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**Determining Greenland Ice Sheet sensitivity to regional climate change: one-way coupling
of a 3-D thermo-mechanical ice sheet model with a mesoscale climate model**

By

Nicole-Jeanne Schlegel

A dissertation submitted in partial satisfaction of the
Requirements for the degree of
Doctor of Philosophy

in

Earth and Planetary Science

in the

GRADUATE DIVISION
of the
UNIVERSITY OF CALIFORNIA, BERKELEY

Committee in charge:
Professor Kurt Cuffey, Chair
Professor William Collins
Professor John Chiang

Spring 2011

**Determining Greenland Ice Sheet sensitivity to regional climate change: one-way coupling
of a 3-D thermo-mechanical ice sheet model with a mesoscale climate model**

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Nicole-Jeanne Schlegel

Abstract

Determining Greenland Ice Sheet sensitivity to regional climate change: one-way coupling of a
3-D thermo-mechanical ice sheet model with a mesoscale climate model

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Nicole-Jeanne Schlegel

Doctor of Philosophy in Earth and Planetary Science

University of California, Berkeley

Professor Kurt Cuffey, Chair

The Greenland Ice Sheet, which extends south of the Arctic Circle, is vulnerable to melt in a warming climate. Complete melt of the ice sheet would raise global sea level by about 7 meters. Prediction of how the ice sheet will react to climate change requires inputs with a high degree of spatial resolution and improved simulation of the ice-dynamical responses to evolving surface mass balance. No Greenland Ice Sheet model has yet met these requirements.

A three-dimensional thermo-mechanical ice sheet model of Greenland was enhanced to address these challenges. First, it was modified to accept high-resolution surface mass balance forcings. Second, a parameterization for basal drainage (of the sort responsible for sustaining the Northeast Greenland Ice Stream) was incorporated into the model. The enhanced model was used to investigate the century to millennial-scale evolution of the Greenland Ice Sheet in response to persistent climate trends. During initial experiments, the mechanism of flow in the outlet glaciers was assumed to be independent of climate change, and the outlet glaciers' dominant behavior was to counteract changes in surface mass balance. Around much of the ice sheet, warming resulted in calving front retreat and reduction of total ice sheet discharge.

Observations show, however, that the character of outlet glacier flow changes with the climate. The ice sheet model was further developed to simulate observed dynamical responses of Greenland's outlet glaciers. A phenomenological description of the relation between outlet glacier discharge and surface mass balance was calibrated against recent observations. This model was used to investigate the ice sheet's response to a hypothesized 21st century warming trend. Enhanced discharge accounted for a 60% increase in Greenland mass loss, resulting in a net sea level increment of 7.3 cm by year 2100. By this time, the average surface mass balance had become negative, and widespread marginal thinning had caused 30% of historically active calving fronts to retreat. Mass losses persisted throughout the century due to flow of dynamically responsive outlets capable of sustaining high calving rates. Thinning in these areas propagated upstream into higher elevation catchments. Large drainage basins with low-lying outlets, especially those along Greenland's west coast and those fed by the Northeast Greenland Ice Stream, were most susceptible to dynamic mass loss in the 21st century.

Professor Kurt Cuffey
Dissertation Committee Chair

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Preface

Of Earth's great ice masses, Greenland Ice Sheet is the most vulnerable to melt in a warming climate, and a significant sea level rise (about 7 meters) would accompany its retreat. To improve prediction of the Greenland sea level contribution, a detailed understanding of the ice sheet's sensitivity to climate variability must be established. This investigation focused on one-way coupling between a high-resolution atmospheric model and an ice sheet model in order to characterize Greenland Ice Sheet's dynamic response to its regional climate. A set of numerical modeling studies have been developed to examine the century to millennial-scale evolution of the ice sheet in response to persistent climatic trends.

The first part of the study incorporated high-resolution surface mass balance mappings derived from a polar-specific version of a regional scale climate model, the NCAR/Penn State Mesoscale Model (MM5) (*Box et al., 2004; Box et al., 2006*). These mappings served as forcing for the University of British Columbia three-dimensional thermo-mechanical Greenland Ice Sheet model (UBCGISM). Experiments examined the century to millennial-scale evolution of the Greenland Ice Sheet in response to persistent climate trends.

The second part of the study involved calibration of the UBCGISM's simulated discharge. Outlet glacier calving discharge was enhanced with respect to local surface mass balance change and was calibrated to be consistent with observed changes in the ice sheet's total mass balance (*Rignot et al., 2008*). We used the enhanced model to examine Greenland's dynamic sensitivity to hypothesized future climatic trends.

The goal of this study was to simulate the processes currently driving rapid changes in Greenland Ice Sheet's outlet glaciers, specifically those presently being captured by advancing technology (such as passive microwave sensors, satellite radar, gravity satellites, GPS, and aircraft laser altimetry). We aimed to calibrate an improved model forced with high resolution surface mass balance input and, ultimately, to predict the ice sheet's dynamic response to 21st century warming.

Introduction

In the last few years, satellite and aircraft measurements have shown with new detail that warming throughout the last decade was characterized by both increased melt and accelerated flow in Greenland's southeastern and southwestern glaciers (*Chen et al., 2006; Luthcke et al., 2006; Ramillien et al., 2006; Rignot and Kanagaratnam, 2006; Velicogna and Wahr, 2006; Rignot et al., 2008; Velicogna, 2009*). In fact, it is possible that, during this time, the rate of Greenland mass loss has doubled. If this trend continues, and more northerly glaciers begin to accelerate too, the rate of sea level rise from the ice sheet's retreat could become strongly positive (*Rignot and Kanagaratnam, 2006*). Rapid melt in the southern ablation margins of Greenland implies the ice sheet is vulnerable to persistent warming trends on long timescales. Results presented by *Cuffey and Marshall [2000]* supported this idea. They used a thermo-mechanical ice sheet model to show that Greenland melt was primarily responsible for the sea level rise during the last interglacial period, 125,000 years ago. If Greenland was capable of being a key contributor of sea level rise during warmer periods of the past, and temperature rise continues in the next several centuries, it is reasonable to pinpoint it as a major source of sea level rise in the near future.

Yet, the ice sheet's exact response to warming can still be considered unpredictable. Model predictions of Greenland's net melt response to future climate fluctuations have significant uncertainties, largely due to the difficulty of accurately resolving snowfall and surface climate. To improve such predictions, *Huybrechts et al. [2002]* examined the response of a three-dimensional thermo-mechanical Greenland Ice Sheet model (GISM) coupled with an atmosphere-ocean general circulation model (AOGCM) to a future climate warming scenario (IPCC SRES B2, mid-range greenhouse gas forcing). They predicted a 4 cm sea level rise by the end of the 21st century, due to a local warming of 4.5 degrees C. In contrast, *Fichefet et al. [2003]*, using the same model coupling, suggested that Greenland warming in the next century could increase freshwater melt to the ocean, therefore slowing down the thermohaline circulation by the end of the 21st century. This feedback forced lower temperatures over eastern Greenland and partly counteracted the effects of warming there. *Ridley et al. [2005]* improved upon these experiments by incorporating feedback of orographic changes. Their results exposed a relationship between Greenland's topographical retreat, sea ice extent, and surface temperature patterns. Model sensitivity to a 4 time preindustrial CO₂ forcing suggested that Greenland would contribute about 5 cm of sea level rise during the 21st century. Almost complete retreat of the ice sheet occurred 3,000 years into the experiment.

Though coupling experiments such as these provide useful insight into future response of Polar regions to a warming climate, they are not without their weaknesses. One disadvantage is rooted in the AOGCM's, which have sparse spatial resolution (eg. ~ 1 - 3 degrees). Greenland Ice Sheet models are run at 5 km - 20 km resolution, thus, interpolation is required to translate climate model output into a higher-resolution description of Greenland's climate. In a one-way experiment, *Huybrechts et al. [2004]* addressed this issue by dynamically downscaling decadal-scale time slices over Greenland and Antarctica into a higher-resolution product (50-100 km).

They compared historical and mid-to-late 21st century time slices and defined a pattern-based statistical downscaling technique for temperature and precipitation as a function of latitude and altitude. They predicted a Greenland sea-level contribution of 2 to 7 cm by the year 2100. Improvements in input resolution continue to enhance GISM coupling experiments (eg. *Gregory and Huybrechts, 2006; Stone et al., 2010*), but no study has yet to use a surface mass balance forcing that is defined at a resolution comparable to that of the ice sheet model itself.

Greenland Ice Sheet model coupling experiments face several additional challenges besides resolution mismatch. First, most ice sheet models require input of Positive Degree Days (PDD's), so climate model output must be parameterized into positive degree days to be used as ice sheet model forcing. This translation introduces uncertainty, and it may lack sufficient analyses of surface processes and synoptic precipitation (*Bougamont et al., 2008; Gardner and Sharp, 2009*). In response to this weakness, *Vizcaino et al. [2010]* created a two-way coupling between a relatively low-resolution (80 km) GISM and an AOGCM (ECHAM5/MPI-OM); their configuration no longer used positive degree days to describe surface conditions, instead, it directly calculated surface mass balance with a surface energy balance scheme. Their experiment predicted a sea level rise of 5 cm by year 2100 and 3.3 meters by year 2700. This improvement in two-way coupling simulations, though still plagued with resolution mismatch and generally low-resolution forcing input, took an impressive step toward an idyllic energy-balance-based coupling.

The incorporation of mesoscale atmospheric models may be the next logical step in improving prediction of Greenland's surface conditions. These regional-scale models can provide surface mass balance input that is more accurate and better resolved in space than AOGCM's; mesoscale models better represent physical processes (how snowfall and melt relate to the atmosphere) as well as spatial distributions of accumulation and melt. In the past several years, meteorologists have made notable progress in running these models over Greenland. For instance, *Box et al. [2006]* calibrated output from a polar-specific version of the NCAR/Penn State Mesoscale Model (MM5), the Polar MM5 (PMM5), with weather station surface observations to develop a 24 km spatially resolved surface mass balance calculation over the entire Greenland Ice Sheet from 1988-2005. Model validation suggested that the results were quite dependable for use in the formulation of an empirically-based surface mass balance determination for the 1990's (*Cassano et al., 2001; Box et al., 2004; Box et al., 2006*). Most recently, *Ettema et al. [2009]* utilized the Regional Atmospheric Climate Model (RACMO2/GR) to produce an even higher-resolution (11 km) surface mass balance product for 1958-2007. This new product had high skill with no post-run calibration applied. Currently, no two-way coupled Greenland Ice Sheet model experiment has incorporated a regional model, mostly due to limitations in computer processing speed and capacity (*Pollard, 2010*).

Surface mass balance products with improved resolution provide valuable detail, especially along the ablation zones of key outlet glaciers. For Greenland, this detail is specifically important along the southeast coast, where large accumulation rates at high elevations feed the steep mountain glaciers responsible almost 40% of the ice sheet's total discharge each year (*Rignot et al., 2008*). *Burgess et al. [2010]* introduced a high-resolution expanded and recalibrated version of the *Box et al. [2006]* accumulation product, and *Rignot et al. [2008]* introduced corresponding surface mass balance results. Their newly reconstructed output spanned the years 1958-2007 and was re-sampled onto a 1.25 km resolution grid. One disadvantage of this output is that the new calibration introduced a positive-degree-day-derived melt calculation; however, it represents the highest-resolution product of its kind and is well

correlated with observed accumulation and temperatures (*Rignot et al., 2008; Burgess et al., 2010*).

Recent Greenland coupling experiments consist of a final weakness: most take into consideration only direct dynamic response to surface mass balance changes. That is, they do not consider what *Huybrechts et al. [2004]* referred to as “unexpected ice-dynamic responses”: any response that is beyond the dynamic acceleration/deceleration resulting from perturbations in surface slope and ice thickness. Analysis of measurements taken in the last decade suggested that Greenland mass loss is split equally between surface processes and dynamic responses (*Rignot et al., 2008, van den Broeke et al., 2009, Velicogna, 2009*). These less-understood responses are likely induced by fast-flowing outlet glaciers, melt water drainage, or abrupt calving discharge, to name a few. *Greve and Otsu [2007]* investigated the sensitivity of the GISM SICOPOLIS (Simulation Code for POLythermal Ice Sheets) with regards to a subset of these processes. They implemented a Northeast Greenland Ice Stream (NEGIS) with basal sliding enhancement and additionally, increased basal sliding as a function of surface melt. SICOPOLIS’s sensitivity to future scenarios forced by a positive-degree-day-based surface mass balance scheme suggested that neither of these processes was responsible for additional Greenland instability. However, increasing melt-induced basal sliding by an order of magnitude did result in an ice sheet that was significantly more susceptible to a warming climate. Results suggested that under a 4xCO₂ stabilization forcing Greenland would contribute about 15 cm to sea level-rise by the year 2100 (*Greve and Otsu, 2007*). Though physical understanding of many dynamic processes are lacking, improved observations during the last decade have provided evidence that these and, more likely, additional dynamic responses are responsible for a significant decrease in Greenland’s total mass balance (*Rignot et al., 2008, van den Broeke et al., 2009, Velicogna, 2009*). Higher-order models have been developed for larger Antarctic ice streams and were shown to improve upon simulation of areas of fast-flowing ice (eg. *Pattyn, 2003*). Ideally, future models will incorporate the complete physics involved in Greenland’s response to climate change (*Pollard, 2010*).

The aim of this study was to improve understanding of the Greenland Ice Sheet's sensitivity to climate change and associated sea level contributions. Modern computational resources offer new, rich opportunities for improved understanding of glacial processes and their response to present, past, and future climates. The unique approach of this investigation was to run improved one-way coupling experiments by taking advantage of these resources. To do so, with use a three-dimensional thermo-mechanical ice sheet model, we: (1) investigated the advantages of using high-resolution direct surface mass balance forcing (as opposed to positive degree day forcing); (2) enhanced the model’s outlet glacier discharge with respect to changes in local surface mass balance; and (3) tuned the model discharge to be consistent with observations. Ultimately, we assessed the enhanced model’s response to 21st century climate warming and offered revised estimates for future ice sheet dynamic mass loss.

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Symbols

Variables

Q	Ice discharge (Gt/year)
\dot{C}	Total accumulation (Gt/year)
\dot{B}	Total surface mass balance (Gt/year)
$\Delta\dot{B}$	Anomaly in total surface mass balance from the 1971-1988 mean (Gt/year) $\Delta\dot{B}_{8805}$: from the 1988-2005 mean
$\Delta\dot{b}$	Anomaly in local surface mass balance from the 1971-1988 mean (m of water equivalent/year)
\dot{d}	Local calving rate (m of ice /year) \dot{d}_N : north, \dot{d}_S : south, \dot{d}_E : east, \dot{d}_W : west \dot{d}_{enh} : calving enhancement
T_d	Local positive degree days (degrees C/year)
ΔT_{2NA}	Anomaly in 2 meter North Atlantic summer surface temperature from the 1971-1988 mean (degrees C)
t	Time (year)
Φ	Peizometric potential (Pa)
z	Elevation (m) z_{ice} : ice surface, z_{bed} : bedrock
H	Thickness (m), H_w : basal water layer H_{ice} : ice, H_{ocean} : ocean water
u	Velocity (m/year), u_w : basal water layer, u_{ice} : ice, u_b : basal ice, u_d : calving velocity
q_w	Advection of basal water layer down the peizometric gradient (m ² /year)

\dot{m}	Local ablation \dot{m}_{snow} : snowmelt, \dot{m}_{ice} : ice-melt (m of water equivalent/year)
\dot{c}	Local accumulation (m of water equivalent/year)
\dot{b}	Local surface mass balance (m of water equivalent/year)
y	Horizontal width of grid cell (m) y_N : north, y_S : south, y_E : east, y_W : west
A	Area of grid cell (m ²)

Constants

g	Gravity (m/s ²)
ρ	Density (kg/m ³) ρ_{ice} : ice, ρ_{water} : water

Parameters

C_w	Scaling factor, directly relating $\nabla \Phi$ to u_w (1/Pa/year)
μ	Tunable slope relating $\Delta\dot{b}$ to \dot{d}_{enh} (1)
C_μ	Scaling factor for μ , representing its regional significance (1)
β	Tunable intercept relating $\Delta\dot{b}$ to \dot{d}_{enh} (m of ice/year)
n	Number of closest (in elevation) grid points within a particular region chosen to calculate transect values
a	Degree Day factor a_{snow} : factor for snow, a_{ice} : for ice (m of water equivalent/day/degree C)
C_d	Scaling factor for calving flux (1/year)

Chapter 1

Future Projections

Introduction

In the last few years, satellite and aircraft measurements have shown with new detail that warming throughout the last decade was characterized by both increased melt and accelerated flow in Greenland's southeastern and southwestern glaciers (*Chen et al., 2006; Luthcke et al., 2006; Ramillien et al., 2006; Rignot and Kanagaratnam, 2006; Velicogna and Wahr, 2006; Rignot et al., 2008; Velicogna, 2009*). In fact, it is possible that, during this time, the rate of Greenland Ice Sheet's mass loss has doubled. If this trend continues, and more northerly glaciers begin to accelerate too, the rate of sea level rise contribution from Greenland could become strongly positive (*Rignot and Kanagaratnam, 2006*). Rapid melt in the southern ablation margins implies the ice sheet is vulnerable to persistent warming trends on long timescales. Results presented by *Cuffey and Marshall [2000]* supported this idea. They used a thermo-mechanical ice sheet model to show that Greenland melt was primarily responsible for the sea level rise during the last interglacial period, 125,000 years ago.

If Greenland was capable of being a key contributor of sea level rise during warmer periods of the past, and temperature rise continues in the next several centuries, it is reasonable to pinpoint the Greenland Ice Sheet as a major source of sea level rise in the near future. Yet, the ice sheet's exact response to warming can still be considered unpredictable. Model predictions of Greenland's net melt response to future climate fluctuations have significant uncertainties; this is largely due to the difficulty of accurately resolving snowfall and surface climate as well as the community's incomplete understanding of the dynamic processes responsible for variability in discharge.

In an effort to improve upon these predictions, a number of studies have made significant progress in establishing a solid two-way coupling between a three-dimensional thermo-mechanical Greenland Ice Sheet model (GISM) and an atmosphere-ocean general circulation model (AOGCM). All studies do not agree on an exact magnitude or origin of key climate feedbacks during the next several centuries, but most predict a sea level rise between 4 cm and 5 cm by the end of the 21st century (*Huybrechts et al., 2002; Fichefet et al., 2003; Ridley et al., 2005; Vizcaino et al., 2010*). *Ridley et al. [2005]* estimated a complete retreat of the ice sheet in response to 4 times preindustrial atmospheric CO₂ concentrations in as little as 3000 years.

