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Climate Investigations Using Ice Sheet and Mass Balance Models with Emphasis on North American Glaciation

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CLIMATE INVESTIGATIONS USING ICE SHEET AND MASS BALANCE MODELS WITH EMPHASIS ON NORTH AMERICAN GLACIATION

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CLIMATE INVESTIGATIONS USING ICE SHEET AND MASS BALANCE MODELS WITH EMPHASIS ON NORTH AMERICAN GLACIATION

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Thesis Advisor: Dr. Peter O. Koons

An Abstract of the Dissertation Presented
in Partial Fulfillment of the Requirements for the
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This dissertation describes the application of the University of Maine Ice Sheet Model (UM-ISM) and Environmental Change Model (UM-ECM) to understanding mechanisms of ice-sheet/climate integration during ice ages. The UM-ECM, written by the author for this research, calculates equilibrium biome and snow/ice mass balance solutions for the globe based on modern input climatology and user-defined parameter values. The program was produced in conjunction with a National Science Foundation ITEST grant meant to seed inquiry-based classroom study of Earth systems using computer models. To that end, the UM-ECM serves as both a research and teaching tool. The model has a web-based interface, which has been tested with a group of middle school science teachers with a focus on local to global-scale climate learning.

Initially, the UM-ISM and UM-ECM are used to reconstruct the former ice cap of the Wind River Mountains, Wyoming, in a companion study to a UMaine field research effort to document worldwide glacier recession during the last termination. It is found that the ice cap likely formed in response to a 5-6 °C cooling in conjunction with a precipitation doubling relative to modern conditions. Moreover, the maximum ice cap could have disappeared within 90 years if subjected to modern climate conditions. These results support hypotheses that the western U.S. became wetter during glacial stadials due to a southward-shifted North American storm track in response to Laurentide Ice Sheet orography, and that ice caps of the western U.S. are exceptionally sensitivity to climatic perturbation.

The UMaine ice sheet and climate models are then used to assess the coupling between the Laurentide Ice Sheet and climate during ice-age cycles. It is shown that the classic "sawtooth" pattern of global sea-level change can be reproduced in the model by linking size of the polar atmospheric cell over eastern Canada to size of the Laurentide Ice Sheet and the magnitude of insolation forcing. Model results also show that mechanical collapse of the Laurentide Ice Sheet is a requisite for the deglaciation of North America. In the absence of this collapse, and with consideration of orography feedbacks, Canada would remain glaciated throughout Holocene with an ice sheet large enough to lower global sea level 15-40 m. These results support a hypothesis that feedbacks inherent to the Laurentide Ice Sheet drive much of the global ice-age signal.

ACKNOWLEDGEMENTS

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I would like to thank my dissertation advisors for their insights and thoughtful criticisms. Special thanks goes to my advisor, Dr. Peter Koons, whose enthusiasm, persistent questions, and confidence in my abilities have shaped this research in profound ways. I also thank Dr. James Fastook who wrote the ice sheet model that I have now used for several years. Without his model and extensive help, this research would not have been possible. I would also like to thank Dr. Bruce Segee and Dr. Yifeng Zhu for their assistance developing the University of Maine Environmental Change Model. I also extend my deepest gratitude to my dissertation committee co-chair Dr. George Denton. Without George, I would not have become interested in the problem of ice ages, and I would not be the person who I am today.

Last, but not least, I would like to thank my mom and dad, who over the years have seen me through this long endeavor. I especially thank my wife, Kristine, for her patience and loving support as I worked seemingly without end on my dissertation. To our little boy Logan: Having finished this, I can now spend more time with you and mother!

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 General Statement

The origin of this dissertation is a glaciological inquiry into the Laurentide Ice Sheet and its coupling to the climate system through feedback mechanisms. In order to examine this problem, it was necessary to modify the existing University of Maine Ice Sheet Model (UM-ISM) (e.g., Fastook and Prentice, 1994) to recognize an insolation-based mass-balance formulation that included a feedback between Laurentide orography and deepness of the atmospheric cold trough over eastern Canada.

