ocean
temperature (2°C) to produce a collapsed ice sheet; followed by the deep-flat shelf (2.5°C) and deep-dipping shelf (3.5°C) (Table 3.1).

3.2 Retreat History

Rate of retreat was calculated by evaluating the position and timing of the grounding line along the black line in Figure 3.3. The rate of retreat indicates the rate at which the ice sheet is losing mass. Ice thickness values along the transect were retrieved from the model and the grounding line was identified by a 0 ice thickness. Incorporating the time taken for all the ice thicknesses to become 0 along the line, permitted the calculation of a rate (Figure 3.4).
Table 3.1: Collapse

<table>
<thead>
<tr>
<th>Shelf Morphology</th>
<th>Collapse Temperature Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fordeepened</td>
<td>2°C</td>
</tr>
<tr>
<td>Deep flat</td>
<td>2.5°C</td>
</tr>
<tr>
<td>Deep dipping</td>
<td>3.5°C</td>
</tr>
<tr>
<td>Shallow dipping</td>
<td>3.5°C</td>
</tr>
<tr>
<td>Shallow flat</td>
<td>3.5°C</td>
</tr>
</tbody>
</table>

Figure 3.3: Calculating retreat. Rate of retreat is calculated along the black line in figure. The red dot denotes the node used to calculate threshold and transition temperatures for the various shelf morphologies.

Ice sheets on foredeepened profiles exhibited the highest rates of retreat, at all temperature changes. Rates of retreat for the foredeepened shelf ranged from 94m/year at 1.5°C to 1485m/year at 4°C (Figure 3.5). The deep-flat shelf, second most unstable shelf, possessed rates of 247m/year to 524m/year (Figure 3.6).

Although the shallow-flat, shallow-dipping, and deep-dipping shelves all required the same amount of forcing to collapse (Table 3.1), inspection of the rates of retreat showed the deep-dipping shelf to be slightly more unstable because less time was needed to bring about a collapse at the temperature increase of 3.5°C (Figure 3.7). Rates of retreat for the shallow-flat shelf were 57m/year to 325m/year (Figure 3.8); shallow-dipping, 71m/year to 317m/year (Figure 3.9) and deep-dipping, 84m/year to 325m/year (Figure 3.10).
Figure 3.4: Retreat of ice sheet on Shallow-flat shelf at temperature increase 3.5°C. Cross-section illustrating change in ice elevation through time at the red dot in Figure 3.3.
Figure 3.5: Retreat history: Foredeepened Shelf. Average rates of retreat were: Blue: 94m/year; Green: 287m/year; Red: 478m/year; Light blue: 735m/year; Purple: 743m/year; Yellow: 1485m/year.
Figure 3.6: Retreat history: Deep-Flat Shelf. Average rates of retreat were: Blue: 247m/year; Green: 386m/year; Red: 519m/year; Light blue: 524.
Figure 3.7: Retreat history: SF, SD, and DD shelves at temperature increase 3.5°C. Average retreat rates were: SF: 261m/year; SD: 265m/year; DD: 271m/year. Although, they all required the same degree of forcing to instigate a collapse, the deep-dipping shelf responded to forcing earlier and collapse before the shallow shelves. Hence, the deep-dipping is somewhat more unstable.
Figure 3.8: Retreat history: Shallow-flat Shelf. Average rates of retreat were: Blue: 57m/year; Green: 170m/year; Red: 265m/year; Light blue: 325m/year.
Figure 3.9: Retreat history: Shallow-dipping Shelf. Average rates of retreat were: Blue: 71m/year; Green: 181m/year; Red: 260m/year; Light blue: 317m/year.
Figure 3.10: Retreat history: Deep-dipping Shelf. Average rates of retreat were: Blue: 84m/year; Green: 208m/year; Red: 271m/year; Light blue: 325m/year.
3.3 Thresholds and Transitions

An analysis of the height of ice, at the node located at the red dot in Figure 3.3, revealed that there were changes in the interior of the ice sheet, in response to varying temperature. It was noted that the ice sheets on deep shelves exhibited a dramatic change from a stable state to an unstable state at a particular ocean temperature increment. However, on shallow shelves the ice sheets appear to transition from stability to instability.