Because two-way coupling is processor and time intensive, many studies resort to one-way coupling for shorter-timescale experiments. Since AOGCMs have sparse spatial resolution (eg. ~ 1 - 3 degrees) and GISMs are run at a 5 km - 20 km resolution, most two-way coupling experiments have to grapple with a resolution mismatch. The choice of a one-way coupling scheme is a convenient concession when attempting to improve upon the quality of model input. Recent studies have used variations of this approach in order to utilize higher-resolution climate products (*Huybrechts et al., 2004; Gregory and Huybrechts, 2006; Stone et al., 2010*).

The incorporation of mesoscale atmospheric models may be the next logical step in improving prediction of Greenland's surface conditions (*Stone et al., 2010*). These regional-scale climate models (RCM's) can provide surface mass balance input that is more accurate and better resolved in space than AOGCM's. In the past several years, meteorologists have made notable progress in running RCM's over Greenland to produce high-quality surface mass balance products (*Cassano et al., 2001; Box et al., 2004; Box et al., 2006; Rignot et al., 2008; Ettema et al., 2009; Burgess et al., 2010*). These products provide valuable detail, especially along the ablation zones of key outlet glaciers. For Greenland, this detail is specifically important along the southeast coast, where large accumulation rates at high elevations feed the steep mountain glaciers responsible almost 40% of the ice sheet's total discharge each year (*Rignot et al., 2008*). Currently, no coupled Greenland Ice Sheet model experiment has incorporated a surface mass balance product from a regional model.

Analysis of measurements taken in the last decade suggested that Greenland mass loss is split equally between surface processes and dynamic responses (*Rignot et al., 2008, van den Broeke et al., 2009, Velicogna, 2009*). The less understood dynamic responses are likely induced by fast-flowing outlet glaciers, melt water drainage, or abrupt calving discharge, to name a few. Though physical understanding of many dynamic processes are lacking, improved observations during the last decade have provided evidence that these and, more likely, additional dynamic responses are responsible for a significant decrease in Greenland's total mass balance (*Rignot et al., 2008, van den Broeke et al., 2009, Velicogna, 2009*). Recent studies have begun to investigate just how sensitive ice sheets are to these dynamics. For instance, ice sheet models have been used to investigate Greenland's sensitivity to enhanced basal velocities (*Greve and Otsu, 2007*), while higher-order models have been developed to simulate large, fast-flowing ice streams within a model of the Antarctic Ice Sheet (*Pattyn, 2003*). Ideally, future models will incorporate the complete physics involved in the ice sheet's response to climate change (*Pollard, 2010*).

The study took an original, phenomenological approach to improving the understanding of Greenland Ice Sheet's sensitivity to climate change and associated sea level contributions. With use of a dynamically-enhanced version of the University of British Columbia three-dimensional thermo-mechanical ice sheet model (UBCGISM), we simulated an observed linear relationship between the ice sheet's yearly discharge and total surface mass balance (*Rignot et al., 2008; Jason Box, personal communication*). The UBCGISM does not run at a resolution capable of capturing the details involved in the physics of fast flowing outlet glaciers, therefore, we further sensitized it to present-day climate variability by tuning its discharge empirically. This unique one-way coupling approach was accomplished by: (1) using RCM-based surface mass balance and accumulation maps as high-resolution input; (2) enhancing outlet glaciers to calve with respect to local surface mass balance changes; (3) increasing outlet glacier basal velocities in correspondence with the discharge enhancements in (2); and (4) calibrating the above processes to simulate an observed relationship between ice sheet discharge and total surface mass balance (*Rignot et al., 2008; Jason Box, personal communication*).

Assuming that our calibration was capable of successfully capturing the majority of dynamic responses observed by *Rignot et al. [2008]* and that the observed relationship between surface mass balance and discharge would hold in the near future, we used the enhanced UBCGISM to investigate Greenland's dynamic sensitivity to future climate warming during the next century. Our experiments used North Atlantic summer temperature output from five different AOGCM's forced with the SRES A2 climate scenario (*Nakicenovic et al., 2000*). We

calculated future surface mass balance forcings regionally, choosing summer temperature trends as proxy, and then allowed the model to respond dynamically to local perturbations in surface mass balance. The UBCGISM was run with and without enhanced outlet glacier response. Below, we assess the model sensitivity to enhanced outlet dynamics by comparing predicted rates of future ice sheet mass loss. Finally, we use these results to bound equivalent sea level rise contribution from the Greenland Ice Sheet in the next century.

Methods

The Model

Description

Ice dynamics calculations were performed with the University of British Columbia three-dimensional thermo-mechanical ice sheet model (UBCGISM), originally developed by Dr. Shawn Marshall (*Cuffey and Marshall, 2000*), and then enhanced, as described below. The UBCGISM is a finite-difference model that runs on a spherical grid. It has a meridional resolution of 0.25 degrees and a zonal resolution of 0.5 degrees, for a total grid of size of 140x108. For these simulations, it was run with a total of 20 vertical levels. Time steps were taken once a year.

Surface Mass Balance

As input for the UBCGISM, we chose RCM-derived surface mass balance and accumulation surface maps (balance years 1958-2007, at a resolution of 1.25 km), provided by Dr. Jason Box (*Rignot et al., 2008; Burgess et al., 2010*). We used the Box output to define transect relationships for twenty-nine different regions of the ice sheet (see APPENDIX B). The UBCGISM was forced with the surface mass balance and accumulation conditions described by these transects, thus eliminating the need to estimate surface mass balance from positive degree day (PDD) input. Typically, glacier models use positive degree day schemes which require the definition of constant degree day parameters for use in melt calculations. We inputted surface mass balance directly, avoiding the need for additional data translation or generalizations often made by traditional ice sheet models (as discussed in CHAPTER 2).

The Greenland Ice Sheet is thought to have been in a virtual steady state during the years 1971 to 1988 (*Rignot et al., 2008*); therefore, we chose the average surface mass balance and accumulation for this period to represent the surface conditions for a steady-state ice sheet. We achieved steady-state by forcing the UBCGISM with the 1971-1988 average surface mass balance and accumulation for 250,000 years. Flow parameters were tuned, placing attention upon achieving a realistic ice sheet profile and upon simulating accurate discharge from Greenland's seven most productive outlet glaciers (*Rignot et al., 2008*) (as discussed in CHAPTER 3). We chose the 1971-1988 steady-state ice sheet because, with respect to these characteristics, it was more realistic than an ice sheet that had been run through past glacial cycles. To compensate for the dynamic ice loss due to Holocene warming, we added a mass loss of 8.25 Gt per year, as estimated by the UBCGISM, to all results presented below.

Basal Drainage

The UBCGISM has been enhanced to simulate basal drainage (as discussed in detail in CHAPTER 2). Basal water was set equal to the melt at the glacier bed plus surface runoff. Modeled basal water traveled down the peizometric potential gradient. Drainage basins were calculated based on peizometric potential gradients, and the accumulation of basal water at any given point was set equal to the sum of the basal water up-gradient from that point. The thickness of the basal water layer was calculated by estimating the velocity of basal water with regards to the peizometric potential gradient.

Consequently, this basal drainage functionality allowed us to initiate a Northeast Greenland Ice Stream (NEGIS). To do so, we increased the NorthGRIP geothermal flux to an average value of 130 mW/m^2 (between the longitudes of 37W and 43W and the latitudes of 74N and 76N) (Dahl-Jensen *et al.*, 2003; Buchhardt and Dahl-Jensen, 2007). As suggested by Greve and Otsu [2007], we tripled the sliding enhancement factor in the area of the observed Northeast Greenland Ice Stream. North of 78 degrees north latitude, we multiplied the sliding enhancement factor by a value of five (instead of three) in order to better fit observations of outlet flux (Rignot and Kanagaratnam, 2006; Rignot *et al.*, 2008).

Outlet Glacier Enhancement

For the purposes of this study, the UBCGISM was enhanced to dynamically respond according to the following observed relationship (see APPENDIX C):

$$(1.1) \quad Q = -0.665 * \dot{B} + 742.1$$

where Q was the total discharge and \dot{B} was the total surface mass balance of the Greenland Ice Sheet, in units of Gt, for any given year (Rignot *et al.*, 2008; Jason Box, *Personal Communication*). Our goal was to simulate an ice sheet with discharge sensitivity equivalent to that expressed by equation (1.1). Development was achieved in two ways. We: (1) forced calving fronts to respond linearly to local anomalies in surface mass balance and (2) enhanced basal velocities within 60 km of the calving front to adjust consequently.

The years 1964, 1992, 1996, 2000, 2004, 2005, 2006, and 2007, were singled out since they were the years used to derive equation (1.1) (Rignot *et al.*, 2008). We forced surface mass balance and accumulation for each of these years onto the 1971-1988 steady-state ice sheet and allowed it to respond for a single year. We tuned the results for these eight years such that the modeled relationship between total surface mass balance and discharge was equivalent to equation (1.1) (as discussed in detail in CHAPTER 3).

Future Warming Scenarios

We chose five different AOGCM's which had been run under the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) SRES A2 scenario to estimate 21st century projections of Northern Atlantic Ocean warming (Nakicenovic *et al.*, 2000; Randall *et al.*, 2007). All selected models were next-generation versions of those investigated previously by the Arctic Climate Impact Assessment (Kattsov *et al.*, 2005). Northern Atlantic summertime average two-meter 21st century temperature trends were extracted from the five

models and used as forcing for 90 years. Table 1.1 lists the AOGCM's used in this study, the temperature trends extracted from each, and the subsequent temperature rise predicted by 2100.

Before applying 90 years of future temperature trends, we forced the tuned steady-state ice sheet with twenty years of warming (representing the 1990's and 2000's), according to the following equation:

$$(1.2) \Delta T_{2NA} = 0.0533 * t - 0.196$$

where t was year 1 through 20 and ΔT_{2NA} was the temperature anomaly. As a result, the historical temperature perturbation reached a value of 0.87 degrees C by the year 2010. We derived the relationship described in equation (1.2) with reconstructed North Atlantic summer temperatures, provided by Jason Box (*Box et al., 2009*).

For a particular region and altitude, we estimated 1988-2005 surface mass balance and accumulation trends as linear functions of temperature anomaly. Removing the year 1998 greatly reduced root-mean-square fit error in many regions, therefore, it was excluded. Temperature anomalies were derived from reconstructed high-resolution historical temperature maps (*Box et al., 2009*) of the North Atlantic. Trends were used to adjust future surface mass balance and accumulation in response to temperature change.

We chose the period 1988-2005 because prior to the 1990's, Greenland's surface mass balance was significantly affected by natural climate modes such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO); however, in the last couple decades, the ice sheet's surface mass balance has become increasingly correlated with Northern Hemisphere temperature trends (*Hanna et al., 2008*). These observations provided impetus for development of the above methods and consequently, for the acceptance of a key assumption. Specifically, our future projections assumed that Greenland's 21st century climate would not be significantly affected by natural variability, but instead would continue to be dominated by trends in temperature.

Results

Steady-State Ice Sheet

In this study, we calculated a steady-state initial condition by forcing the UBCGISM with 1971-1988 average surface mass balance and accumulation for 250,000 years. The resulting ice sheet topography had an area 16.5% larger than and a volume 12.5% larger than observed. The mean misfit over the area of the ice sheet was approximately 100 meters. The simulated ice sheet topography was a good fit above 1500 meters. Areas in lower elevations contributed to the majority of misfit, especially between 500 and 1000 meters, where the ice sheet was on average thicker than observed (see CHAPTER 3).

Future Climate Scenarios

In Figure 1.1, average yearly mass balance for the historical periods 1990-2000, 2000-2010, 2000-2008, and 2003-2008 are graphed. Since we estimated historic temperature change with a linear trend (equation 1.2), we did not expect to match observations on a year to year basis; however, we did attempt to simulate, on average, mass balance changes that occurred

during the period. For comparison, Figure 1.1 includes observed mass balances for periods 2000-2008 and 2003-2008, derived from Gravity Recovery and Climate Experiment (GRACE) satellites (*van den Broeke, 2009*). Our historical simulations overestimated mass loss earlier in the decade, but underestimated it in the latter part.

Figure 1.1 also compares the average yearly 21st century total mass balance for the calving-enhanced and non-enhanced UBCGISM runs in response to five different AOGCM forcings. During all runs, the 21st century average mass loss was greater than the average mass loss prior to 2010. For all cases the enhanced model lost at least 40% more ice than the non-enhanced model, suggesting that calving enhancement made a significant difference in our results.

Table 1.2 and Figure 1.2 further support this conclusion, as clear distinctions exist between the enhanced and non-enhanced run results. In Table 1.2 the average 21st century mass loss is broken up into decades. Results for both enhanced (Table 1.2A) and non-enhanced (Table 1.2B) are included. In Figure 1.2, we plot a yearly time series of ice sheet volume, including the enhanced (solid) and the non-enhanced (dashed) experiments for each future forcing.

In Table 1.2 the decades where melt exceeded accumulation (negative surface mass balance) are highlighted in bold. During the four moderate warming scenarios, calving enhancement forced the surface mass balance to become negative at least a decade sooner. Total surface mass balance became negative after a temperature rise of 2.3 degrees C for the calving-enhanced case and 2.4 degrees C for the non-enhanced case. These values are slightly lower than those reported by *Gregory and Huybrechts* [2006] (2.7 degrees) and *Fettweis* [2008] (2.5 degrees). A 10-year-running-mean of surface mass balance (grey) for the INGV-SXG forcing is plotted in Figure 1.3. (In Figures 1.3 and 1.4, we chose to present results from the INGV-SXG forcing runs because INGV-SXG trends were closest to the five-model average.) During the enhanced model runs, the surface mass balance decreased faster and became negative sooner than during the non-enhanced runs. These results suggest that the dynamic responses simulated by our enhanced model strengthened the positive feedback between increased melt and topographical retreat.

Figure 1.4 presents spatial results from the INGV-SXG forcing. Qualitatively, all five models responded similarly. The change in surface topography (in meters) that resulted from the calving-enhanced 21st century forcing is shown in Figure 1.4A. By 2100, the interior of the ice sheet had thickened slightly while the margins had thinned, especially along the western coast. Though mostly thinning occurred, some areas along the southeast Greenland coast thickened. The area occupied by the Northeast Greenland Ice Stream also thinned into the interior of the ice sheet, and concurrently, the ice front advanced.

Figure 1.4B compares 21st century topographical changes which occurred during the calving-enhanced runs and the non-enhanced runs. The largest differences occurred directly upstream from Greenland's major outlet glaciers and along the steep margins of the southeast coast. These results are not surprising, since calving enhancements should more strongly affect areas where ice discharge is already a significant process. As demonstrated by Figure 1.3, calving behavior (red) played an important role in determining yearly mass balance changes (black) during the enhanced model runs (solid), even as discharge decreased with consistent loss of calving fronts (blue). By the year 2100, the average number of calving cells decreased by 30% in the enhanced runs and 20% in the non-enhanced runs. It is also evident in Figure 1.4B that thinning was able to propagate upstream from the major outlets, especially in the west, where large drainage basins feed into low-lying (below sea level) outlets.

In Table 1.3, we present simulated flux from seven major outlet glaciers. We compare steady state fluxes with fluxes predicted for the end of the 21st century by the UBCGISM. In this case, we chose to present the ECHAM5 results as an example of extreme warming. All other future forcing results were similar, though flux changes were not as dramatic. At Kangerdlugssuaq, the most productive outlet during steady state, a flux decrease occurred by the year 2100. This decrease was amplified by the enhanced model. In all other cases, calving enhancement was responsible for flux increases. Enhancement drove modest accelerations at the two outlets fed by the Northeast Greenland Ice Stream, while Helheim Glacier experienced the most dramatic acceleration. Smaller flux increases occurred in the other three outlet glaciers investigated.

A closer look at Table 1.2 reveals that the calving-enhanced and the non-enhanced ice sheets did not lose mass in a parallel fashion. At the beginning of the century, the enhanced ice sheets were losing an average of about 100 Gt more mass than were the non-enhanced ice sheets. This difference became smaller with time, reducing to about 50 Gt by the end of the century. In Figure 1.3, differences in calving losses (red) are similarly unparallel. Table 1.2 also suggests that in the enhanced case, there was a drop in mass loss during the 2020's for four out of the five forcing conditions. In Figure 1.3, it is evident that this temporary decrease during the enhanced runs (solid) did not occur during the non-enhanced runs (dashed), but it in fact coincided with deceleration in calving loss (red) that lasted from about 2010-2030.

21st century sea level rise predictions for our ten forcing experiments are included in the final column of Table 1.2. During the non-enhanced experiments, sea level rise ranged from 3.7 to 6.1 cm for an average of 4.5 cm. This value is comparable to past estimates (*Huybrechts et al., 2002; Fichefet et al., 2003; Ridley et al., 2005; Fettweis, 2008; Vizcaino et al., 2010*). During calving-enhanced experiments, sea level rise ranged from 6.4 to 8.8 cm for an average of 7.3 cm, representing a 60% increase in mass loss as a result of dynamic enhancement. These results suggest that the dynamic responses simulated by the enhanced model played a significant role in accelerating mass loss, though changes in surface mass balance dominated slightly.

Discussion

Many full scale three-dimensional thermo-dynamical ice sheet models, including the model used here, lack the necessary physics to describe the dynamic response of Greenland's outlet glaciers to climate warming. Our study took a phenomenological approach towards enhancing the UBCGISM to encompass these responses (*Rignot et al., 2008*). We described Greenland's surface conditions during a historical period of near-steady-state (1971-1988) with use of validated high-resolution surface mass balance (in lieu of positive degree days) as model input. We then tuned the UBCGISM so that it would discharge at a rate comparable to that described by equation (1.1). Finally, using future North Atlantic temperature trends from five different AOGCM's as a proxy, we developed a simple downscaling technique for perturbing Greenland's surface conditions in the future. This study utilizes the above resources to investigate whether the incorporation of dynamic outlet glacier response would significantly change Greenland's sensitivity to 21st century warming.

While we made our best attempt at tuning the UBCGISM to respond as would the actual ice sheet, it is important to point out the differences between the two. First of all, though the UBCGISM is run at a relatively high resolution, this resolution is not sufficient enough to properly model narrow outlet glacier speed and responsiveness. In addition, our time step is only

a year; hence, short-term or seasonal accelerations in ice velocity are not explicitly modeled. These shortcomings, as well as other bulk assumptions about the ice sheet made by the UBCGISM, help to explain the topographical and dynamical differences between the observed and modeled ice sheet.

In acknowledgement of these model limitations, we were able to develop an approach based in current large-scale understanding of outlet glacier physics. Our enhancements allowed the UBCGISM to *simulate* recently observed Greenland Ice Sheet dynamics, including calving responses and corresponding accelerations upstream. We subsequently extrapolated these dynamic responses into the future. To do so, it was absolutely necessary to make a number of assumptions that one should take into account when considering our results. First, we assumed that equation (1.1), derived from observations, adequately described reality. We also assumed that the dynamic behavior described by equation (1.1) would affect active outlet glaciers in a warming climate. Similarly, our downscaling routine assumed that the relationship between Greenland surface parameters and temperature anomaly would remain constant in the future. Finally, we assumed that the temperature of the North Atlantic would continue to be a valid proxy for climate change over Greenland.