Code changes that I made to the ice sheet model spurred the development of a secondary program through which new input bedrock topography and climatology grids for the UM-ISM could be generated. Around the same time, my dissertation funding source shifted to a National Science Foundation ITEST grant (see description in Chapter 1.1.2) that sought to seed earth science inquiry-based learning using computer models. In response, I combined my paleoclimate research goals with those of ITEST to produce the University of Maine Environmental Change Model (UM-ECM). The UM-ECM is a simple climate model that generates equilibrium biome and snow/ice mass balance solutions based on user-defined parameter departures from modern climatology. The model can also generate input fields for UM-ISM. A particularly useful aspect of the UM-ECM is that it is operative at resolutions limited only by available input topography and climatology (which is ~1 km or finer for the entire globe). Thanks to the help of

several undergraduates, the UM-ECM has been ported from its original MATLAB code to C, and the program is now available online through an HTTP/PHP-based web framework.

The exceptional high-resolution capability of the UM-ECM afforded a means to revisit the problem of North American glaciation, at a small scale as opposed to continental. It was in this vein that I then sought to model the Pleistocene Wind River Ice Cap in west-central Wyoming. The Wind River modeling study emerged in part from a University of Maine field research effort to document the worldwide recession of mountain glaciers during the last termination using the ^{10}Be surface exposure-age dating method (e.g., Putnam et al. in press). My role in the project was to conduct a sensitivity analysis on the ice cap response to climate. Prior to building the UM-ECM, there was no easy way of importing bedrock or climatology grids at a high resolution suitable for mountain-range scale glaciological problems. The model was more or less restricted to 2-minute elevation data from ETOPO1, and climatology schemes either undocumented, or based on 2.5 x 2.5 degree NCEP reanalysis grids. Using the UM-ECM, I was able to reconstruct the Wind River Ice Cap formation, maintenance, and deglaciation at 0.8 km resolution in supplement to my analysis of the large-scale evolution of the Laurentide Ice Sheet.

Thus, my dissertation has evolved from a study of Laurentide Ice Sheet reconstruction, to one that now also includes significant expansion of UM-ISM functionality, the

development of the UM-ECM as a research and teaching tool, and a simulation of ice cap glaciation over the Wind River Mountains.

1.2 Detailed Problem Description and Chapter Arrangement

Climate research increasingly demands usage of high-resolution models capable of producing solutions for local-global problem domains. This dissertation is the description of two such models developed at the University of Maine, and their application to ice-age climate reconstruction. The first model utilized here is the University of Maine Ice Sheet Model (UM-ISM), an existing program that has been under continual development for more than two decades (Fastook, 1993; Fastook and Prentice, 1994; Kleman et al., 2002). The UM-ISM is a time-dependent finite element solution of the mass continuity equation of ice flow, which is used to model the behavior of ice sheets. The second model is the University of Maine Environmental Change Model (UM-ECM), a new program written by the author to facilitate high-resolution (up to 1 km) equilibrium climate simulations. The UM-ECM calculates local-global biome and snow/ice mass balance distribution from modern climatology grids and user-defined parameter values.

In Chapter 2 of this dissertation, I provide a detailed description of the UM-ECM and its global high-resolution capability. The UM-ECM development was funded by a National Science Foundation grant for the ITEST[1]/IDEAS[2] program. The purpose of this program

[1] Innovative Technology Experiences for Students and Teachers.

is to bring supercomputing technology into science classrooms for inquiry-based climate education. Thus, in my description of the UM-ECM, I emphasize the model as an educational tool, and provide examples of how it can be used in a classroom setting to examine past and modern climate. I then discuss how the UM-ECM can be linked to the UM-ISM. In short, the UM-ECM provides mass-balance and bedrock topography input needed in order for the UM-ISM to generate paleo ice sheets.

In Chapter 3, I use the UM-ISM and the UM-ECM to examine the evolution of a Pleistocene ice cap that formed over the Wind River Mountains ("Wind Rivers") in west-central Wyoming, U.S.A. This modeling exercise is companion to a University of Maine research effort to document worldwide glacier recession during the last termination using ^{10}Be surface-exposure age dating on moraine deposits (Putnam et al. in press)[3]. For my role in the project, and in the context of this dissertation, I determine the probable climate conditions that supported the Wind River Ice Cap during the Pinedale and Bull Lake glaciations. Furthermore, I examine how quickly the ice cap might have retreated during the last termination.