For example, on the deep-dipping shelf (Figure 3.11) one can see the distinct difference in curves representing temperature increases of 0.5°C to 2°C and the curves representing 2.5°C to 4°C. The threshold temperature for an ice sheet on this shelf was 2.5°C. At this temperature the ice sheet could not attain an equilibrium state and finally collapsed. The threshold temperatures for the deep-flat (Figure 3.13) and foredeepened shelves (Figure 3.12) were 2.5°C and 2°C respectively.

Alternatively, the curves representing temperature increases on the shallow-dipping shelf (Figure 3.14) appear to transition from a stable to unstable state. The “transition” temperature was 2.5°C for both shallow shelves (Figure 3.15).

3.4 Present Shelf Comparisons

A comparison between the simulated foredeepened shelf and the present shelf was conducted. On the present shelf there are troughs and banks. Troughs may act as conduits for warm water to melt the ice at the grounding line destabilizing the ice sheet (Rignot et al., 2008; Thoma et al., 2008). Conversely, banks act as pinning points facilitating a more stable ice sheet (Denton and Hughes, 2000). The present shelf underwent the same conditions as the other shelves and the results were evaluated. Firstly, the present shelf required an increase of 2.5°C in ocean temperature before its ice sheet collapsed within 10,000 years. In comparison to the foredeepened shelf, it was noted that the rate of retreat was less at each increase in ocean temperature. Rates ranged from 168m/year at 2°C to 750m/year at 4°C.
Figure 3.11: Threshold temperature: Deep-dipping Shelf. Ice elevation at red dot in Figure 3.3. Curves representing temperature increments 0.5°C to 2°C can be easily differentiate from curves representing temperature increments 2.5°C to 4°C. The sharp shift in ice thickness on the interior signifies that the ice sheet has approached a limit. A threshold temperature change 2.5°C has been designated for the deep-dipping shelf.
Figure 3.12: Threshold temperature: Foredeepened Shelf. Ice elevation at red dot in Figure 3.3. The threshold temperature for an ice sheet on the foredeepened shelf is $2^\circ C$. 
Figure 3.13: Threshold temperature: Deep-flat Shelf. Ice elevation at red dot in Figure 3.3. The threshold temperature for an ice sheet on the deep-flat shelf is 2.5°C.
Figure 3.14: Transition temperature: Shallow-dipping Shelf. Ice elevation at red dot in Figure 3.3. The shallow shelves appeared to transition from a state of stability to instability. The transition temperature for an ice sheet on the shallow-dipping shelf is 2.5°C.
Figure 3.15: Transition temperature: Shallow-dipping Shelf. Ice elevation at red dot in Figure 3.3. The transition temperature for an ice sheet on the shallow-flat shelf is 2.5°C.
(Figure 3.16). It was also seen that the present shelf possessed a threshold temperature, namely $2^\circ$C (Figure 3.17).
Figure 3.16: Retreat history: Present-day Shelf. With different increases in ocean temperature, average modeled rates of retreat were: Blue: 168m/year; Green: 359m/year; Red: 466m/year; Light blue: 500m/year; Purple: 750m/year.
Figure 3.17: Threshold temperature: Present-day Shelf. Ice elevation at red dot in Figure 3.3. The threshold temperature for the present shelf is $2^\circ$C.
Chapter 4
Discussion

The data presented in this study have been synthesized to yield average retreat rates of the Ross Sea sector of the West Antarctic Ice Sheet over 10,000 model years as ocean temperature increases. The experiments are idealized and intended to test the sensitivity of the ice sheet to the continental shelf configuration on which it is grounded. The intentions of this study was not to simulate any past glacial cycles nor to make any explicit predictive statements on the timing of collapse of the WAIS. Instead, the purpose is to confirm, quantitatively, that WAIS is indeed inherently unstable because it rests on bedrock that is overdeepened and foredeepened.