For purposes of validation, we compared observed mass balance with simulated results from the same time period. In Figure 1.1, the average mass balance for the periods 2000-2008 and 2003-2008, derived from Gravity Recovery and Climate Experiment (GRACE) satellites (*van den Broeke, 2009*), are presented alongside the simulated mass balance for the same years. Since 1990-2010 was simulated using a simple temperature trend (equation 1.2), there is no reason why simulated mass balance during a specific year should be comparable to the observed value, especially since the UBCGISM itself displays inherent yearly discharge variability. Therefore, we attempted to compare average mass balance over extended time periods. Results suggest that our simulation overestimated mass balance early in the 2000's, but then underestimated it in the latter years. On average, however, the enhanced simulation reasonably represented the 2000's (Figure 1.1) and marked substantial improvement over the non-enhanced predictions (Figure 1.3).

The Greenland Ice Sheet is a dynamically changing multi-feedback system. A complex model such as the three-dimensional thermo-mechanical ice sheet model captures the physics involved in a multitude of ice sheet responses to climate. More importantly, it is capable of simulating how these responses may interact with and affect each other in the future. Certain feedback relationships are foreseeable in a warming climate. For instance, inherent in the UBCGISM are two key positive feedbacks that are inevitably initiated by increased ablation. As the ice thins, surface elevation is lowered. As a result, melt increases even more, steepening the ice gradient, increasing the driving stress, ultimately speeding up outlet velocities, and promoting more thinning. Simultaneously, increased melt lubricates the ice sheet bed, resulting in basal velocity acceleration and additional thinning. These well understood feedbacks were responsible for accelerating retreat in both the enhanced and non-enhanced future projection runs.

Other feedbacks, such as the ones involved with accelerated ice discharge in Greenland's major outlets, are less understood. By incorporating calving enhancement into the UBCGISM, we attempted to investigate Greenland Ice Sheet's sensitivity to these types of feedbacks. In fact, it was unclear whether calving enhancement would have promoted or inhibited ice sheet retreat in response to climate warming. That is, it was difficult to predict how temperature rise would alter equation (1.1), which is derived from historical observations of Greenland's outlet glaciers. To one extreme, the calving enhancements could have rendered Greenland more

vulnerable to a warming climate by increasing its discharge efficiency. On the other hand, if calving rates were too aggressive, calving fronts could quickly be lost, locally halting calving and dramatically reducing discharge. While we applied enhancement directly to calving fronts, the dynamic response of the interior ice ultimately determined Greenland's fate. In other words, the ice sheet's vulnerability was dependent on its ability to transfer ice from the interior of the ice sheet fast enough to supply demand from the outlet glaciers downstream.

During the 21st century, one might expect demand to rise with increases in low elevation melt, but if outlets retreat above sea level, demand would diminish entirely. How these feedbacks might respond to Greenland's recent dynamic behavior, as described in equation (1.1), is unclear. By forcing the enhanced UBCGISM with 21st century warming, we hoped to gain insight into the ice sheet's sensitivity to recently-observed and future outlet accelerations. Are Greenland's drainage basins efficient enough to supply ice to its outlet glaciers at a sufficient rate? Our results suggest that, to a certain degree, they may be. Over the course of a century, calving enhancement clearly forced thinning to propagate upstream (Figure 1.4B) while, as margins thinned (Figure 1.4A), most major outlets maintained or even increased in flux (Table 1.3). However, there is evidence that this process played a much larger part at the beginning of the 21st century, as the number of calving cells and calving rates continuously declined throughout the experiment (Figure 1.3). In fact, by the year 2070, the rate of change in total mass balance for the enhanced runs became comparatively small (Table 1.2A), something which did not happen in the non-enhanced runs (Table 1.2B). It appears that, in latter parts of the 21st century, negative surface mass balance, instead of dynamic discharge, began to dominate ice sheet mass loss as calving fronts in steeper areas were lost. In the southeast, results were inconsistent, indicating that response was driven by local conditions. In the steep margins of this region, calving enhancement was capable of dramatically decelerating (e.g. Kangerdlugssuaq) or accelerating (e.g. Helheim) major outlet glaciers. At the same time, ice fluxes in low-lying outlets such as those in the west and those draining the Northeast Greenland Ice Stream were maintained, and in some cases they accelerated. In these locations, thinning had already propagated to higher elevations upstream; therefore it is possible to pinpoint large, low-lying basins as the most capable of draining significant amounts of ice from higher elevations in a warming climate.

Finally, it is important to note that for this study, the UBCGISM was trained to behave in a manner consistent with observations, but only during simulated historical periods. Tuning was aimed at simulating Greenland's short-term responses to changes in surface mass balance. Once tuned, however, the model was allowed to freely evolve in response to 21st century forcing. As model dynamics adjusted throughout the 21st century, ice along the margins thinned, and the number of calving fronts gradually declined. It was evident that, as a consequence of these changes, equation (1.1) was no longer applicable during the latter half of the 21st century. Our results suggest that Greenland Ice Sheet, within decades, is capable of somewhat stabilizing the responses predicted by equation (1.1). Therefore, use of equation (1.1) should most likely be restricted to predictions made for the next few decades, under the assumption that calving fronts remain static.

Conclusion

This study took a phenomenological approach toward improving the understanding of Greenland Ice Sheet's sensitivity to climate change. With use of a dynamically-enhanced version

of a three-dimensional thermo-mechanical ice sheet model, we simulated an observed linear relationship between the ice sheet's yearly discharge and total surface mass balance, expressed in equation (1.1) (*Rignot et al., 2008; Jason Box, personal communication*). Enhancement was applied directly to calving fronts, and velocities directly upstream were forced to respond accordingly.

We investigated Greenland Ice Sheet's dynamic sensitivity to calving enhancement by forcing our model with future surface mass balance and accumulation derived from projected 21st century North Atlantic temperature trends. Overall, the calving enhancement did not result in dramatic instabilities, but it did force a 60% increase in Greenland ice loss throughout the next century. By the year 2100, the average amount of ice lost during the calving-enhanced runs was equivalent to 7.3 cm of sea level rise, while the loss during the non-enhanced runs was equivalent to 4.5 cm of sea level rise.

During 21st century, calving continuously decreased due to loss of calving fronts. In the calving enhanced runs, even more ice fronts were lost. Still, we found that for at least seventy years, increased ice flux from a number of major outlet glaciers was able to compensate for the loss. Throughout that time, mass loss persisted due to flow of dynamically responsive outlets capable of sustaining high calving rates. Thinning in these areas propagated upstream into higher elevation catchments. Large drainage basins with low-lying outlets, especially those along Greenland's west coast and those fed by the Northeast Greenland Ice Stream, were most susceptible to long periods of warming.

Acknowledgements

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Figures

Table 1.1:

Five representative AOGCM's from the IPCC AR4 (*Randall et al., 2007*); the North Atlantic average two-meter summer temperature trend used as forcing for 21st century projections; and the North Atlantic temperature anomaly reached by 2100. AOGCM output was acquired from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset available at <https://esgcat.llnl.gov:8443/index.jsp>.

Table 1.2:

Results of 21st century (SRES A2) trends forced upon the 1971-1988 steady state ice sheet. Average Total Mass Balance (Gt/yr) for each decade is presented as well as Greenland's estimated sea level rise contribution by the year 2100. Decades where melt exceeds accumulation (negative surface mass balance) are in bold. (A) Results from dynamic calving-enhanced version of UBCGISM. (B) Results from non-enhanced version of UBCGISM.

Table 1.3:

Simulated yearly upstream ice flux of seven of Greenland's major outlet glaciers. Steady state fluxes and fluxes reached at year 2100 (ECHAM5 forcing run) are included. Differences between steady state and the enhanced/non-enhanced cases are also presented.

Figure 1.1

One hundred year average mass loss (Gt/yr) for five different AOGCM's in response to 21st century (SRES A2) forcing. Also, average mass loss for historical time periods in response to imposed linear warming trend (equation 1.2) and observed estimates, derived from Gravity Recovery and Climate Experiment (GRACE) satellites, for comparison (*van den Broeke, 2009*).

Figure 1.2:

Volume of Greenland Ice Sheet during 21st century (SRES A2) forcing runs. Forcing was derived from five different AOGCM's. Calving-enhanced UBCGISM (solid) and non-enhanced UBCGISM (dashed) runs are included.

Figure 1.3:

The ten year running mean of total surface mass balance (grey), total mass balance (black), total mass of calving loss (red), and number of calving cells (blue). The first three variables are given in Gt, the last in number of cells. Calving-enhanced UBCGISM (solid) and non-enhanced UBCGISM (dashed) results presented are from a 21st century (SRES A2) forcing trend from AOGCM INGV-SXG.

Figure 1.4

(A) Difference in ice topography (m) between year 2100 and the steady-state starting condition for calving enhanced UBCGISM experiment. (B) Difference between (A) and the equivalent for the non-calving enhanced UBCGISM experiment. Results are from a 21st century (SRES A2) temperature trend (INGV-SXG forcing run).

TABLE 1.1:

Model ID	Sponsor	Country	Temperature trend (degrees C / yr)	Temperature change by 2100 (degrees C)
CCSM3	National Center for Atmospheric Research	USA	+0.0175	+2.45
CGCM3.1 (T47)	Canadian Centre for Climate Modelling and Analysis	Canada	+0.0134	+2.08
ECHAM5-MPI-OM	Max Planck Institute for Meteorology	Germany	+0.0348	+4.00
INGV-SXG (with ECHAM4.6)	Instituto Nazionale di Geofisica e Vulcanologia	Italy	+0.0199	+2.66
UKMO-HadCM3 *	Hadley Centre for Climate Prediction and Research/Met Office	UK	+0.0183	+2.52

* © Crown copyright 2005, Data provided by the Met Office Hadley Centre

TABLE 1.2:**A.**

Model	2010-2019	2020-2029	2030-2039	2040-2049	2050-2059	2060-2069	2070-2079	2080-2089	2090-2099	Sea Level Rise (cm)
CCSM3	-219	-206	-215	-226	-236	-256	-278	-278	-272	6.9
CGCM3.1	-216	-200	-203	-208	-212	-213	-251	-257	-258	6.4
ECHAM5-MPI-OM	-230	-240	-263	-298	-335	-348	-373	-384	-391	8.8
INGV-SXG	-221	-211	-220	-233	-240	-281	-290	-296	-302	7.2
UKMO-HadCM3	-220	-208	-215	-230	-241	-257	-284	-278	-283	7.0
MEAN ENHANCED	-221	-213	-223	-239	-253	-271	-295	-298	-301	7.3

B.

Model	2010-2019	2020-2029	2030-2039	2040-2049	2050-2059	2060-2069	2070-2079	2080-2089	2090-2099	Sea Level Rise (cm)
CCSM3	-100	-112	-127	-138	-155	-174	-186	-201	-215	4.1
CGCM3.1	-98	-105	-116	-126	-137	-149	-160	-173	-183	3.7
ECHAM5-MPI-OM	-110	-140	-170	-204	-230	-261	-287	-340	-368	6.1
INGV-SXG	-102	-116	-132	-149	-165	-180	-204	-215	-234	4.4
UKMO-HadCM3	-101	-113	-128	-143	-159	-179	-191	-205	-221	4.2
MEAN NOT ENHANCED	-102	-117	-135	-152	-169	-188	-206	-227	-244	4.5

TABLE 1.3:

Name	Simulated Steady State Flux (km ³ ice/year)	Simulated ECHAM5 Flux Year 2100 and Difference with Steady State (km ³ ice/year)			
		Not Enhanced		Enhanced	
Petermann	7.5	8.0	+0.5	8.0	+0.5
Nioghalvfjærdsbrae*	14.2	13.8	-0.4	17.6	+3.4
Zachariae I.*	17.6	17.0	-0.6	23.3	+5.7
Kangerdlugssuaq	31.0	28.6	-2.4	25.8	-5.2
Helheim	21.4	20.8	-0.6	38.9	+17.5
Jakobshavn I.	28.2	29.3	+1.1	28.4	+0.2
Rinks	9.2	10.1	+0.9	10.1	+0.9

* Outlets fed by the Northeast Greenland Ice Stream

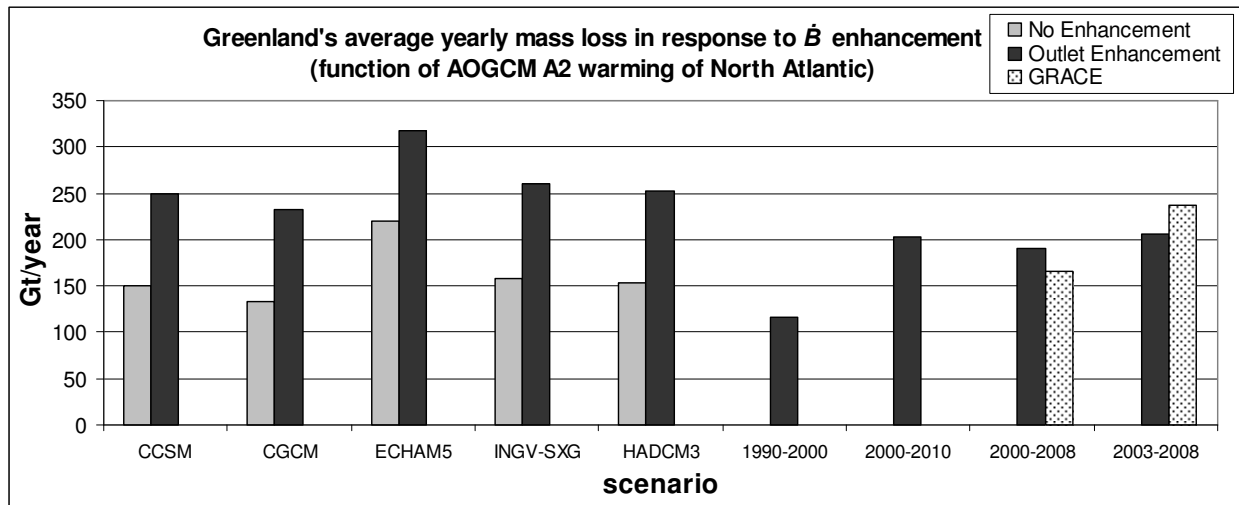
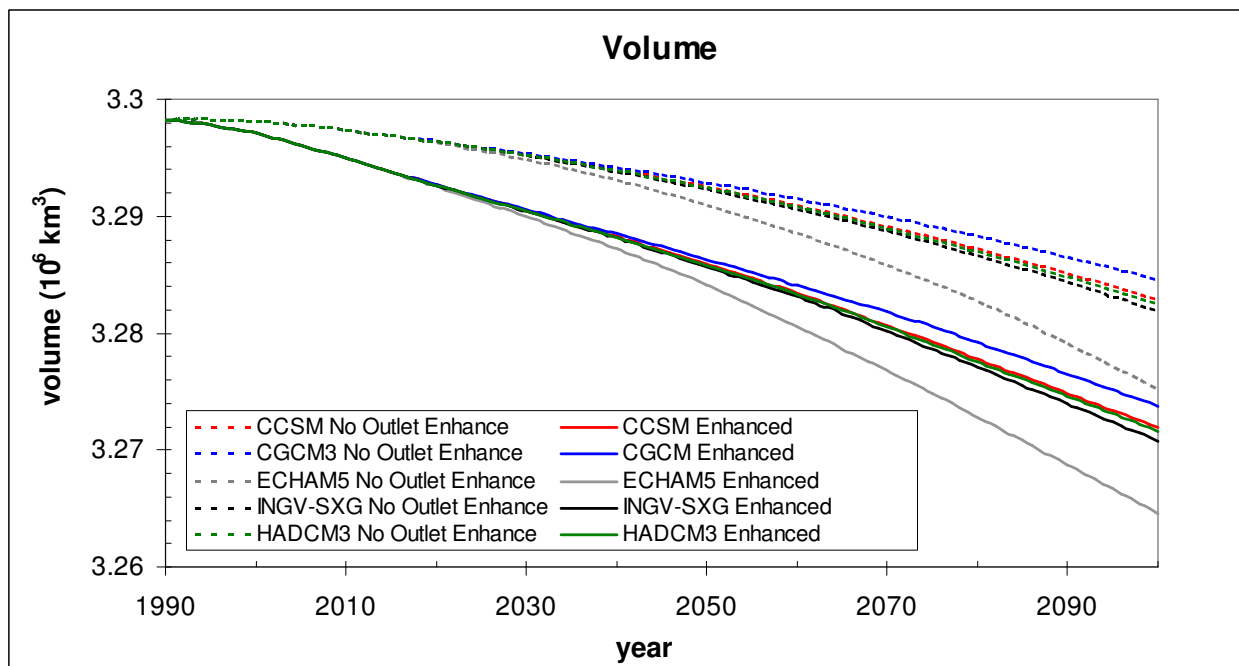
FIGURE 1.1:**FIGURE 1.2:**

FIGURE 1.3:

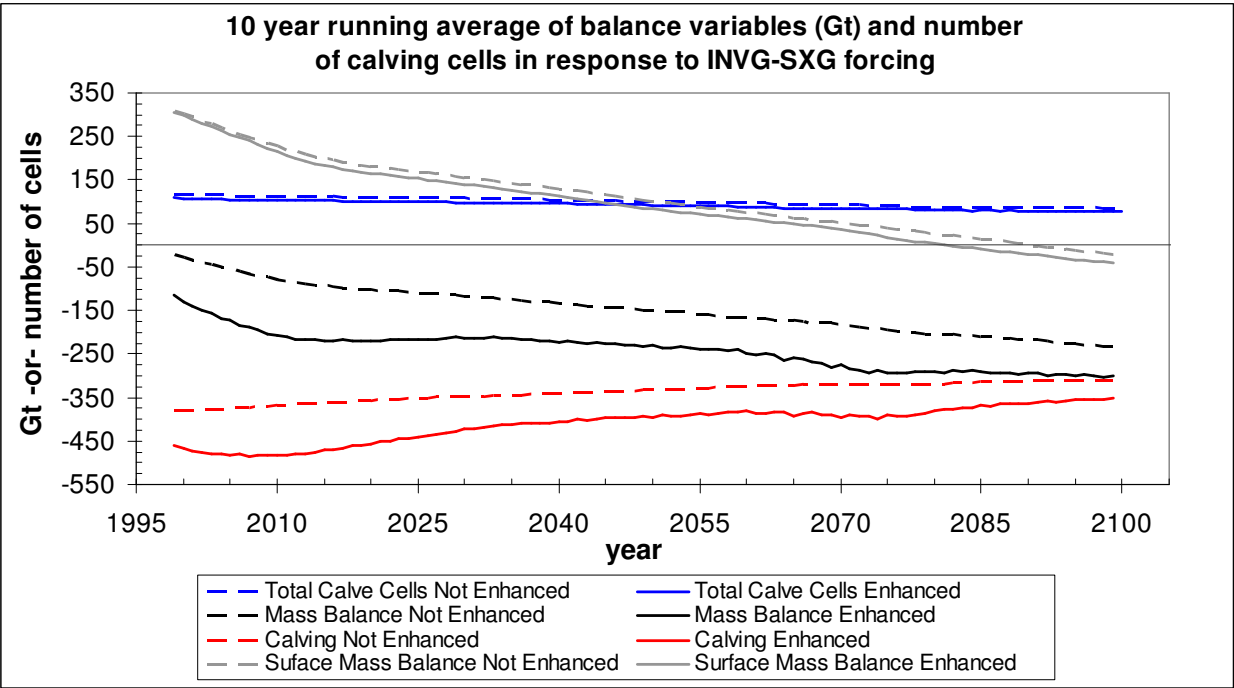
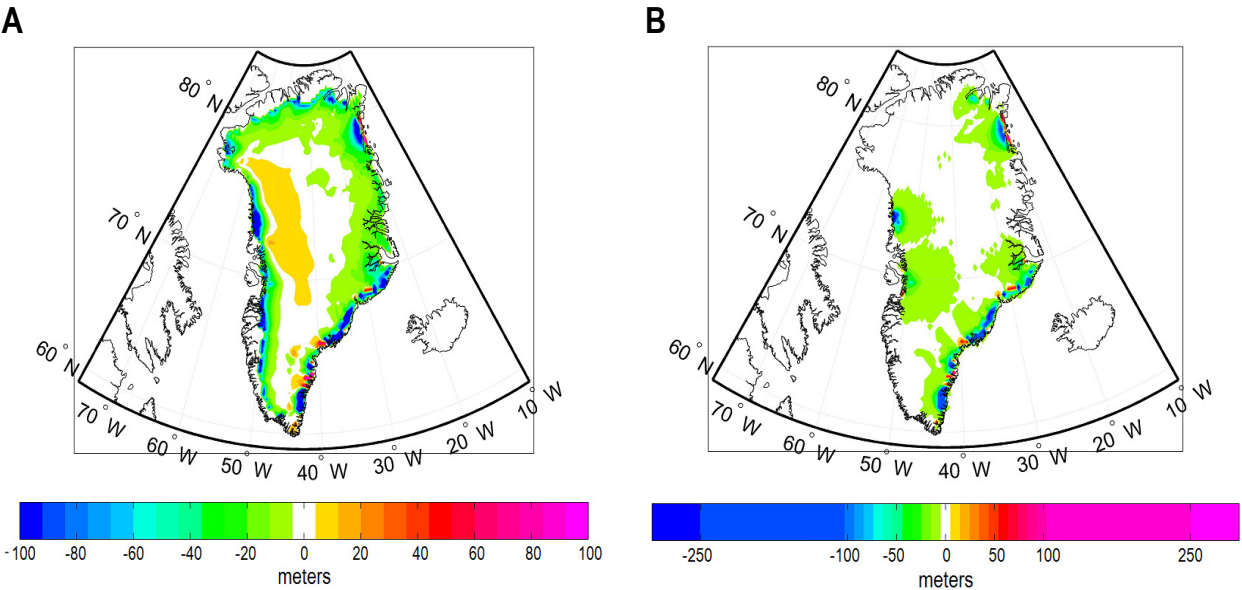


FIGURE 1.4:



Chapter 2

Sensitivity of UBCGISM

Introduction

Within the last decade, a variety of modeling experiments have coupled three-dimensional thermo-mechanical Greenland Ice Sheet models (GISM's) with atmosphere-ocean general circulation models (AOGCM's) in order to investigate possible repercussions of climate change (*Huybrechts et al., 2002; Fichet et al., 2003; Ridley et al., 2005; Vizcaino et al., 2010*). These types of studies provide useful insight into the fate of the Greenland during periods of climate warming, however they are not without their weaknesses.

Most ice sheet models, for instance, use a positive degree day (PDD) forcing, which requires that climate model output be parameterized into positive degree days. The ice sheet model internally translates the positive degree days into surface mass balance values. This translation introduces uncertainty and may lack sufficient analyses of surface processes (*Bougamont et al., 2008; Gardner and Sharp, 2009; Vizcaino et al., 2010*). In addition, AOGCM's have sparse spatial resolution (eg. $\sim 1 - 3$ degrees) relative to that of ice sheet models (5 km - 20 km). This mismatch poses a disadvantage, since interpolation is required to translate climate model output into a higher-resolution description of Greenland's climate. Recently, coupling experiments have made continual improvements upon the resolution of ice sheet model input (e.g. *Huybrechts et al., 2004; Stone et al., 2010*), but no study has yet to use a surface mass balance forcing that is defined at a resolution comparable to that of the ice sheet model itself.

Regional climate models (RCM's) can provide surface mass balance input that is more accurate and better resolved in space than AOGCM's; these mesoscale models better represent physical processes (how snowfall and melt relate to the atmosphere) as well as spatial distributions of accumulation and melt. In the past several years, meteorologists have made notable progress in running regional climate models over Greenland. For instance, *Box et al. [2006]* calibrated output from a polar-specific version of the NCAR/Penn State Mesoscale Model (MM5), the Polar MM5 (PMM5), with weather station surface observations to develop a 24 km spatially resolved surface mass balance calculation over the entire Greenland Ice Sheet from 1988-2005. Model validation suggested that the results were quite dependable for use in the formulation of an empirically based surface mass balance determination for the 1990's (*Cassano et al., 2001; Box et al., 2004; Box et al., 2006*). Most recently, *Ettema et al. [2009]* utilized the Regional Atmospheric Climate Model (RACMO2/GR) to produce an even higher-resolution (11 km) surface mass balance product over the Greenland Ice Sheet for 1958-2007. This new product had high skill with no post-run calibration applied. Currently, no two-way coupled Greenland Ice Sheet model experiment has incorporated a regional model, mostly due to limitations in computer processing speed and capacity (*Pollard, 2010*). However, high resolution surface mass balance products such as these provide valuable detail, especially along the ablation zones of key outlet glaciers. For Greenland, this detail is specifically important along the southeast coast, where large accumulation rates at high elevations feed the steep

mountain glaciers responsible almost 40% of the ice sheet's total discharge each year (*Rignot et al., 2008*).

The unique approach of this investigation was to take advantage of new resources by utilizing high-resolution input derived from a regional climate model. Our ultimate goal was to examine the century to millennial-scale evolution of the Greenland Ice Sheet in response to a variety of persistent climate trends. To do so, we attempted to improve upon past one-way coupling experiments. First, we dynamically enhanced the University of British Columbia three-dimensional thermo-mechanical Greenland Ice Sheet model (UBCGISM) by adding basal drainage functionality and a North East Greenland Ice Stream (NEGIS). Second, we examined the advantages of running the UBCGISM through 420,000 years of past glacial cycles. Finally, we compared results from experiments forced with positive degree days to those forced with surface mass balance in order to investigate whether positive degree day input was capable of adequately describing observed surface climate variability.

Methods

Models

Yearly surface mass balance maps (calendar years 1988-2005, at a resolution of 24 km) provided by Dr. Jason Box (*Box et al., 2006*) were used to force a Greenland Ice Sheet model. Ice dynamics calculations were performed with an enhanced version of the University of British Columbia three-dimensional thermo-mechanical ice sheet model (UBCGISM), originally developed by Dr. Shawn Marshall (*Cuffey and Marshall, 2000*). The UBCGISM is a finite-difference model that runs on a spherical grid. It has a meridional resolution of 0.25 degrees and a zonal resolution of 0.5 degrees, for a total grid of size of 140x108. For these simulations, it was run with a total of 20 vertical levels.

UBCGISM Development

Phase I: Basal Drainage Enhancement

The first enhancement made to the UBCGISM was the incorporation of basal drainage. Basal water was set equal to the basal melt at the glacier bed plus the surface runoff of any given model cell. Modeled basal water traveled down the peizometric potential gradient where:

$$(2.1) \quad \Phi = g * (\rho_{ice} * z_{ice} + (\rho_{water} - \rho_{ice}) * z_{bed})$$

Φ was the peizometric potential, g was gravity, ρ_{ice} and ρ_{water} were the densities of ice and water respectively, and z_{bed} and z_{ice} were the elevations of bedrock and ice respectively. Basal drainage basins were calculated based on peizometric potential gradients, and the accumulation of basal water at any given point was set equal to the sum of the basal water up-gradient from that point. The UBCGISM time step was a year, so this summation represented the average thickness of water per year that passed through each grid cell.

We multiplied this average thickness by the distance the water travels within each grid cell in order to obtain q_w , a value equivalent to the advection of basal water thickness down the peizometric gradient, or:

$$(2.2) \quad q_w = H_w * u_w$$

where H_w was the average basal water thickness throughout the year and u_w was the velocity with which the water passed through the grid cell. H_w was the quantity of interest, since it represented the available water thickness responsible for basal sliding. Assuming that the value of u_w was directly related to the peizometric potential gradient by the empirical relationship:

$$(2.3) \quad u_w \sim C_w * |H_w| * |\nabla \Phi|$$

where C_w was a constant scaling factor equivalent to viscosity⁻¹, we obtained an estimate for u_w . Finally, by combining equations (2) and (3), we calculated H_w as:

$$(2.4) \quad H_w = (q_w / (C_w * |\nabla \Phi|))^{-2}$$

In the UBCGISM, we used the magnitude of H_w to directly scale basal velocity. For this study, C_w was assumed to be 1, and tuning of basal sliding was accomplished within the sliding law itself.

The new basal drainage functionality allowed us to initialize and maintain a Northeast Greenland Ice Stream (NEGIS) in the model. To initiate the ice stream, we increased the geothermal heat flux around NorthGRIP (between the longitudes of 37W and 43W and the latitudes of 74N and 76N) to an average value of 130 mW/m² (Dahl-Jensen *et al.*, 2003; Buchhardt and Dahl-Jensen, 2007), while the rest of the ice sheet remained at the default geothermal heat flux, 53 mW/m². This resulted in basal melt which drained northeast, down the peizometric gradient, where it promoted basal sliding. We further enhanced sliding by prescribing an enhancement factor of three in the area of the observed Northeast Greenland Ice Stream, as suggested by Greve and Otsu [2007]. The north branch of the ice stream (north of 78 degrees north latitude) was enhanced to a factor of five (instead of three) in order to better fit outlet flux observations (Rignot and Kanagaratnam, 2006; Rignot *et al.*, 2008).

Phase II: Mass Balance Forcing Development

The UBCGISM's standard input scheme translates average monthly or yearly temperature and precipitation data into surface mass balance values with use of a positive degree day method (see APPENDIX A). For this study, we enhanced the ice sheet model to accept accumulation and positive degree day input from Box *et al.* [2006] PMM5 output directly. We also updated it to accept the Box *et al.* [2006] PMM5 surface mass balance output. As a result, we could force the ice sheet with either positive degree day or surface mass balance input that was derived from the same atmospheric model run. To implement the new forcing scheme, we split Greenland into twenty-nine different regions. For each region and parameter (surface mass balance, accumulation, or positive degree days), we used gridded input to define a relationship between the parameter value and surface elevation. We will refer to these relationships as regional transects. We further developed the UBCGISM to map the regional transects onto any simulated topography (see APPENDIX B).

We chose this scheme because it allowed for easy recalculation of surface mass balance onto the topography of an evolving ice sheet, while it also conserved the three-dimensional

information provided by the input product. One disadvantage of this scheme is that anomalous grid-level details were expected to be lost in translation. In addition, it assumed that parameter-altitude relationships would remain static with orographic change, an assumption which would likely hold in early stages of Greenland Ice Sheet retreat (*Vizcaino et al., 2010*). Finally, the lack of sea level surface mass balance values in certain regions (particularly in the southeast) made it necessary to prescribe a value below an elevation of 100 meters. In these cases, average sea level values from neighboring regions were used where deemed appropriate. Southern coast values were never used to estimate surface mass balance in a more northern region, while east coast and west coast values were kept strictly independent from one another. In the UBCGISM regions where this was an issue, land-based ice thicknesses below 100 meters rarely existed, due to resolution restraints and steep topography. Therefore, these estimations served mostly to dissuade the growth of unrealistic ice shelves where sea level accumulation was high.

Forcing Experiments

In order to assess differences between the two *Box et al.* [2006] forcing products, we first ran the UBCGISM with positive degrees day input and then with direct surface mass balance input. Both experiments used the same *Box et al.* [2006] accumulation rates. Initial, steady-state topographies were created for the two distinct input products by running the model through 250,000 years of a 1988-2005 average forcing. The surface-mass-balance-based initial condition profile will be known as IC-8805 and the positive-degree-day-based initial condition steady-state profile will be known as IC-PDD. Degree-day melt parameters associated with the positive degree day input were defined as $4.2 \text{ mm day}^{-1} \text{ degreeC}^{-1}$ and $18.7 \text{ mm day}^{-1} \text{ degreeC}^{-1}$, for snow and ice respectively (*Stone et al., 2010*). A third initial condition, which will be known as IC-420K, was created by running the model through 420,000 years of climatic history. As a representation of the Holocene, the last 10,000 years of this run was forced with the 1988-2005 average surface mass balance.

We forced each of the three initial topographies with surface mass balance (IC-8805/IC-420K) and positive degree days (IC-PDD) from 18 different years (1988-2005), for a total of 54 runs. All runs proceeded for a thousand years, following a 1988-2005 average spin-up of 100 years. Each year's forcing represented a realistic climate scenario, and together the eighteen years characterized variability in ice sheet surface conditions. The range of yearly conditions allowed us to examination relationships between bulk climate parameters and Greenland volume change in response to persistent climate. We placed focus upon the years 1998 and 2005 (warm years) and 1992 (cold year), since they were realistic examples of climatic extremes.

Results

In Figure 2.1, we plot the IC-8805 ice flux. The Northeast Greenland Ice Stream is clearly represented by a regional increase in flux that stretches from the center of the northern dome of the ice sheet to outlet glaciers of Greenland's northeast coast. Major outlet glaciers and their corresponding drainage basins are also evident.

Results from the eighteen IC-8805 runs are presented in Figure 2.2. Each run represents 100 years of spin-up followed by 1000 years of persistent surface mass balance and accumulation forcing from a historic year (1988-2005). Figure 2.2A shows how the volume of the ice sheet changed through the 1000 years of forcing, while Figure 2.2B shows how the area

of the ice sheet changed. Both plots show very similar trends and illustrate the climatic diversity of the eighteen different forcing years. 1992 and 1998 stand out. Respectively, they forced the most dramatic increase and decrease in ice sheet area and volume. In Figure 2.2C, we plot the yearly mass balance, or rate of volume change, throughout the 1000 years. The largest changes occurred within the first decade and then slowly lessened with time as the model adjusted to its new surface climate. This response was partly driven by changes in calving rates (ice volume per year), which we plot in Figure 2.2D. During cooler years, the calving rates increased towards a new equilibrium value, resulting in ice loss which counteracted the increased surface mass balances. During warmer years, calving rates decreased as the ice sheet retreated, likewise counteracting ice sheet retreat.

Spatial results from the IC-8805 runs are presented in Figure 2.3. Taking 1998 as an extreme warm year and 1992 as an extreme cold year, we spatially compare their impacts on Greenland topography. We plotted the difference between the 1998 and 1992 changes in surface topography (in meters) in order to illustrate the topographical differences between a Greenland forced with a thousand years of a persistently warm climate and a thousand years of a persistently cold climate. After 1000 years, the two topographies differed in mass by 183,000 Gt (or about 50 cm of equivalent sea level rise). In Figure 2.3 the largest topographical differences occurred in the southwest of the ice sheet, especially around the Jakobshavn Isbrae basin. These results suggest that the southwest glaciers are the most vulnerable to thinning and retreat in a warmer climate.

Figure 2.4 illustrates relationships between basic climatic parameters (*Box et al., 2006; Cassano et al., 2001*) and IC-8805 volume change after 1000 years for each of the 18 forcing years. Due to anomalous snowfall, 2003 stood out as a clear outlier in many of the plots, as accumulation strongly outweighed melt. Figure 2.4B suggests that, on average, accumulation rates had a weak relationship with volume change. However it is important to note that years of extreme accumulation did affect results more distinctly. In contrast, strong relationships between ice sheet volume change and key parameters like surface mass balance, runoff, and summer temperature were more evident. For example, mean summer surface temperature and consequential runoff (Figure 2.4E,C) were strongly related to volume change. 1992 (1998), which stood out as the year of most positive (negative) volume change had the coldest (warmest) average summer temperatures and smallest (largest) runoff. In comparison to average summer temperature, the maximum monthly summer temperature displayed a relatively weak relationship (Figure 2.4F). These results suggest that sustained warm temperatures throughout the summer played a much more dramatic role in forcing large-scale melt than did single months of anomalously high temperatures. Figure 2.4D illustrates a strikingly strong relationship between Jakobshavn Isbrae basin runoff and ice volume lost. Consistent with Figure 2.3, these results pinpoint southwest outlets, especially those which are low-lying and have large drainage basins, as areas that are highly sensitive to climate change.

In order to determine whether a Greenland Ice Sheet evolved through past glacial cycles is significantly more sensitive to warming, we compare results from IC-8805 and IC-420K runs. Both topographies were forced with surface mass balance from 18 different years (1988-2005). Figure 2.5 illustrates a distinct similarity between the two sets of output. The stars and the dashed line represent results from IC-420K runs and circles and solid line represent results from IC-8805 runs. On average, the IC-420K runs lost 14 Gt (less than 10%) more ice, or 0.04 mm of sea level rise, each year. These differences were somewhat expected due to distinctive characteristics of an ice sheet affected by past climate fluctuations, including layers of warmer

ice at depth and dynamic ice loss forced by Holocene warming. In Figure 2.6B, the volume and area changes for extreme years are compared. Results suggest that IC-420K runs were more sensitive to additional ice loss during colder years. Most likely, these differences occurred because calving was a much more effective process during colder years (Figure 2.2D), and the ice sheet's capability to dynamically transport ice to the outlet glaciers was already well established in IC-420K.

In Figure 2.6, we compare results from all runs. The differences between the IC-8805 and the IC-PDD were substantial. We included volume equivalent total surface mass balance anomalies in Figure 2.6A for comparison. The IC-8805 ($R^2=.66$) and IC-420K ($R^2=.65$) results were more significantly related to surface mass balance anomalies than were the IC-PDD results ($R^2=0.45$). Aside from year 2003, which had already been established as an outlier, the PDD-results failed to express the observed year-to-year variability of Greenland's climate. Volume and area changes during extreme years 1992, 1998, and 2005 are presented in Figure 2.6B. Despite the extreme climates represented by 1992 and 1998, the IC-PDD results were rather subdued. This was especially true considering our liberal choices for degree-day factors.