In Chapter 4, I use the UMaine ice sheet and climate models to explore the large-scale problem of North American glaciation, and how feedbacks inherent to the Laurentide Ice Sheet may drive much of the known global ice-age climate signal. These feedbacks are the expansion and contraction of the polar atmospheric cell in response to insolation

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[2] Inquiry-based Dynamic Earth Applications of Supercomputing.
[3] I was a member of the field team who collected boulder samples in the Wind Rivers during the summers of 2008 and 2009. UMaine graduate student Aaron Putnam is undertaking sample analysis in the lab as part of his doctoral dissertation.

forcing, albedo, and ice sheet orography, and the mechanical collapse of marine-based ice over regions of severe isostatic depression. In my analysis, I model the last full glaciation cycle, and demonstrate how the Laurentide Ice Sheet could have survived throughout the Holocene had it not disintegrated from a marine instability mechanism during the last termination.

In the fifth and final chapter of this dissertation, I summarize the major findings of chapters 2-4, and suggest avenues of future work.

CHAPTER 2: CLIMATE INQUIRY WITH THE UNIVERSITY OF MAINE ENVIRONMENTAL CHANGE MODEL

2.1 Introduction

Increasing political and media attention on climate change underscores the importance for students to gain an understanding of how the global climate system works. In order to facilitate this learning, high-quality climate and environmental datasets must be easily accessible, and there must be robust means for dataset visualization, interrogation, and inquiry.

I have sought to address this need by developing the web-based University of Maine Environmental Change Model (UM-ECM) (see http://ecm.um.maine.edu). The UM-ECM uses existing climatology to calculate biome distribution, annual snow mass-balance, and other environmental conditions based on user input parameters. The model is operative at a spatial resolution of 1 km over the entire globe, and solutions may be viewed through either the UM-ECM web framework, or in Google Earth™ (Figure 2.1). The UM-ECM is also interfaced with the University of Maine Ice Sheet Model (UM-ISM) (Appendix A) in order to provide topographic and climatology input grids (e.g., Chapters 3 and 4 of this dissertation). These features together make the UM-ECM a powerful research and educational tool for examining climatic datasets in extraordinary detail.