4.1 Patterns and Trends

Retreat of the grounding line occurs when ablation is greater than accumulation and the ice sheet loses mass. As the ocean becomes warmer, ablation is enhanced and exceeds accumulation which can result in grounding-line retreat. From the UMISM results, there appeared to be a distinctive and dissimilar pattern of retreat between shelves that could host stabler ice sheets (shallow-flat, shallow-dipping and deep-dipping) versus shelves with less stable ice sheets (deep-flat and foredeepened).

Initially, the stabler ice sheets retreated quickly, following an increase in ocean temperature; however, the retreat slowed within 1,000 to 2,000 years. At particular temperature increases, the rapid retreat resumed and eventually the ice sheet collapsed. Conversely, the
majority of the ocean temperature scenarios with ice sheets on the unstable shelves exhibited a slower primary retreat, followed by an increased retreat rate after a couple thousand years.

The differences in the pattern of grounding-line retreat indicate a general stability distinction. On shallow and deep-dipping shelves, ice sheets appear to be able to re-equilibrate themselves much more efficiently, after temperature change, than ice sheets on any of the remaining configurations. The acceleration of grounding-line retreat on the foredeepened and deep-flat shelves imply that a collapse is inevitable. However, it may not occur within the time frame of this experiment (10,000 years). Shepherd et al. (2001) referenced several authors (Weertman, 1974; Thomas, 1979; der Veen, 1985; Hindmarsh, 1996) as they asserted shelf topography, along with lack of ice shelf, as the key causes for the high rates of retreat by the Pine Island glacier (PIG) of West Antarctica (Figure 4.1). Rignot (1998), used satellite radar interferometry to reveal that the PIG retreated approximately 5 kilometers inland between 1992 and 1996.

Figure 4.1: Map showing drainage area for Pine Island Glacier, West Antarctica. Taken from Shepherd et al. (2001).

Differentiating ice sheets by the timings of their collapse can indicate which configuration is more sensitive to ocean temperature increase and which ice sheet will potentially be more
unstable. The general observed trend from the UMISM results indicate that deeper shelves host more inherently unstable ice sheets, and specifically when the shelf is foredeepened because the ice sheet collapsed with an increase of ocean temperature of 2°C. The deep-flat followed closely requiring 3.5°C for its ice sheet to collapse. The deep-dipping, shallow-dipping and shallow-flat shelf all require 3.5°C increase in ocean temperature to collapse, however, a more detailed analysis of the retreat history reveals that the deep-dipping shelf responded quicker to the forcing than the shallow shelves collapsing at year 18,000 rather than 19,000. It appears that the shallow shelves respond similarly regardless of the slope. On the other hand, the deep-flat, deep-dipping, and foredeepened shelves all behave differently and suggests that ice sheet responses on deep shelves is influenced by the gradient and direction of slope.

The major difference between an ice sheet grounded on a shallow versus a deep shelf, is the amount of ice exposed to the marine environment. Therefore, one may logically deduce that changes in the bathymetric conditions will have more of an effect with deeper grounding lines, as established in the results. Utilizing a similar evaluation, one may also infer the rationale for foredeepened shelves being the most unstable of all deep shelves. The deep-dipping shelf, which shallows inland, is the most stable deep shelf because as the grounding line retreats less of the ice is exposed to the relatively, warm ocean water. In comparison, as the grounding line retreats on the deep-flat shelf, the amount of ice in contact with the ocean remains the same. On the foredeepened shelf, as the ice sheet shrinks, the amount of ice affected by the ocean increases, making the ice sheet more susceptible as the grounding line retreats. Another explanation is presented by Rignot and Jacobs (2002) which maintains that “a rise in ocean temperature that increases the bottom melt rate and steepen the ice thickness gradient near the grounding line”, triggers glacier acceleration resulting in grounding-line retreat. On a shelf that deepens inland, a positive feedback arises as the ocean comes into contact with deeper ice. Alternatively, a grounding line retreating upslope affords more stability because
the glacier thickens and its velocity decreases. Regardless of the rationalization, shelves with a foredeepened profile harbors ice sheets that have a propensity for instability.