Discussion

Both surface mass balance and total ice sheet discharge are important in determining the total mass balance of an ice sheet. This study focused on forcing Greenland Ice Sheet model steady state topographies with diverse climates. The observed surface mass balance and accumulation of each individual historical year described a unique climate. We persistently forced the model with the surface mass balance and accumulation for each year and allowed the model to respond for a thousand years.

In Figure 2.5, we draw best fit lines through the IC-8805 and the IC-420K results. In response to only surface mass balance changes, one would expect the slope of these lines to equal 1. Both lines, however, are less steep than expected, indicating that a negative feedback had occurred. Figure 2.2C illustrates that this negative feedback was related to ice sheet discharge. Throughout this study, outlet glacier processes dominated the UBCGISM's responses to climate change by altering the ice sheet's total discharge. Large outlet glaciers, especially, were influential in counteracting the effects of the ice sheet's new surface mass balance. During warm year runs, calving rates were reduced due to marginal thinning and loss of calving fronts. This, in turn, decreased total discharge and slowed retreat. During cool years, the opposite occurred. Calving rates increased due to marginal thickening, increasing total discharge and slowing ice sheet growth.

Recent observations, however, contrast these results. Specifically during the past few years, ice sheet discharge has been increasing along with temperatures (*Rignot et al., 2008, van den Broeke et al., 2009, Velicogna, 2009*). Additional dynamic processes are believed to be driving rapid changes in Greenland Ice Sheet's outlet glaciers. These dynamic processes likely go beyond basal drainage and the presence of a Northeast Greenland Ice Stream. Therefore, it is important to note that our results do not include the full dynamic response of Greenland's outlet glaciers to climate warming. In reality, the negative feedback described previously must compete with these additional dynamic responses and may not be the most dominant process induced by climate change.

Nonetheless, the simplified results presented here make a clear distinction between positive degree day and surface mass balance input. Because the surface mass balance input has

been validated by observations (*Box et al., 2006*), we confidently accept that they closely resemble truth. Figure 2.6A suggests that our surface mass balance forcing scheme was successful in maintaining the variability of the original *Box et al. [2006]* product; 2003, a year of anomalous snowfall, stands out as an exception. Overall, the positive degree day forcing failed to simulate the same range of variability. Even though the degree day parameters chosen for these experiments were very liberal and should have promoted even more melt than expected, results for the warm year 1998 differed greatly between IC-8805 and IC-PDD. These results suggest that a positive degree day forcing scheme does not capture surface mass balance conditions in as great a detail as does a direct surface mass balance forcing.

Conclusion

The years 1988-2005 represented a diversity of climatic conditions over the Greenland Ice Sheet. With regards to balance, certain years were strongly positive and others strongly negative, while the majority were average. The volume change sensitivity to mean summer surface temperature for 1000 years of forcing was approximately $85,000 \text{ km}^3$ per degree C (Figure 2.4E). The millennial-averaged mass balance for the warm years 1998 and 2005 (approximately $120 \text{ km}^3/\text{yr}$) was slightly below the average value for measurements of Greenland volume loss for 2002-2006 (*Chen et al., 2006; Luthcke et al., 2006; Ramillien et al., 2006; Rignot and Kanagaratnam, 2006; Veliconga and Wahr, 2006*).

Difference in results between extreme years 1998 (warm) and 1992 (cool) illustrate the vulnerability of Greenland's southwestern margin to a warming climate. By comparison, the southeast margin was protected by its high bedrock topography. Results also suggest that summer temperatures exert a more consistent control on ice volume change than do precipitation rates (Figure 2.4B,E,F). Nonetheless, in years of high or low precipitation, accumulation can play a forceful role in dictating if total mass balance will be positive or negative.

A 420,000 year climatic spin-up has little effect on results. On average, it decreased volume change by less than 10%; however, cooler years were affected more than warmer years. In contrast, the use of positive degree day input changed results dramatically. Though it did capture the general warming trend which occurred from 1988-2005, the positive degree day scheme could not simulate the complete variability in Greenland surface conditions which occurred during the same period. Adoption of a direct surface mass balance forcing scheme in our ice sheet model made a marked improvement in describing the full range of observed year-to-year Greenland Ice Sheet climate variability.

Acknowledgements

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Figures

Figure 2.1:

Ice flux (km^3/yr) of the steady state initial condition, IC-8805.

Figure 2.2:

Results of spin-up plus 1000 year run, forcing IC-8805 with surface mass balance from specific years: (A) Volume, (B) Area, (C) Yearly Rate of Volume change, (D) Total Yearly Calving Rate

Figure 2.3:

The difference in ice thickness (m) between a Greenland Ice Sheet forced with 1998 (warm year) and 1992 (cold year) after 1000 year run. Initial starting condition is IC-8805.

Figure 2.4:

Volume change of ice sheet after 1000 years of surface mass balance forcing from specific years as a function of *Box et al.* [2006] values for (A) total surface mass balance (\dot{B}), (B) total precipitation (\dot{C}), (C) total runoff, (D) Jakobshavn Isbrae basin runoff; and *Cassano et al.* [2001] values of (E) mean summer surface temperature, and (F) max summer surface temperature. Results are from IC-8805 runs [Blue (1988-1990), Black (1991-2000), Red (2001-2005)].

Figure 2.5:

Average simulated total mass balance (Gt/yr) during 1000 years of surface mass balance forcing from specific years as a function of total surface mass balance anomaly from the 1988-2005 mean ($\Delta\dot{B}_{8805}$) (*Box et al.*, 2006). *Circles and solid line* are from runs using IC-8805 [Blue (1988-1990), Black (1991-2000), Red (2001-2005)]. *Stars and dashed line* are results from runs using IC-420K. In calculating the best fit lines, year 2003 was omitted as an outlier.

Figure 2.6:

(A) Change in ice sheet volume and area after forcing different initial scenarios with 1000 years of surface mass balance (\dot{B}) and accumulation (\dot{C}) for individual years 1988-2005. Ice volume equivalent (km^3/yr) of total surface mass balance anomaly ($\Delta\dot{B}_{8805}$) is also included for comparison (blue dashed line). (B) Change in ice sheet volume and area after forcing different initial scenarios with 1000 years of extreme surface mass balance and accumulation for individual years 1992, 1998, and 2005. IC-8805: Steady State profile from mean of 1988-2005 mass balance; IC-420K: 420k year historical run using mean 1988-2005 to represent the Holocene; and IC-PDD: the same as IC-8805 but forced with mean of 1988-2005 PDD input instead of surface mass balance.

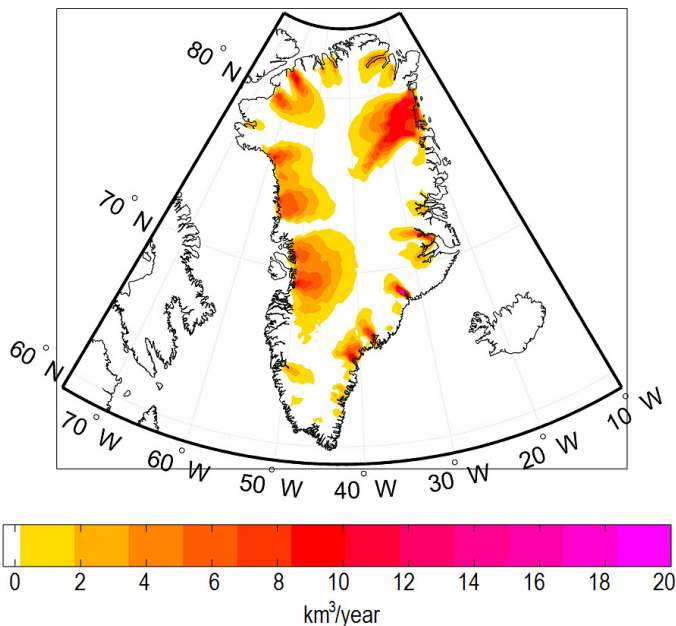
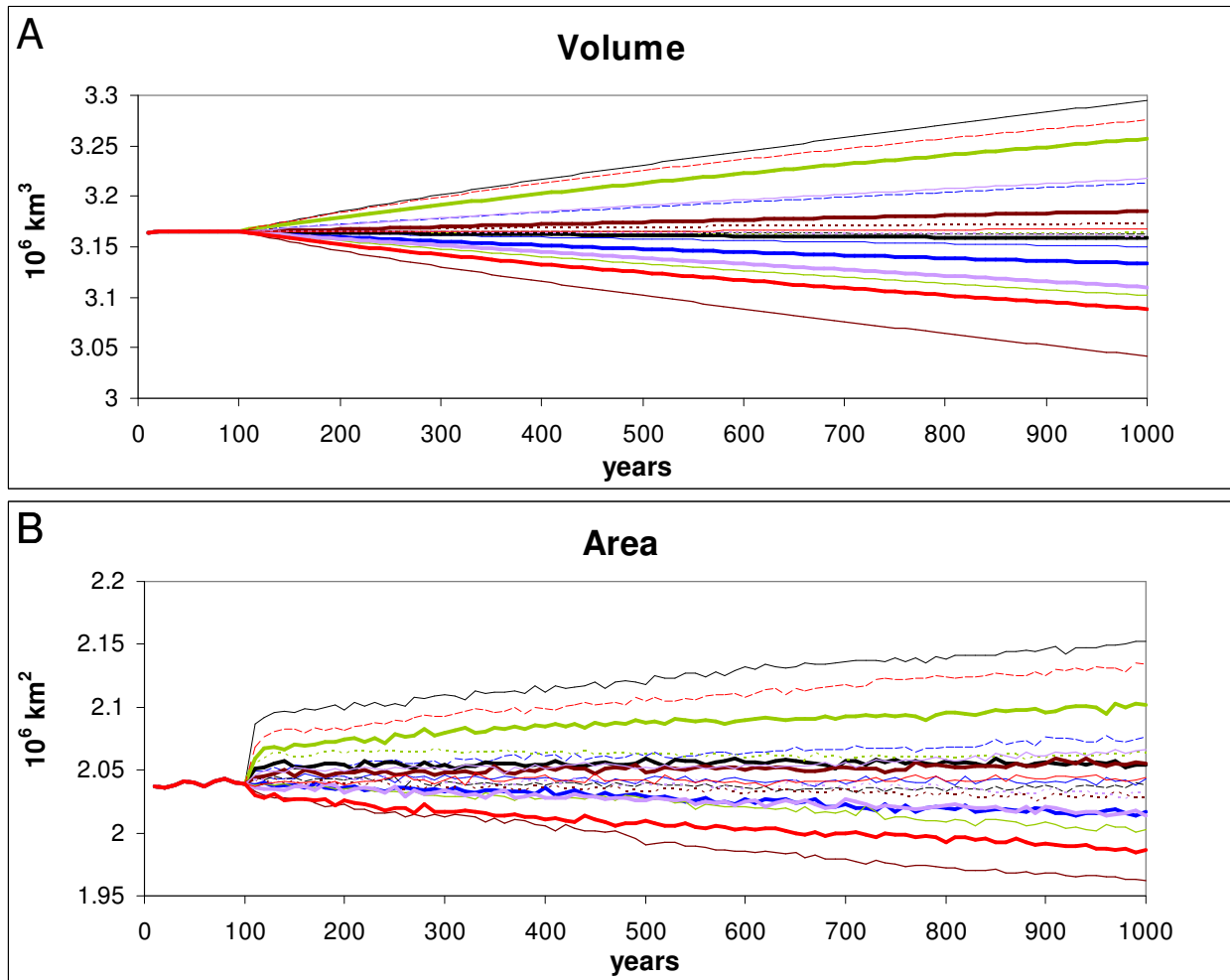
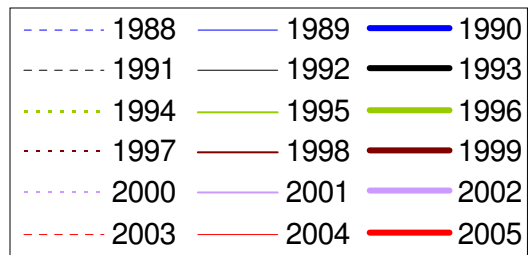
FIGURE 2.1:

FIGURE 2.2:

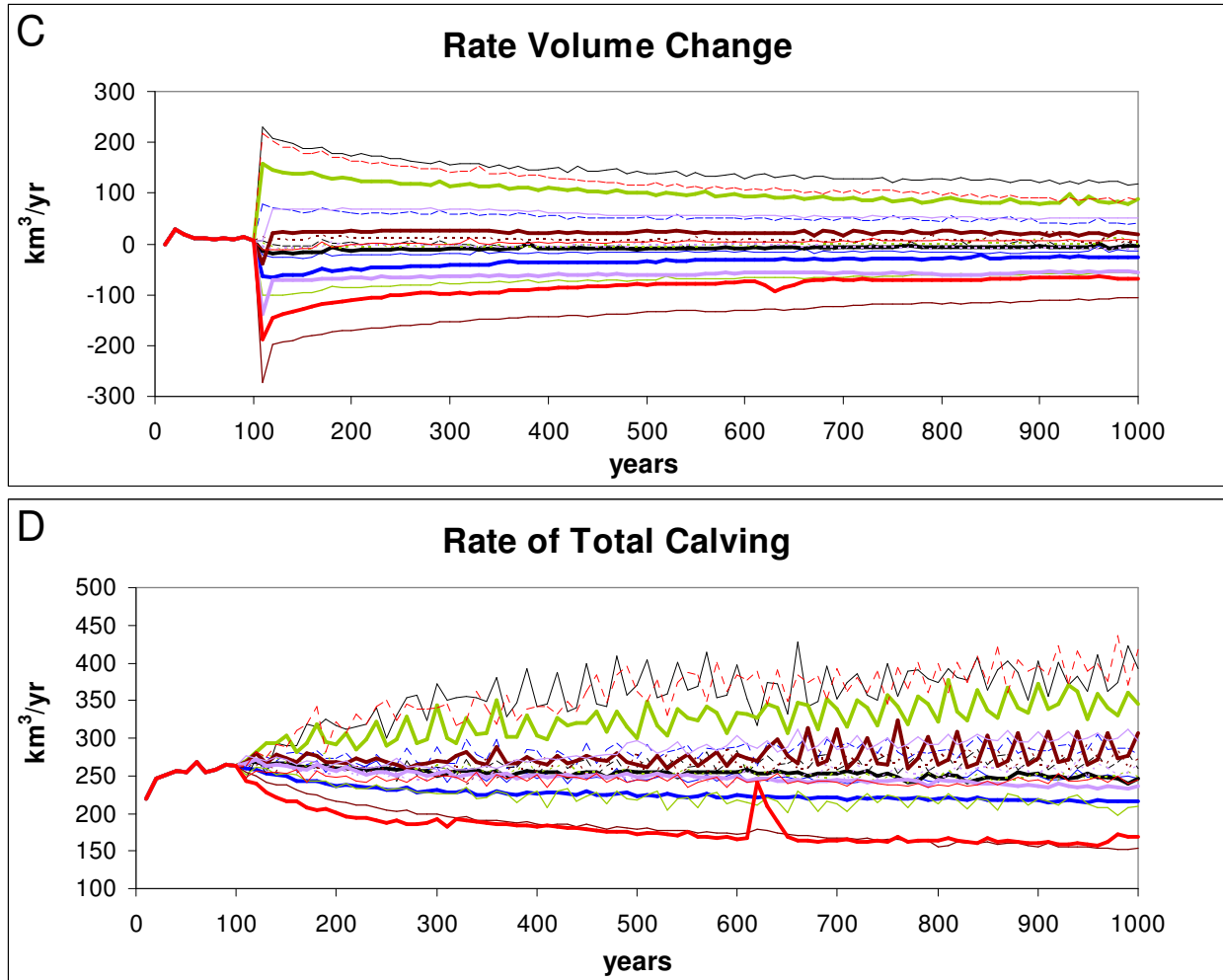


FIGURE 2.3:

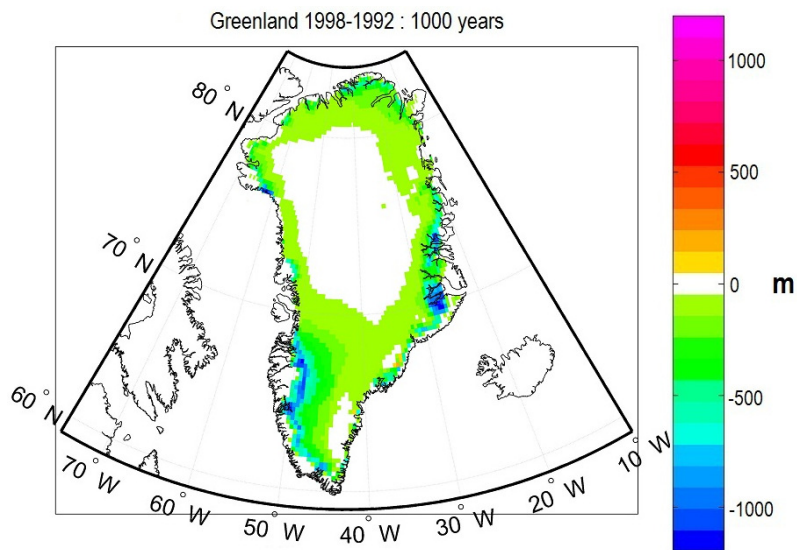
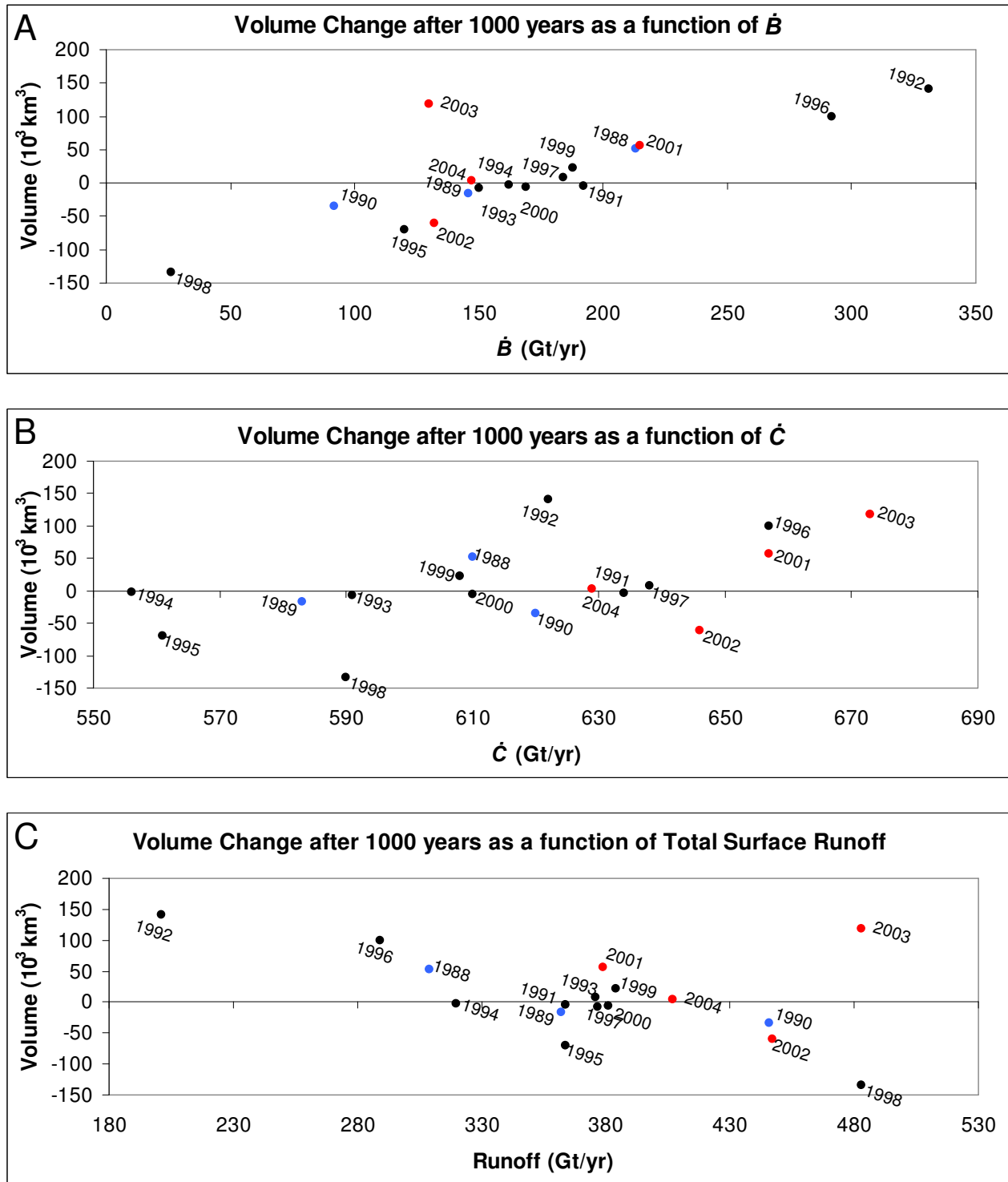