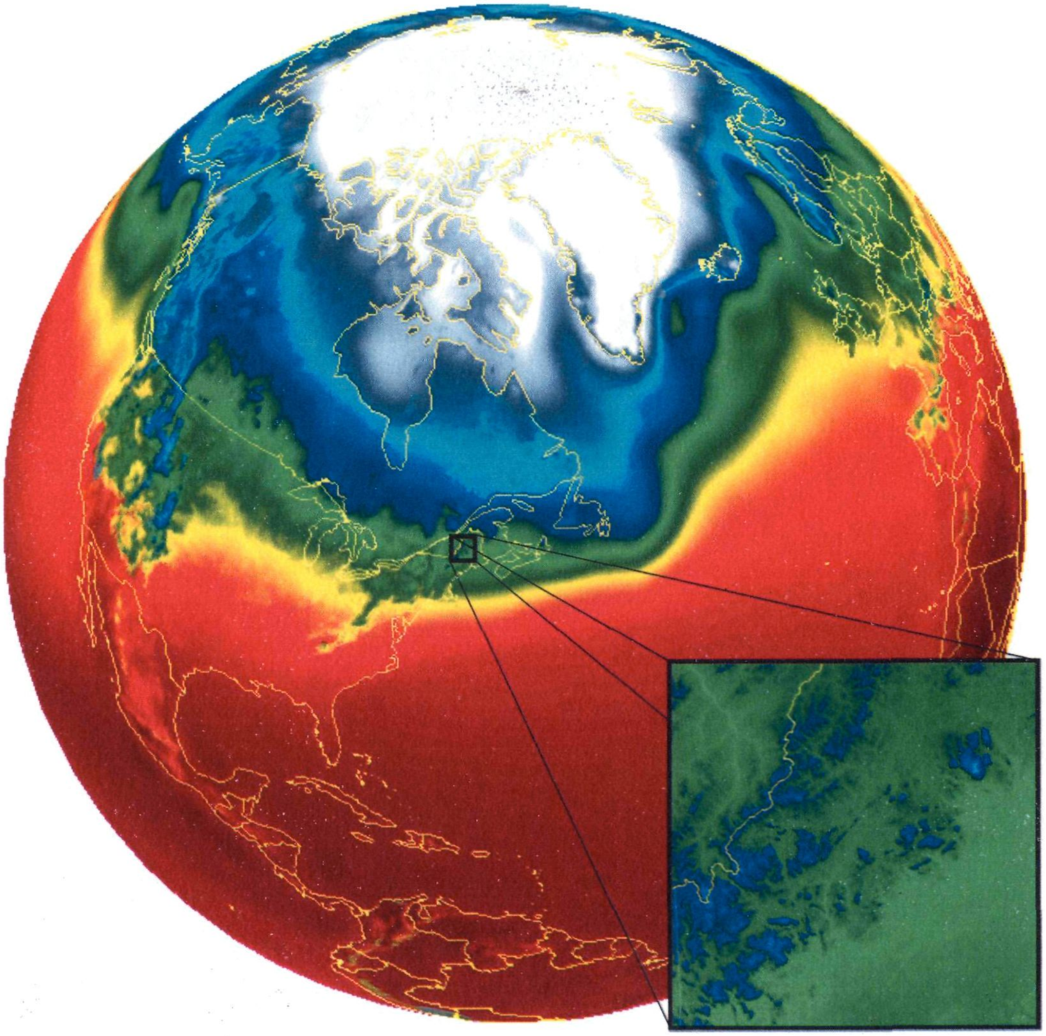


Figure 2.1. ECM output imaged in Google Earth™. The inset shows a detail of Maine in which individual mountains and valleys are resolved. The Google Earth™ background and controls have been removed for figure simplicity.

Described in brief in Chapter 1, the UM-ECM was designed as part of IDEAS, a University of Maine inquiry-based science technology program funded through a National Science Foundation ITEST grant. IDEAS draws U. Maine researchers together with middle school teachers and students in an effort to utilize computer modeling and visualization of earth science processes in the classroom. One aspect of IDEAS is to investigate how small climate perturbations can lead to big environmental changes. For example, how would the distribution of biomes across the globe be affected by a 1 °C increase in average surface temperature? A second IDEAS goal is to have students link global and local-scale changes in a meaningful way. In that vein, the question of global response to climatic warming is supplemented by that of local response. How might the natural environment of a student's home state or town change over time?

Although the UM-ECM itself is the basic IDEAS framework for answering these questions, the learning experience is enhanced greatly by utilizing a display "Wall". That is, an assemblage of up to 25 computer displays (5x5 array) constituting an ultra-high resolution viewport. In such a setup, students can image a broad geographic region preserving detail fine enough to also make local observations. It is noteworthy that, because of the Maine Laptop Initiative in which laptops are provided to all middle school students in the state (e.g., Silvernail and Lane, 2004), Maine classrooms are particularly well suited for this type of experimentation. Thus, the IDEAS group has the means of running the UM-ECM web utility at 1 km resolution with the output displayed across exceptionally high-resolution displays. The model output can also be displayed in Google Earth™ using this same networking ability.

2.2 The Environmental Change Model

The core of the UM-ECM is an integrated solver that computes snow mass-balance and equilibrium biome distribution from climatological mean-monthly temperature and precipitation input grids. Mass balance is found by adding frozen precipitation for the winter months, and then reducing this amount using a melt rate based on the total number of melting degrees (e.g., Braithwaite and Olesen, 1989) (Figure 2.2). Biomes are differentiated at each gridpoint on the basis of the temperature of the warmest month and total annual precipitation. The UM-ECM biome rubric includes fifteen zones calibrated using information from the USGS Gap Analysis Project (http://gapanalysis.nbii.gov) and the National Atlas of Canada 5th Edition (Figure 2.3). Climate change is effected in the model by specifying parameter values on the user interface. These parameters include temperature and precipitation anomalies, snow and ice melt rates, snow and ice densities, an atmospheric lapse rate, and a sea-ice growth rate. In all, the UM-ECM output includes biome distribution, snow and ice mass balance, snow depth, precipitation, temperature, melting and thawing degrees, and seasonality.