At the onset of forcing, it was noted that as the grounding line retreated, the ice sheet continued to thicken in regions on the interior of the ice sheet. As the forcing continued, the ice elevations inland either remained fixed or began to decrease. This phenomenon was recognized on ice sheets grounded on all shelf configurations. However, the amount and duration of inflation differed with shelf profile and temperature change. The duration of inflation on deep shelves was short-lived, while ice sheets on shallow shelves grew as much as 700 meters at places inland with retreat occurring at the ice front. Ackert et al. (1999) explains that it is possible, with extended grounded lines, for an ice sheet to not have sufficient time to equilibrate. Consequently, “interior elevations continue to thicken during grounding line retreat until the initial wave of thinning reaches the interior of the ice sheet”. This implies that ice-sheet instability, or constraining the timing of collapse, can not be determined by grounding-line analysis only. The incorporation of interior ice elevations are necessary in formulating a more accurate estimation.

Another significant observation from the model results reveals the rapidity of the switch from inflation to deflation of the interior on all but the shallow shelves. This abrupt shift suggests that ice sheets on deep shelves possess a sort of threshold, with respect to ocean temperature. Both the ice sheets on deep-flat and foredeepened shelves collapse came within the 10,000 years at their threshold temperatures. With the deep-dipping shelf, collapse was not achieved within the model time frame but it is assumed that the ice sheet would not stabilize but eventually collapse. In contrast, shallow shelves did not display a sharp shift from one state to the next. Consequently, transition, rather than threshold, is the best adjective to describe this phenomena in the shallow shelves. Once more, this observation solidifies the proposition that deeper shelves host unstable ice sheets, especially an overdeepened and foredeepened shelf.
An interesting point to note is, all shelf configurations, with the exception of the fore-deepened, had threshold/transition temperature increases of 2.5°C. Although, most shelves needed a higher temperature increment before their ice sheets disintegrated within 10,000 years, there was an undeniable turning point in their state at 2.5°C.

4.2 Present Shelf Comparisons

This study is a first order consideration of the relationship between the stability of marine ice sheet, morphology (depth and shape) of the shelf on which it is grounded and ocean temperature. It was deemed noteworthy to conduct a comparative analysis of the present day shelf and the modeled foredeepened shelf. As stated earlier, the modeled foredeepened shelf lacks the topographic highs and lows of the modern day continental shelf. The Ross Sea floor is characterized by northeast-southwest oriented banks, 40 to 130 kilometers wide, and troughs, 170 to 200 meters deep (Denton and Hughes, 2000).

The results revealed that the present shelf exhibits more stability than the modeled foredeepened shelf. The present shelf required warmer ocean temperatures to collapse, notably, 2.5°C. The retreat pattern was similar to that of the foredeepened shelf but the rates of retreat was lower than the foredeepened shelf at every temperature increment.

Therefore, it appears that the stability provided by the presence of banks or topographic highs on the present day Ross Sea continental shelf is sufficient to counter the destabilization of troughs, under the conditions of this model experiment. However, the present day shelf displayed a threshold temperature, 2°C, which coincides with the foredeepened shelf.

4.3 Implications

Changes in the state of glaciers and ice sheets are very relevant to our existence. Their influence is not only limited to humans and animals that reside in close proximity to them, but to life on a global scale, because they influence climate and sea level (Sarmiento, 1993). Alley et al. (2005) concurs, stating that even minor rises in sea-level would have a consider-
able effect on humanity because a large concentration of the populace lives near coastlines. Awareness of glacial processes is necessary in attaining the capability to respond to, and/or predict, rises in sea-level for the near future.

This study confirms the supposition that a foredeepened shelf contributes to its ice sheet’s instability. This implies that the WAIS may have responded differently to ocean conditions prior to its surrounding shelves being overdeepened and foredeepened. This acknowledgement should be taken into consideration when attempting to simulate past advances and retreats of WAIS.