FIGURE 2.4:

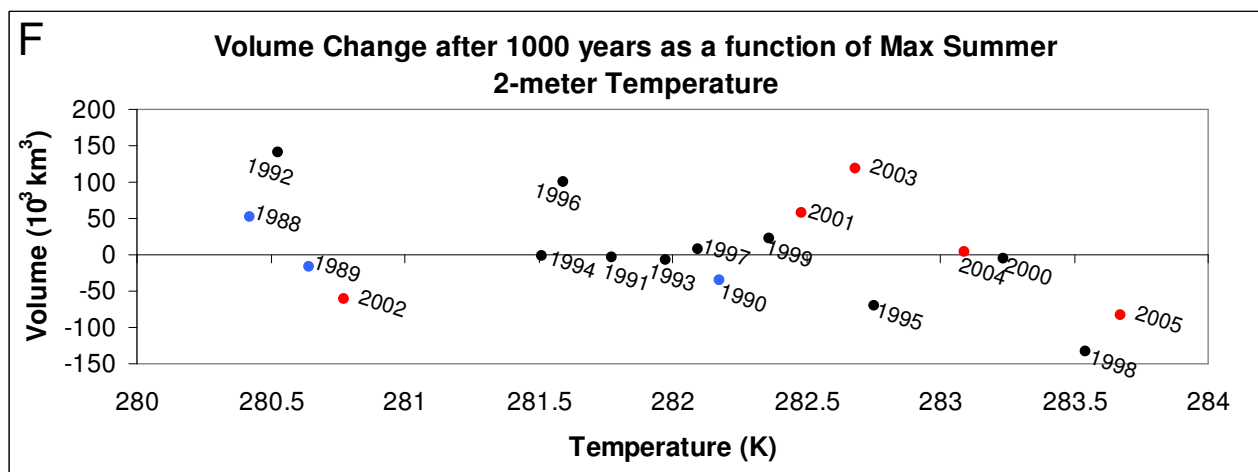
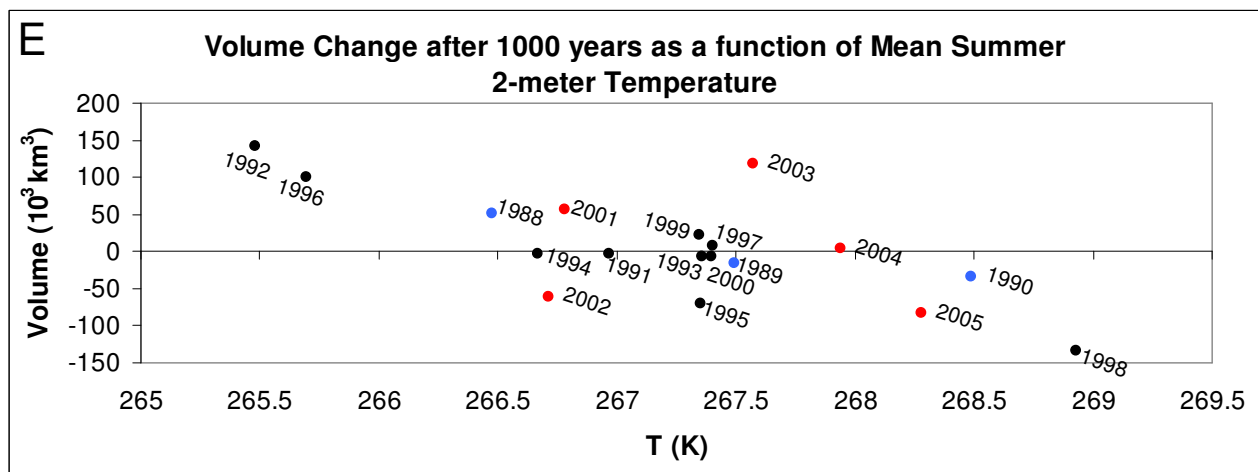
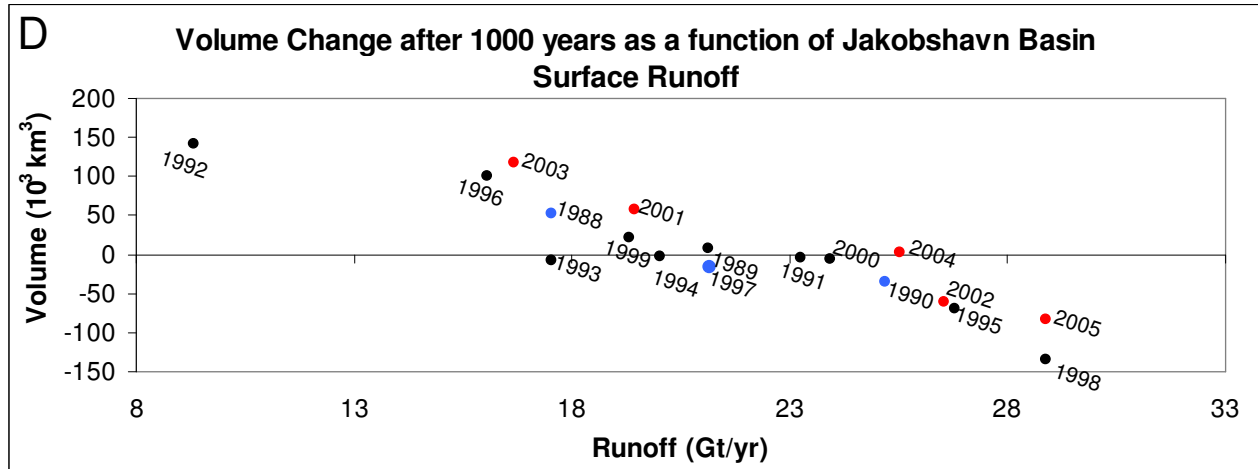
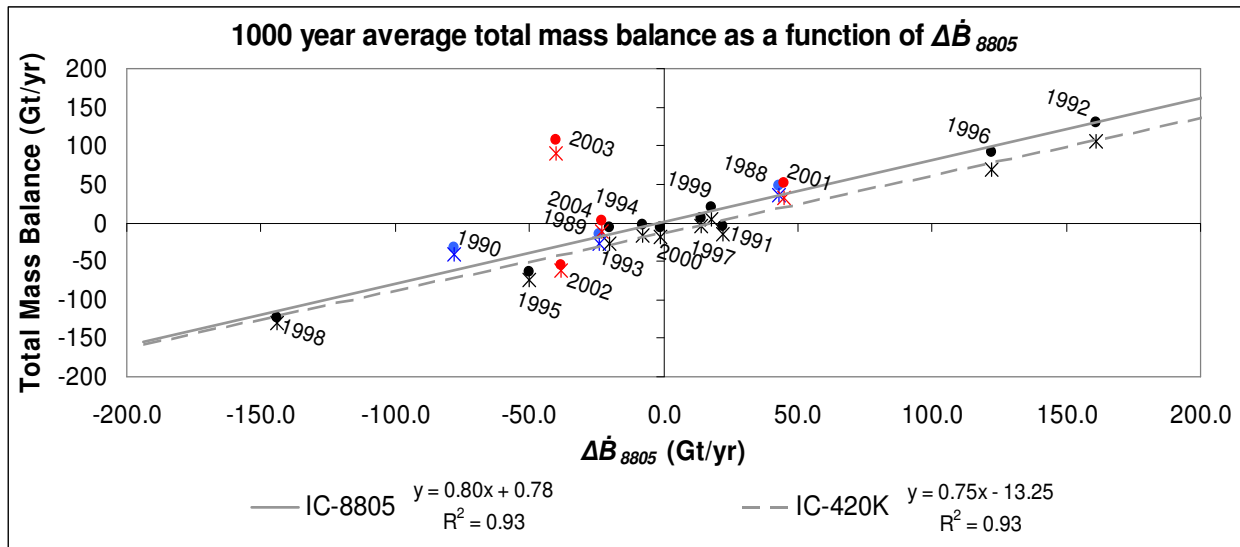
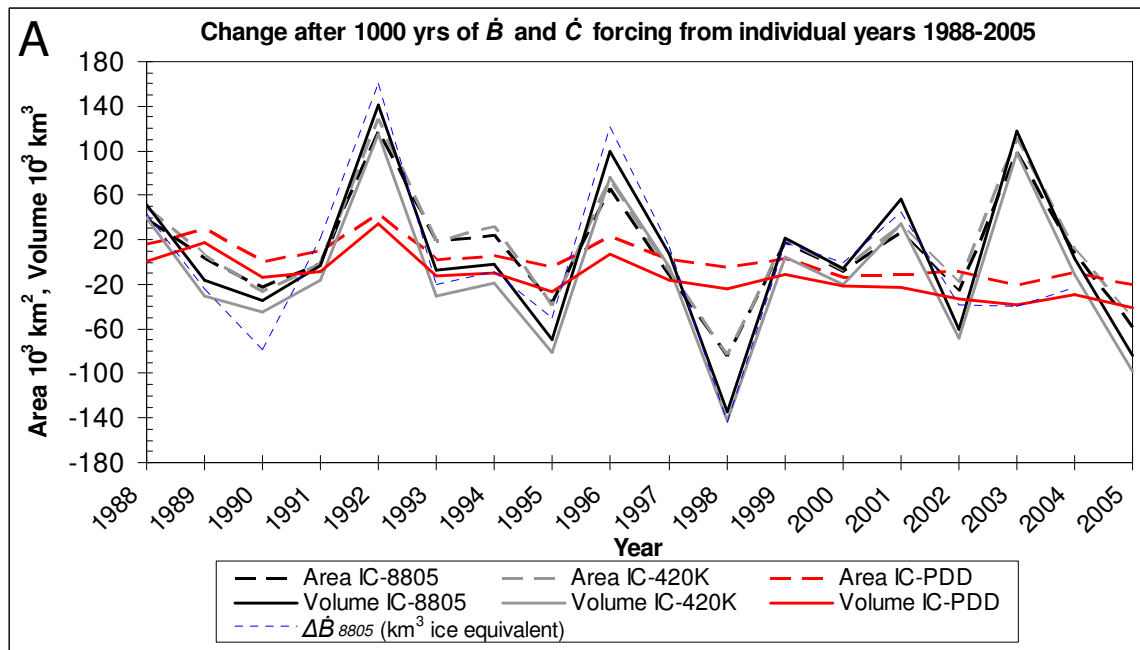
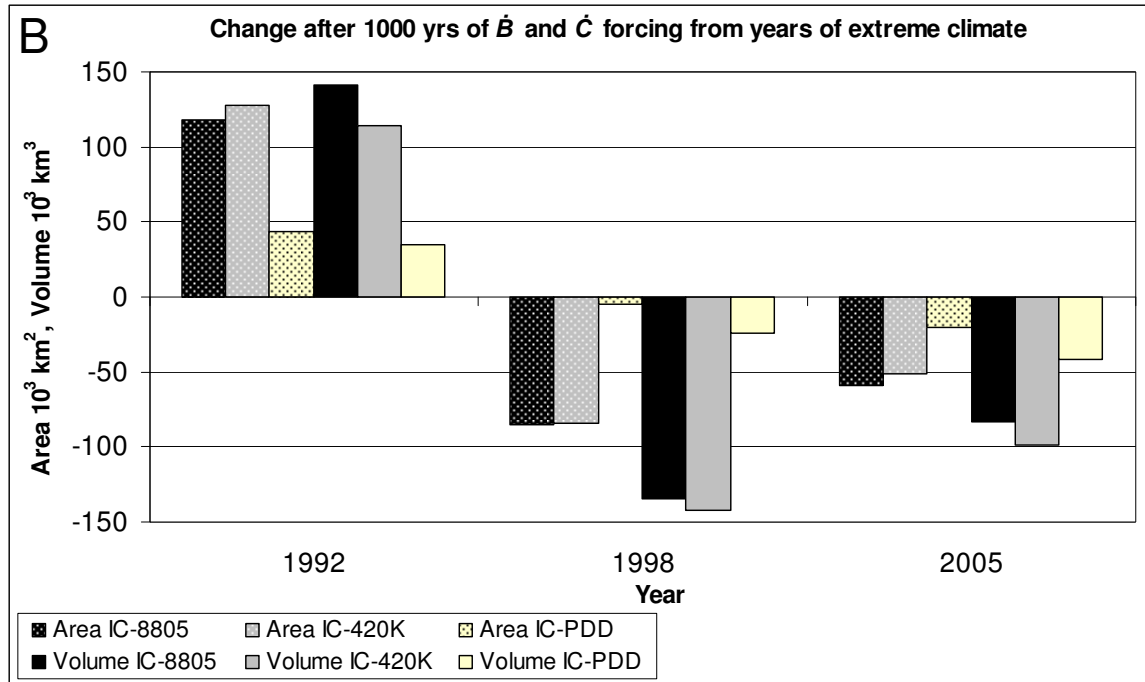


FIGURE 2.5:**FIGURE 2.6:**



Chapter 3

Tuning UBCGISM dynamic discharge

Introduction

Improved observations during the last decade have provided evidence that enhanced ice sheet dynamics are responsible for a significant decrease in Greenland's total mass balance. In fact, they suggest that Greenland mass loss is split equally between surface processes and dynamic responses (*Rignot et al., 2008; van den Broeke et al., 2009, Velicogna, 2009*). Even so, most three dimensional thermo-mechanical Greenland Ice Sheet model (GISM) coupling experiments do not take into consideration direct dynamic response to surface mass balance changes. That is, they do not consider what *Huybrechts et al. [2004]* referred to as “unexpected ice-dynamic responses”: any response that is beyond the dynamic acceleration or deceleration resulting from perturbations in surface slope and ice thickness. These less-understood responses are likely induced by fast-flowing outlet glaciers, melt water drainage, or abrupt calving discharge, to name a few.

Greve and Otsu [2007] investigated the sensitivity of the GISM Simulation Code for POLythermal Ice Sheets (SICOPOLIS) with regards to a subset of these processes. They implemented a North East Greenland Ice Stream (NEGIS) with basal sliding enhancement and additionally, increased basal sliding as a function of surface melt. SICOPOLIS's sensitivity to future scenarios forced by a positive-degree-day-based surface mass balance scheme suggested that neither of these processes caused additional Greenland Ice Sheet instability. However, they did conclude that when melt-induced basal sliding was increased by an order of magnitude, the ice sheet became significantly more susceptible to climate warming.

More recently, *Rignot et al. [2008]* observed a significant relationship between Greenland's total discharge and total surface mass balance. Results suggested that unexpected dynamics were indeed magnifying ice sheet mass loss. Using satellite interferometric synthetic-aperture radar (InSAR) measurements made during the last fifteen years, *Rignot et al. [2008]* derived past and present velocities of Greenland's major outlet glaciers. They utilized airborne radio echo sounding data collected during the same period to estimate outlet glacier ice thicknesses. This information made it possible to calculate historic ice flux through Greenland's major outlet glaciers and subsequently, the ice sheet's total discharge. For the years 1958, 1964, 1992, 1996, 2000, 2004, 2005, 2006, and 2007, *Rignot et al. [2008]* presented estimates for Greenland's total discharge and surface mass balance. (Surface mass balance values were derived from regional climate model simulations described by *Burgess et al. [2010]*.) A robust linear interpolation between these two parameters provided evidence that unexpected dynamics were responsible for an additional 60% to 70% of ice sheet mass loss. Results suggested that Greenland was more dynamically sensitive to marginal melt than previously predicted by ice sheet models. Ideally, future Greenland Ice Sheet models will incorporate the complete physics involved in Greenland's response to climate change, particularly outlet glacier dynamics (*Pollard, 2010*).

In this investigation, we attempted to improve upon an existing model (an enhanced version of the University of British Columbia three-dimensional thermo-mechanical ice sheet model, or UBCGISM) by tuning its outlet dynamics. Because the UBCGISM does not run at a resolution capable of capturing the details involved in the physics of fast flowing outlet glaciers, we attempted to tune the UBCGISM empirically, in order to simulate the observed dynamic responses (as predicted by *Rignot et al.* [2008]) in a physically-based, yet simplified manner. This phenomenological approach was accomplished by: (1) using regional-climate-model-derived surface mass balance and accumulation maps as high-resolution model input (*Rignot et al., 2008; Burgess et al., 2010*); (2) enhancing the model's outlet glaciers to discharge with respect to local surface mass balance changes; and (3) tuning the model to simulate observed ice sheet discharge (*Rignot et al., 2008; Jason Box, personal communication*).