Input climatology datasets configured for use by the UM-ECM include WorldClim (Hijmans et al., 2005), PRISM (Daly et al., 1994), NCEP (Kalnay et al., 1996), and also a combination of the three. I have chosen multiple datasets in order to provide a range of probable climatology. Both WorldClim and PRISM are operative at 30 arcsecond resolution (~1 km), whereas NCEP is operative at a much lower resolution of 2.5

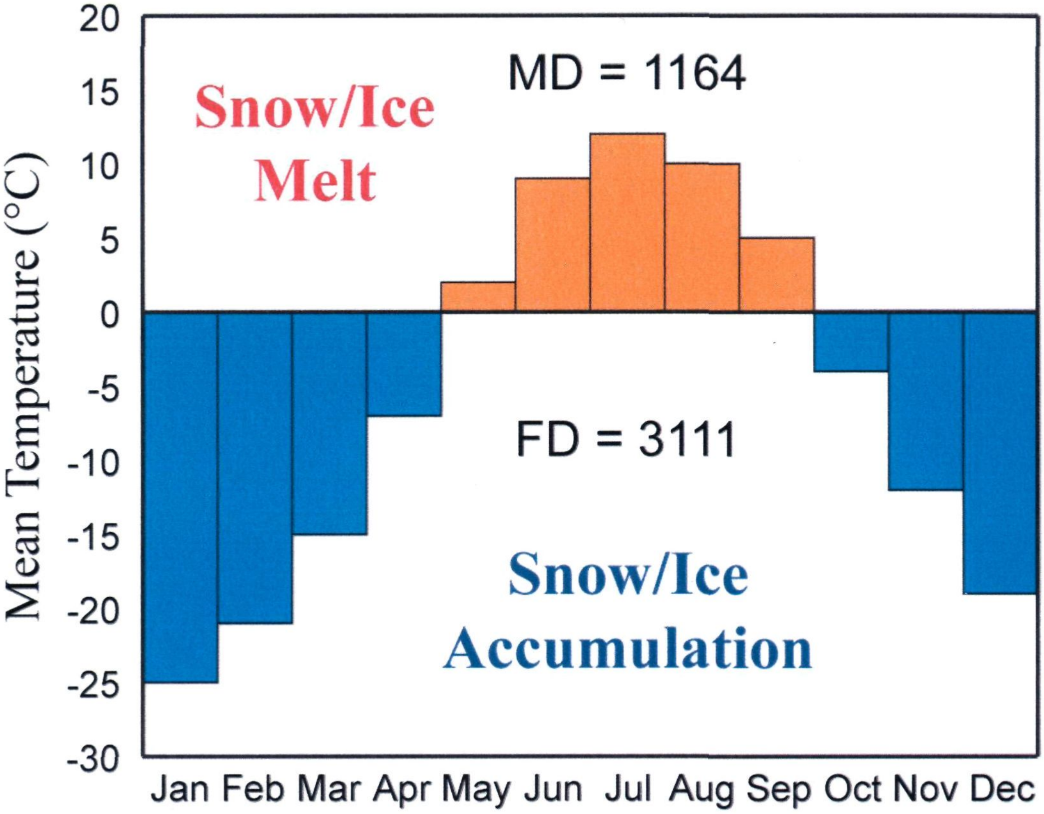


Figure 2.2. Schematic seasonal cycle used for calculating mass balance. First, the total number of melting and freezing degrees (labeled MD and FD, respectively) are found by summing the number of monthly positive and negative degrees, respectively. Second, frozen precipitation (not shown) is tallied based on whether or not the mean temperature of a given month is at or below freezing. Snow mass balance is then calculated by dividing the total snow amount (m water equiv.) by a user-changeable snow melt rate (m water equiv./MD). Freezing degrees are used in the model to calculate sea-ice thickness over cold ocean areas using a user-changeable growth rate. Mass-balance for this term is calculated in the same manner as for snow, but using an ice melt rate. Sea ice and snow mass-balance values are then added together to produce a combined total.