In attempting to predict future collapse, investigations must be done on interior, as well as, at the grounding line. The fact that the decreasing thicknesses on the interior, along with grounding line retreat, indicated the arrival of some sort of threshold for the ice sheet, may be used as a warning for WAIS collapse.
Chapter 5
Conclusions

5.1 Summary

Ice-sheet stability is affected by numerous factors that may be difficult to constrain. This study endeavored to examine one of the many variables that exert some control on the retreat of grounding lines. The evaluation of various shelf morphologies and their ice sheets have allowed the following points to be expressed.

1. Ice sheet stability is influenced by shelf morphology, but is limited to deep shelves. It appeared that ice sheets on shallow shelves, regardless of shelf morphology, responded similarly to forcing. Conversely, deep shelves responded very differently depending on its profile.

2. Ice sheets on foredeepened shelves exhibited the most instability. In general, deeper shelves host more inherently unstable ice sheets. It was apparent that the foredeepened shelf is the most unstable of them all collapsing with a temperature increment of 2°C. The overdeepened shelf followed closely with a temperature increase of 2.5°C. The remaining shelves needed at least a 3.5°C rise in ocean temperature to instigate a collapse within 10,000 years.

3. Ice sheets on deep shelves possessed threshold temperatures, whereas ice sheets on shallow shelves seemed to transition from stability to instability. It was seen that, on occasion, although the grounding line retreated, interior elevations continued to rise. This phenomenon occurred on all shelves at most temperatures. However, it was noted
that at particular temperatures the interior ice elevations would decrease rapidly and the result would be a collapsed ice sheet. The occurrence was more noticeable on the deep shelves versus the shallow shelves.

4. The ice sheet on the present day shelf demonstrated more stability than the modeled foredeepened shelf at every temperature increase. There was uncertainty whether the existence of banks and troughs on the present shelf would result in a more stable or unstable shelf, in contrast to the modeled foredeepened shelf. Results confirmed that banks help stabilize the ice sheet more than troughs (which allow relatively warm water to intrude) destabilize the ice sheet.

5. The present day shelf exhibited a threshold temperature similar to the modeled foredeepened shelf. For the present shelf, reduction in ice thickness on the interior of ice sheet concurrent with high retreat rates at the grounding line may be an indication of near future disintegration of the ice sheet.

5.2 Future work

There are a variety of paths one can proceed along depending on the desired objective. A prudent next step will be the incorporation of an oceanographic model. This will eliminate the assumption that there are no feedback mechanisms between the ice sheet and the ocean, as well as, produce results a bit more comparable to reality.

Potential work include analyzing other forcing mechanisms such as sea level, air temperature, precipitation etc. Performing the same experiment, but substituting the forcing, would be helpful in deciphering whether other forcings affect ice sheets, on different morphologies, to the same degree as basal melting.

Lastly, an analysis of the results in terms of sea-level rise will give us ideas of probable rates of sea-level rise and can be put to use in a predictive sense.
References


Fastook, J. (1990). A map-plane finite-element program for ice sheet reconstruction: a steady-state calibration with Antarctica and a reconstruction of Laurentide Ice Sheet for 18,000 BP. *Computer Assisted Analysis and Modeling on the IBM 3090*. 

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Vita

Rhonika entered the world in July, 1977. She grew up on the outskirts of Port of Spain, the capital of Trinidad and Tobago. She attended Sacred Heart Girls Primary School, Woodbrook Government Secondary School and Polytechnic Sixth Form Government School. Subsequently, she went to work as an accounts clerk at Royal Caribbean Insurance for three years then Inglefield/Ogilvy Advertising for two years. After deciding to switch careers she applied to Dillard University in New Orleans to pursue a bachelor’s degree in computer science. She was accepted with a full scholarship. In her junior year she participated in a summer program at LSU entitled, Geoscience Alliance for the Enhancement of Minority Participation (GAEMP). After completing the program she decided, once again, to switch careers. She graduated with honors from Dillard University and entered the geology program at LSU. Following graduation from LSU, Rhonika will begin a career as an Earth Scientist at Chevron, U.S.A. in the Seismic and Earth Modeling Research Group.