Methods

Models

We chose surface mass balance and accumulation surface maps (balance years 1958-2007, at a resolution of 1.25 km), provided by Dr. Jason Box, as model input (*Rignot et al., 2008; Burgess et al., 2010*). Ice dynamics calculations were performed with the University of British Columbia three-dimensional thermo-mechanical ice sheet model (UBCGISM), originally developed by Dr. Shawn Marshall (*Cuffey and Marshall, 2000*), and then enhanced with basal drainage as well as a Northeast Greenland Ice Stream (NEGIS) (as discussed in CHAPTER 2).

The UBCGISM is a finite-difference model that runs on a spherical grid. It has a meridional resolution of 0.25 degrees and a zonal resolution of 0.5 degrees, for a total grid size of 140x108. For these simulations, it was run with a total of 20 vertical levels. We used the Box surface mass balance and accumulation input to define transect relationships for twenty-nine different regions of the ice sheet, and forced the UBCGISM with the surface mass balance and accumulation conditions described by these transects (see APPENDIX B).

UBCGISM Development

The Greenland Ice Sheet is thought to have been in a virtual steady state during the years 1971 to 1988 (*Rignot et al., 2008*). For this reason, we chose to force our steady state ice sheet with 1971-1988 average surface mass balance and accumulation. The UBCGISM, forced with 1971-1988 surface mass balance and accumulation, was tuned and run for 250,000 years in order to achieve a steady state initial condition comparable in profile to the present day ice sheet. We will refer to this initial condition as IC-7188. Attention was placed upon achieving realistic discharge for Greenland's largest seven outlet glaciers (*Rignot et al., 2008*). We chose the 1971-1988 steady-state ice sheet because, with respect to these characteristics, it was more realistic than an ice sheet that had been run through past glacial cycles. To compensate for the dynamic ice loss due to Holocene warming, we added a yearly mass loss of 8.25 Gt per year, as estimated by the UBCGISM, to all results presented below.

The goal of this exercise was to develop the UBCGISM so that it would dynamically respond in a way consistent with the following observed relationship:

$$(3.1) \quad Q = -0.665 * \dot{B} + 742.1$$

where Q was the total discharge and \dot{B} was the total surface mass balance of the Greenland Ice Sheet, in units of Gt, for any given year (Rignot *et al.*, 2008; Jason Box, *Personal Communication*). Taking 400 Gt as the mean 1971-1988 \dot{B} (Rignot *et al.*, 2008; Jason Box, *Personal Communication*), we derived the following relationship that is equivalent to (3.1):

$$(3.2) \quad \dot{B} - Q = \Delta\dot{B} * 1.655 - 80$$

where $\Delta\dot{B}$ was the difference between the total ice sheet surface mass balance for a particular year and the total surface mass balance average for the years 1971-1988. To achieve simulated discharge comparable to those predicted by the above equations, we enhanced the UBCGISM to respond to variations in local surface mass balance (see APPENDIX C). Grid cells containing calving fronts and neighboring cells upstream from these fronts were affected.

Development was achieved in two ways: (1) discharge of calving cells was fixed to respond linearly to local surface mass balance anomalies and (2) the basal velocities of grid cells within 60 km of a calving outlet were enhanced in response to calving velocity changes forced by (1).

Calving

The UBCGISM calving algorithm was after Nick and Oerlemans [2006], where calving flux was directly related to ice thickness, ocean water depth, and a constant calving factor (see APPENDIX C). The new algorithm enhanced calving at the fronts by:

$$(3.3) \quad \dot{d}_{enh} = C_{\mu} * \mu * \Delta\dot{b} * (\rho_{water}/\rho_{ice}) + \beta$$

where \dot{d}_{enh} was the enhancement and $\Delta\dot{b}$ was the grid cell surface mass balance anomaly from the 1971-1988 mean. The value $\Delta\dot{b}$ was in meters of water equivalent thickness and \dot{d}_{enh} was in meters of ice thickness. The parameters μ and β were used to tune \dot{d}_{enh} and consequently, total ice sheet discharge. The parameter C_{μ} was a regional scaling factor.

Because not all outlets respond in the same fashion or with the same sensitivity to surface mass balance changes, μ was scaled regionally by the parameter C_{μ} . To estimate outlet sensitivity, we used correlations between estimates of basin-wide surface mass balance and basin discharge derived by Lei Yang and provided by Jason Box (Rignot *et al.*, 2008; Box *et al.*, 2009; Jason Box, *Personal Communication*; Lei Yang, *Personal Communication*). We scaled the magnitude of C_{μ} according to regional significance between outlet discharge and basin-wide surface mass balance. In regions with insignificant correlations, C_{μ} was set to zero.

Basal Velocities

Directly upstream from calving fronts, we enhanced basal velocities in response to the calculated changes in calving (see APPENDIX C). At the calving front, we set the basal velocity increment equal to the calving velocity equivalent of \dot{d}_{enh} . The calving velocity represented the rate at which the calving front would retreat solely in response to a discharge of \dot{d}_{enh} . The basal velocity increments propagated upstream and decreased proportionally to the

distance removed from the calving front. The radius of influence for this effect was 60 km, so no enhancement occurred beyond that distance upstream.

Tuning

We forced surface mass balance and accumulation for each individual year, 1958-2007, upon the IC-7188. The years 1964, 1992, 1996, 2000, and 2004-2007 were singled out since they were observational years used to derive equation (3.1) (*Rignot et al.*, 2008). With this subset of years, our goal was, after one single year of forcing, to simulate the relationship expressed by equation (3.2). To do so, we tuned the parameters μ and β . We also investigated how results from all 50 years of forcing compare, in an attempt to assess the temporal universality of equation (3.2).

Results

Steady-State Ice Sheet

Profile

The steady-state ice sheet topography and ice thickness resulting from 250,000 years of average 1971-1988 surface forcing are shown in Figure 3.1A and Figure 3.1B, respectively. We include observed Greenland Ice Sheet topography (Figure 3.1B) for comparison. Our steady-state ice sheet had an area that was 16.5%, and a volume that was 12.5% larger than observed. Figure 3.1D compares the simulated and observed topographies. The mean misfit over the area of the ice sheet was around 100 meters. The main source of misfit was located in the lower elevation of the ice sheet. While the simulated ice sheet was a good fit above 1500 meters, it was clearly too thick in some areas, especially between 500 and 1000 meters.

Discharge

Table 3.1 lists seven of the largest outlet glaciers, with respect to ice flux, on the Greenland Ice Sheet. For comparison, it includes the observed flux rates of each outlet as well as their simulated steady-state flux rates. The simulation overestimated three out of the seven outlets while it underestimated the rest. Because the simulated ice sheet was in steady-state, one should not expect the outlet fluxes to match exactly. However, we took the magnitudes of these seven glacier fluxes into consideration when tuning the UBCGISM's flow parameters.

Calving Enhancement

We present the results of the UBCGISM calving enhancement in Figure 3.2A and Figure 3.2B. These figures represent yearly total mass balance (or the difference between total surface mass balance and discharge, $\dot{B} - Q$) as a function of surface mass balance anomaly ($\Delta\dot{B}$). Results of one year runs for years 1964, 1992, 1996, 2000, and 2004-2007 are plotted in Figure 3.2A. Here, we compare the enhanced version of the UBCGISM (squares), the non-enhanced version of the UBCGISM (stars), and values predicted by equation (3.2) (circles). The solid line represents the best fit line through the calving-enhanced results ($R^2=.96$). This line closely

resembles equation (3.2) and marks a distinct improvement over the non-enhanced model simulations.

For comparison, we plot results from the one-year-long (squares) and ten-year-long (triangle) runs for all 50 years of input (Figure 3.2B). Values are in Gt of average total mass balance per year. The best fit line through the one year runs (solid) has a slope of 1.5 while the best fit line through ten year runs (dashed) has a slope of 1.37. Both are less steep than the slope of 1.65 predicted by equation (3.2).

Discussion

The UBCGISM, like many other Greenland Ice Sheet models, lacks the complete physics needed to model the observed dynamic response of Greenland's outlet glaciers to recent climate change. Our study took a phenomenological approach towards enhancing the model to simulate these responses. The ultimate goal of this experiment was to tune the UBCGISM so that it would discharge at a rate comparable to that predicted by equation (3.1) (*Rignot et al., 2008*).

Results suggest that we were successful in training the model to behave accordingly (Figure 3.2A). The enhanced model results represent a distinct improvement over the non-enhanced model results. Years of negative surface mass balance anomaly were affected more dramatically than those of positive surface mass balance anomaly. This result was not surprising since outlet glaciers with negative surface mass balance were expected to be more responsive due to additional sliding provided by basal drainage of increased surface melt within their catchments.

Inclusion of all years (1958-2007) into the analysis made little difference (Figure 3.2B), though the resulting slope was found to be less steep than that predicted by equation (3.2) (1.50 versus 1.65). This indicates that the handful years used to derivation equation (3.1) did not completely represent the variability of the last fifty years. It also suggests that equation (3.1) may slightly overestimate historic ice sheet dynamic response. However, our goal was to use this equation to predict future response to climate warming. In the last fifty years, Greenland's climate was significantly affected by natural climate modes such as the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). Since it is only in the last twenty years that the ice sheet's surface mass balance has become strongly related to Northern Hemisphere temperature trends (*Hanna et al., 2008*), mass balance from this century should be most telling of future ice sheet behavior. All but one year used to derive equation (3.1) occurred in the last twelve years, thus we expect this equation to sufficiently generalize Greenland's dynamic response to climate change. A linear relationship like equation (3.1) may not completely encompass the full variability of Greenland's dynamics, but our results suggest that it does do a decent job of characterizing how the ice sheet has responded to historical changes in surface mass balance.

In Figure 3.2B, we included results from runs lasting ten years for comparison with the single-year runs. The slope of the ten year line is less steep than the one year line, suggesting that after the first year of simulation, a negative feedback decreased the magnitude of ice sheet mass balance change. For warmer years, this feedback was most likely related to the loss of calving fronts, which would reduce total ice sheet discharge. A handful of years stand out as exceptions to this behavior. During four years in the early 1980's and in 1998, discharge increased in magnitude after the first year of simulation, indicating that a positive feedback affected the ice sheet's mass balance. This feedback was most likely caused by anomalously low

sea level surface mass balance in the southeast, a characteristic shared by all five years. A number of smaller outlet glaciers in the southeast were sensitive to the increased ablation and responded dramatically. These outlets did not suffer from loss of calving fronts and were able to accelerate throughout the first ten years of simulation. Even though they are outliers, these years give insight into how the calving enhanced ice sheet model may respond to future changes in surface mass balance. As melt increases along the margins, the glaciers of the southeast may be capable of sustaining high calving rates and continued acceleration.

Conclusion

The goal of this study was to train the UBCGISM to behave in accordance with equation (3.1), which describes a linear relationship between Greenland's total discharge and total surface mass balance. Equation (3.1) was recently developed using observational estimates of ice sheet total mass balance and high resolution surface mass balance maps derived from mesoscale model output (*Rignot et al., 2008*). We enhanced the model's calving algorithm such that outlet glacier discharge responded to local changes in surface mass balance and upstream, we adjusted glacier basal velocities accordingly.

The enhanced model successfully simulated the dynamic changes predicted by equation (3.1), and results represent a distinct improvement over the non-enhanced model results. In response to calving enhancement, outlet glaciers, particularly those in the southeast, were sensitive to marginal surface mass balance anomalies. Following the first simulation year, both positive and negative feedbacks played a part in determining outlet dynamic response. During the majority of experiments, the loss of calving fronts dominated and served as a negative feedback to counteracted increases in discharge. In other cases, however, anomalously low surface mass balance drove outlet glaciers to dynamically discharge at a significant rate and to accelerate. If this latter process were to dominate in the future as warming occurs along the ice sheet margins, the incorporation of calving enhancement into ice sheet models could considerably improve estimates of how Greenland would respond to climate change.

Acknowledgements

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Figures

Table 3.1:

Observed and simulated yearly upstream ice flux of seven of Greenland's major outlet glaciers. Satellite radar interferometry observations are from *Rignot and Kanagaratnam* [2006], measured in the year 1996 (except Rinks, measured in 2000).

Figure 3.1:

Steady-state (A) topography (m) and (C) ice thickness (m) of the Greenland Ice Sheet after 250,000 years of average 1971-1988 surface mass balance (\dot{B}) and accumulation (\dot{C}) forcing. (B) Observed topography (m) (*Ekholm, 1996*) and (D) Comparison between observed topography and the steady-state simulated ice sheet shown in (A).

Figure 3.2:

(A) The change in Greenland Ice Sheet mass after one year of forcing (1964, 1992, 1996, 2000, 2004-2007), as a function of the year's total surface mass balance anomaly from the 1971-1988 mean. Results from the calving-enhanced UBCGISM (*squares, solid line*) and the non-enhanced UBCGISM (*stars, dashed line*) are compared with values estimated from equation (3.2) (*circles*).

(B) The average yearly change in Greenland Ice Sheet mass after one year (*squares, solid line*) and ten years (*triangles, dashed line*) of forcing (1958-2007), as a function of the year's total surface mass balance anomaly from 1971-1988 mean ($\Delta\bar{B}$). Results are from the calving-enhanced UBCGISM and are compared with those estimated from equation (3.2) (*circles*).

TABLE 3.1:

Name	Observed Historic Flux (km ³ ice/year)	Simulated Steady State Flux (km ³ ice/year)
Petermann	12.2	7.5
Nioghalvfjærdsbrae	14.3	14.2
Zachariae I.	11.7	17.6
Kangerdlugssuaq	27.9	31.0
Helheim	26.2	21.4
Jakobshavn I.	27.0	28.2
Rinks	12.1	9.2

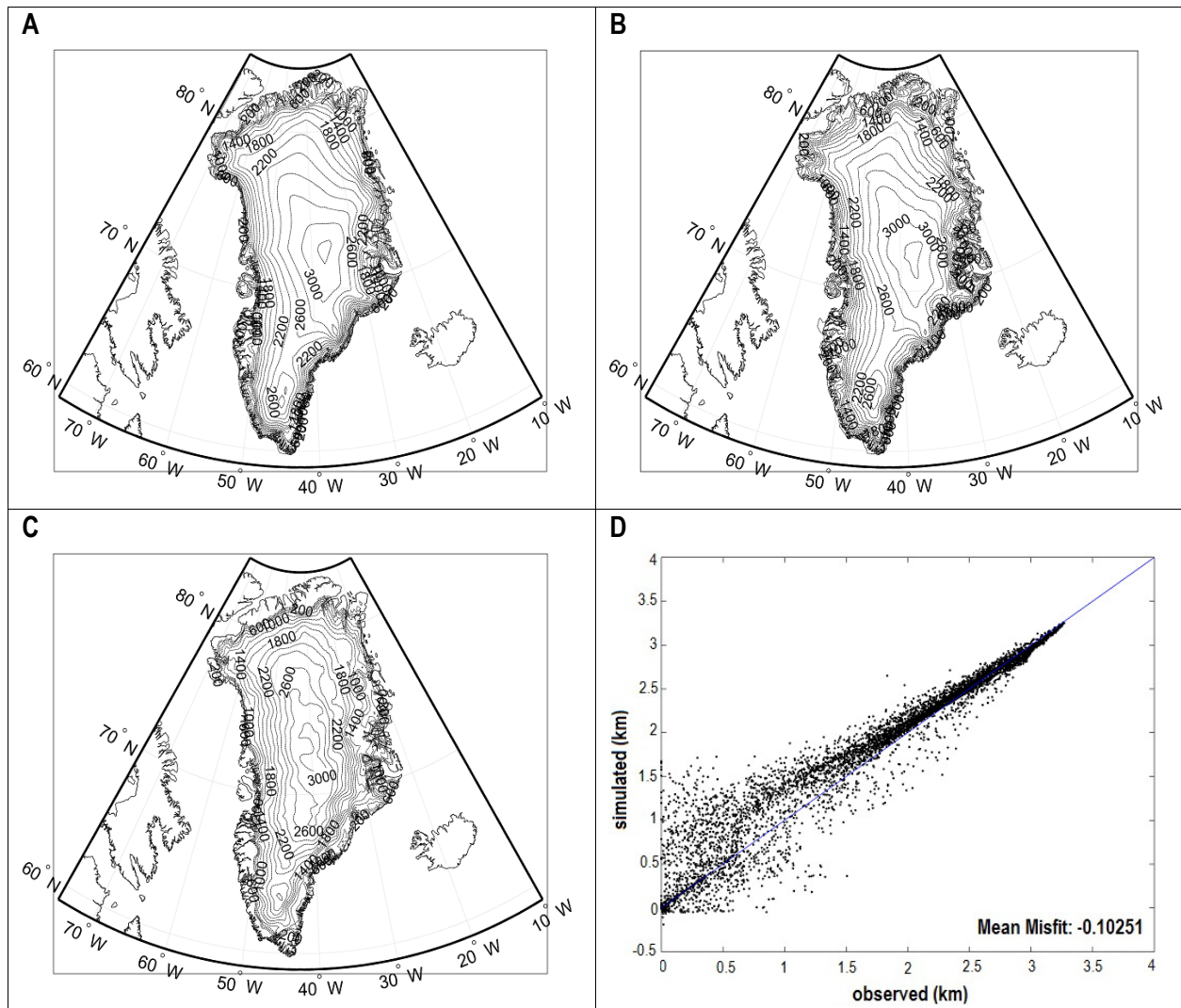
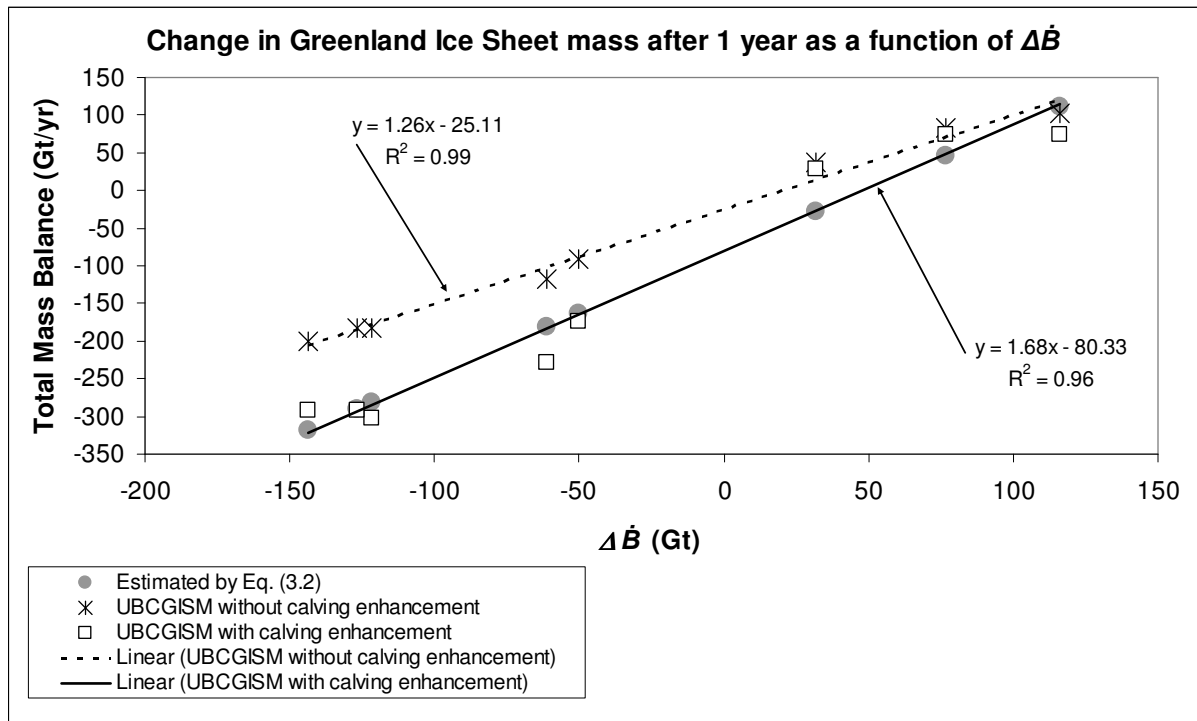
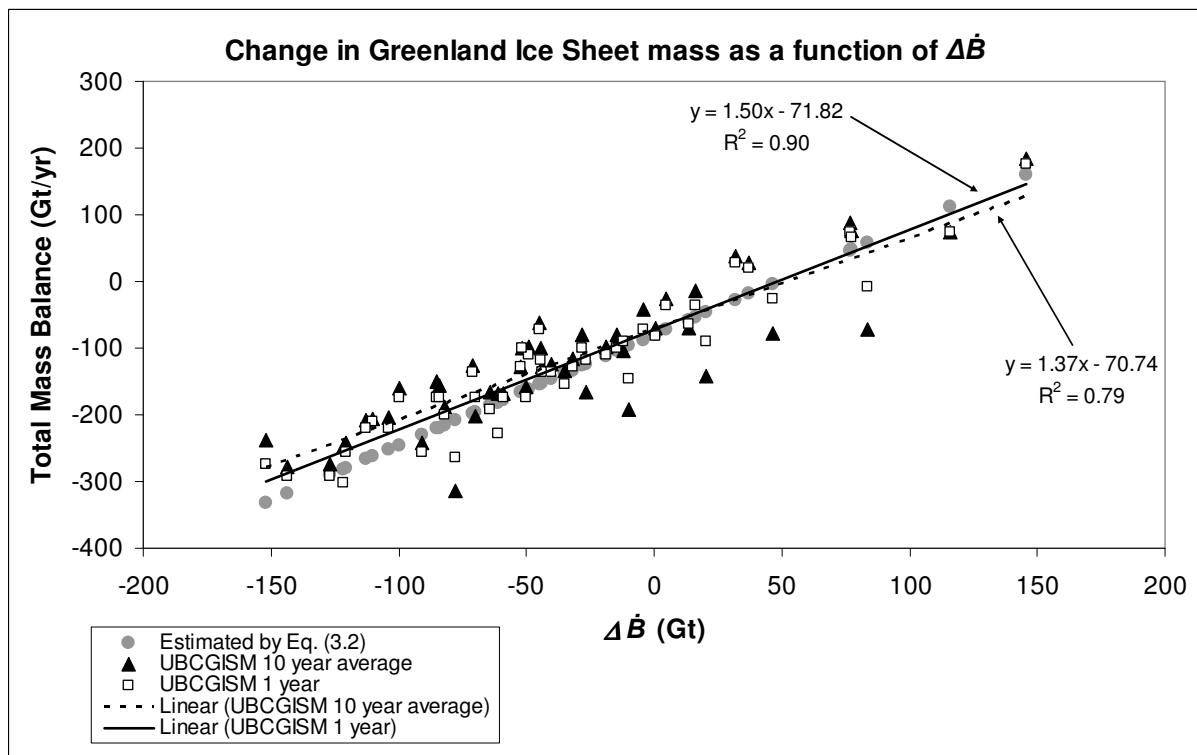
FIGURE 3.1:

FIGURE 3.2:**A****B**

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Appendix A

Surface Mass Balance Forcing

Positive Degree Days vs. Surface Mass Balance

Positive Degree Days

Originally, the University of British Columbia Greenland Ice Sheet Model (UBCGISM) calculated surface mass balance with a positive degree day (PDD) forcing scheme. At each grid cell, the model calculated the amount of yearly snowmelt (\dot{m}_{snow}) in the following manner:

$$(A.1) \quad \dot{m}_{snow} = \min(T_d * a_{snow}, \dot{c})$$

where T_d was the yearly positive degree days measured, a_{snow} was the positive degree day factor for snow, and \dot{c} was the local yearly accumulation. If $T_d * a_{snow}$ was less than or equal to the value of \dot{c} , then only snow was ablated. If $T_d * a_{snow}$ was greater than \dot{c} , then ice-melt (\dot{m}_{ice}) was calculated in the following way:

$$(A.2) \quad \dot{m}_{ice} = (T_d - \dot{m}_{snow}/a_{snow}) * a_{ice}$$

where a_{ice} was the positive degree day factor for ice. Here, T_d less the degree days already used to melt snow represented the degree days remaining to melt ice.

The model calculated total melt (\dot{m}), or ablation, as the sum of a grid cell's snowmelt and ice-melt:

$$(A.3) \quad \dot{m} = \dot{m}_{ice} + \dot{m}_{snow}$$

The model subsequently calculated the grid cell's local surface mass balance (\dot{b}) as the difference between the surface accumulation and melt.

$$(A.4) \quad \dot{b} = \dot{c} - \dot{m}$$

Direct Surface Mass Balance

In this study, we adopted a new surface mass balance scheme. The new scheme eliminated the need for the positive degree day calculations because model input was in units of surface mass balance instead of positive degree days. Since we applied surface mass balance directly, the model no longer needed to run the estimation algorithm described above.

Appendix B

Surface Forcing Methods

Initial Input

We chose high-resolution gridded surface mass balance, accumulation, and positive degree day (PDD) maps (*Box et al., 2006; Rignot et al., 2008; Burgess et al., 2010*) as input for the model's surface conditions. This input describes conditions that occurred on the surface of the present day ice sheet. In order to force the gridded input onto modeled topography (which differed from the observed), it was necessary to translate the maps using functions capable of projecting onto the model's evolving topography. Here, we describe the forcing method developed to do so.

Regions

In developing this method, our first step was to split the Greenland Ice Sheet into climatic regions. The twenty-nine different regions are depicted in Figure B.1. We chose these regions based on latitude, accumulation patterns, drainage basins, and location with respect to the ice divide. Each region was forced independently.

Regional Transects

For each region, we created three scatter plots (elevation vs. value): one for surface mass balance, one for accumulation, and one for positive degree days. We plotted only grid points associated with land-types containing glacial ice. We used the scatter plots to construct transects, relating parameter value to elevation, for every region and parameter. Figure B.2 is an example of a surface mass balance scatter plot (blue crosses) and resulting transect (red circles) for Region 20 during the years 1992 and 1998.

Transect elevations ranged from -499 meters to 3999 meters. We calculated transect values at intervals of 10 meters. (Note Figure B.2 depicts intervals at 50 meters.) At any given transect elevation, we set the transect value equal to the average of the n neighboring points closest in elevation. The value of n is dependent on the resolution of the parameter grid. For the 24 km x 24 km grid, n was equal to 10. For the 1.25 km x 1.25 km grid, n was equal to 200.

When calculating surface mass balance and PDD transects below 1000 meters in elevation, we used the n neighbors to linearly interpolate an alternative transect value. We set the final transect value equal to the minimum of the average value and the interpolated value.

Particularly in the steep regions of the southeastern ice sheet, very few parameter values were available below 100 meters in elevation. In these instances, we chose additional points below 100 meters from regions directly north of the region in question and included them in the scatter plots used for transect calculation (as discussed in CHAPTER 2, Methods).

Lookup Tables

For each parameter, we combined the 29 transects into a lookup table. A forcing table has 29 rows, one for each region, and 450 columns, one for each transect elevation. The ice sheet model read in these tables at startup. At each time step, the model utilized the lookup tables to determine surface parameter values at every grid point. First, the model extracted a grid point's region and elevation. In the row corresponding to the point's region, the model extracted transect values for elevations above and below the grid point elevation. Finally, the model calculated the transect gradient between the two elevations and used it to estimate a parameter value at the grid point's elevation.

This method allowed the ice sheet's surface conditions to evolve freely, with each region and altitude forced independently from one other. The model projected gridded input onto any ice surface, therefore establishing a feedback between climate and the simulated ice sheet topography (as discussed in CHAPTER 2, Methods).

Figures

Figure B.1:

Twenty-nine Greenland transect regions. For each region, we constructed a transect based on gridded maps of observed ice sheet elevation and surface mass balance, accumulation, or PDD. We combined the twenty-nine transects into a lookup table, which the UBCGISM used to translate a grid point's region and elevation into a parameter value.

Figure B.2:

Example surface mass balance scatter plot (*blue crosses*) and resulting transect (*red circles*) at a 50m interval for Region 20 during the years (A) 1992 and (B) 1998 for a 24 km x 24 km grid.

FIGURE B.1:

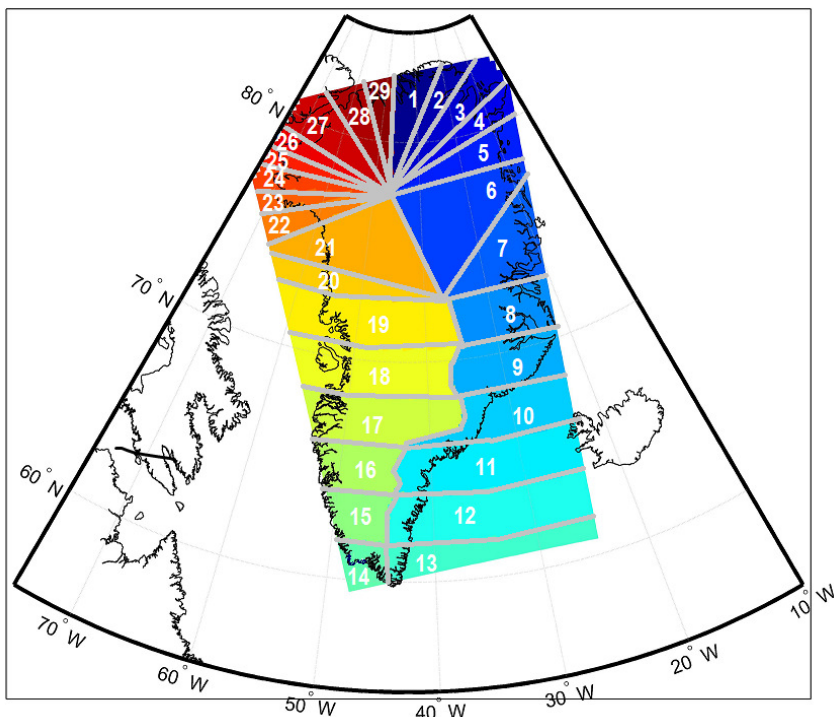
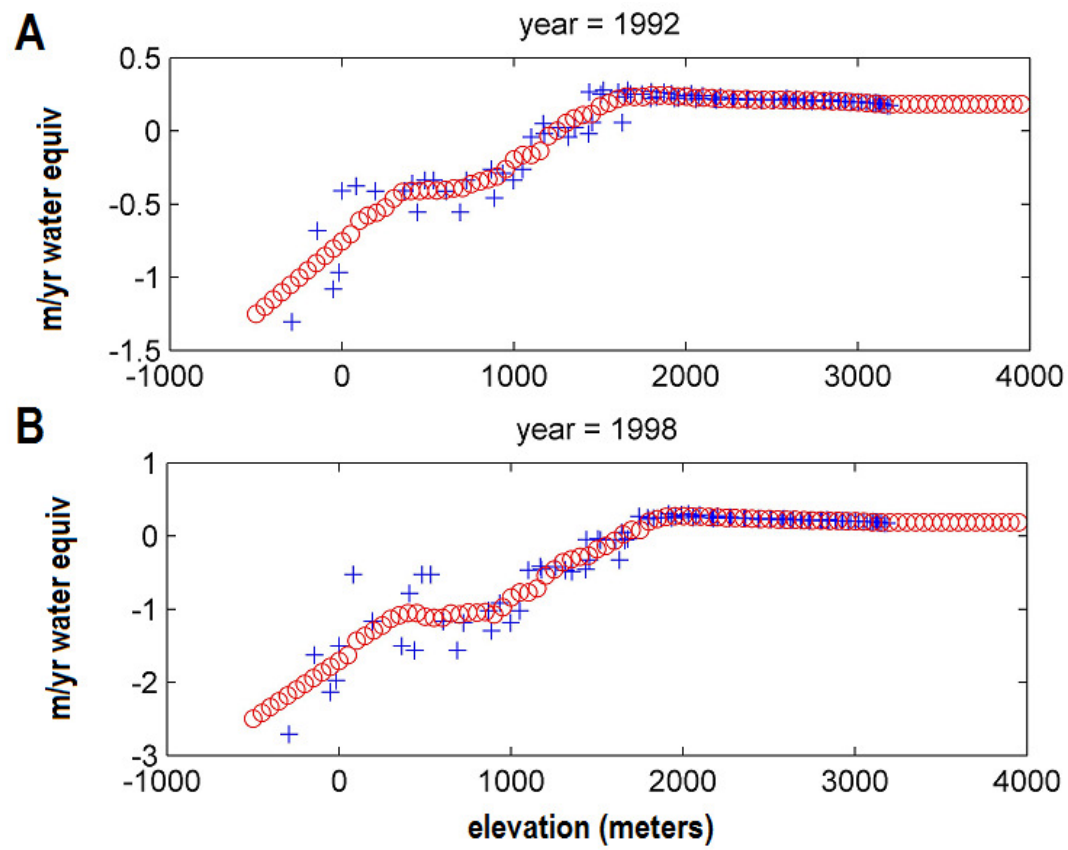


FIGURE B.2:

Appendix C

Calving Enhancement Treatment

Calving Algorithm

The UBCGISM calving algorithm was after the *Nick and Oerlemans* [2006] description of a minimal model for a tidal glacier. Our model calculated local calving flux as the product of ice thickness at the calving front (H_{ice}), ocean water depth (H_{ocean}) at the calving front, and a constant calving factor (C_d). Any border between ice and ocean was considered a calving front. In theory, a grid point could have up to four fronts, one in each direction. The calving rates were determined according to the following equations:

$$(C.1) \quad \dot{d}_N = (C_d * H_{ice} * H_{ocean}) * y_N$$

$$(C.2) \quad \dot{d}_S = (C_d * H_{ice} * H_{ocean}) * y_S$$

$$(C.3) \quad \dot{d}_E = (C_d * H_{ice} * H_{ocean}) * y_E$$

$$(C.4) \quad \dot{d}_W = (C_d * H_{ice} * H_{ocean}) * y_W$$

where \dot{d}_N was the calving rate to the north, y_N was the width of the northern calving front, and so on for each direction.

Nick and Oerlemans [2006] concluded that this simple model did an acceptable job in estimating the calving flux of a glacier that terminates in deep water and is affected by tidal currents. We assumed that this model adequately captured the behavior of Greenland's major outlets relative to each other. We believed this assumption was reasonable because (1) the steady-state flux values of major outlet glaciers were comparable to the observed (Table 3.1); and (2) the steady-state ice sheet did not unreasonably grow ice shelves.

Calving Enhancement

At active ice fronts, the new calving algorithm enhanced the calculated calving rate by a value \dot{d}_{enh} . The value of \dot{d}_{enh} , or calving enhancement, was calculated according to the following equation:

$$(C.5) \quad \dot{d}_{enh} = C_\mu * \mu * \Delta b * (\rho_{water} / \rho_{ice}) + \beta$$

where Δb was the grid cell surface mass balance anomaly from the 1971-1988 mean. The parameters μ and β were used to tune \dot{d}_{enh} and consequently, total ice sheet discharge. The parameter C_μ was a regional scaling factor for μ . The total local calving rate (\dot{d}) was set to the

sum of the original calculated calving rates in each direction and the enhanced calving rate where:

$$(C.6) \quad \dot{d} = (\dot{d}_N + \dot{d}_S + \dot{d}_E + \dot{d}_W) + \dot{d}_{enh}$$

Not all outlets respond in the same fashion or with the same sensitivity to surface mass balance changes, thus we scaled μ regionally, with use of the parameter C_μ . To estimate outlet sensitivity, we used correlations between estimates of basin-wide surface mass balance and basin discharge derived by Lei Yang and provided by Jason Box (*Rignot et al., 2008; Box et al., 2009; Jason Box, Personal Communication; Lei Yang, Personal Communication*). Each climatic region (see APPENDIX B) had a different value for C_μ , ranging from 0 to 0.55. We scaled the magnitude of C_μ according to regional significance between outlet discharge and basin-wide surface mass balance. The parameter C_μ had a value of zero in regions with insignificant correlations.

Calving Velocity

Directly upstream from calving fronts, we enhanced basal velocities in response to \dot{d}_{enh} . At the calving front, we set the basal velocity increment equal to the calving velocity (u_d) equivalent of \dot{d}_{enh} . The calving velocity represented the rate at which the calving front would retreat solely in response to a discharge of \dot{d}_{enh} . It was calculated in the following way:

$$(C.7) \quad u_d = (\dot{d}_{enh} * A) / (H_{ice} * y)$$

where A was the area of the calving grid cell, H_{ice} was the ice thickness directly upstream, and y was the calving cell's width.

At the base of the calving cell, we incremented the velocity by the total magnitude of u_d , such that the resulting velocity at the base of the ice sheet (u_{ice}) was determined by the following equation:

$$(C.8) \quad u_{ice} = u_d + u_b$$

where u_b was equal to the calving cell's basal velocity prior to calving velocity enhancement. The basal velocity increments propagated upstream to a distance of 60 km. No enhancement occurred beyond this distance upstream. For each cell upstream, we decreased u_d proportionally to the distance it was removed from the calving front, such that u_d was equal $\frac{1}{2} * u_d$ at 30 km upstream and zero beyond a distance of 60 km.

Tuning Results

We tuned the values of the parameters μ and β until the total simulated discharges matched those predicted by the observation-based relationship between surface mass balance and discharge (as discussed in CHAPTER 3) (*Rignot et al., 2008; Jason Box, Personal Communication*). The resulting value for μ was 13 and the resulting value for β was 1.8 m/yr.