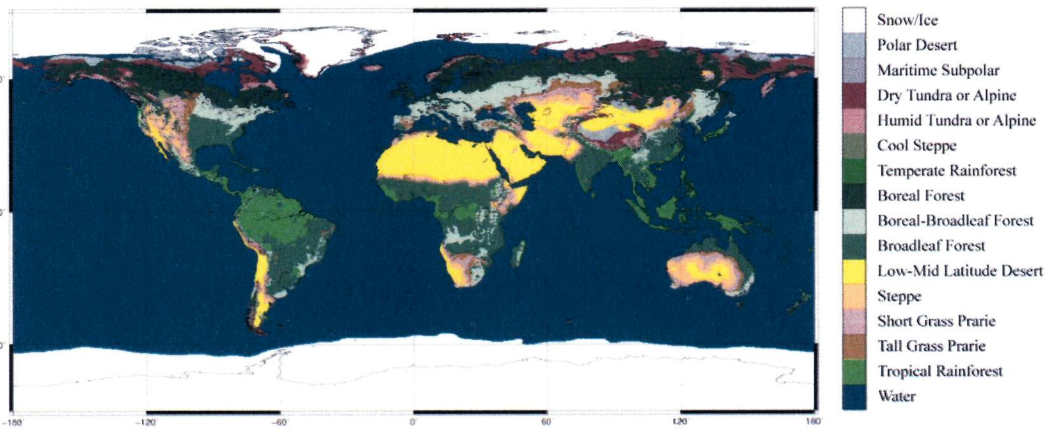


Figure 2.3. Calculated global distribution of biomes under modern climate.

degrees. The NCEP dataset is included for coverage over Antarctica and the world oceans, areas that are not part of either WorldClim or PRISM. The resolution disparity between datasets is addressed by resampling the NCEP grids using bicubic interpolation to 1 km. The temperature fields alone are then adjusted to topography at runtime using a surface-elevation differencing scheme and user defined vertical lapse rate. Topography information at native resolution is packaged with each climatology dataset. ETOPO1 topography (Amante and Eakins, 2009) is also included for NCEP scaling, and for displaying world ocean bathymetry.

2.3 Examples/Results

The UM-ECM was tested with a group of middle school science teachers at an ITEST/IDEAS seminar in August, 2010. After a brief overview of the model web interface, seminar participants made observations on the mean state of global climate. Most teachers noted significant latitudinal asymmetries in the parameter fields, particularly over the Northern Hemisphere. The group surmised that these complex temperature and precipitation patterns arise from atmospheric circulation. This led to a discussion on how land-sea contrasts, mountain orography, surface albedo, ocean currents, and ice sheets are major factors interwoven with mean climate (Figure 2.4).

In a second lesson block, seminar participants investigated the problem of ice ages over North America. From previous meetings, group members were familiar with the concept of ice sheets expanding and contracting over the continent on 100,000-year timescales.

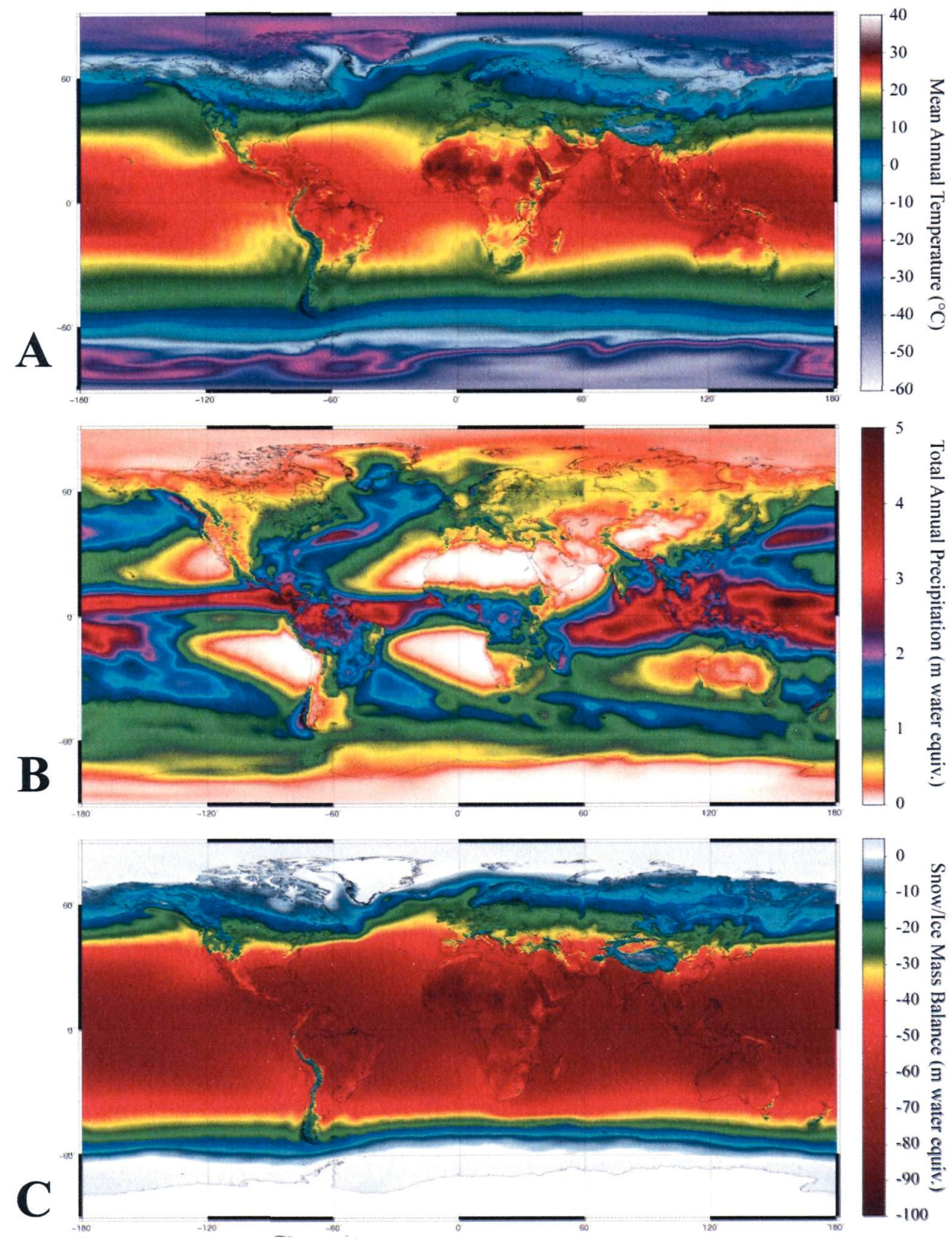


Figure 2.4. Sample UM-ECM input and output. A) Mean annual air temperature. B) Total annual precipitation. C) Snow/ice mass balance. Note that significant latitudinal asymmetries result from large-scale ocean and atmospheric circulation processes, and land-sea surface contrasts.

For this exercise, modern climate was compared with that of the last glacial maximum 15-20 thousand years ago. The group was asked to determine what amount of cooling would produce snow accumulation areas from which the Laurentide and Cordilleran ice sheets could develop. After running experiments in which the mean-annual temperature was dropped incrementally, seminar participants learned that no one single temperature anomaly solved the problem (Figure 2.5). Instead, it was found that the eastern and western halves of the continent needed to be cooled by different amounts. For example, a 6 °C cooling was necessary to produce snow accumulation over the west suitable for the Cordilleran Ice Sheet, whereas a 15 °C cooling was needed to produce sufficient accumulation over the east for the Laurentide Ice Sheet. Thus, there was a dramatic difference in glacial-age climate change from west to east across North America.

The ice-age problem highlights the nonlinear behavior of the climate system in response to changing boundary conditions. Climate scientists know that, in general, ice ages are driven by changes in Earth's orbital parameters (axial tilt, precession of the equinoxes, and eccentricity), which impart small changes in the distribution and intensity of incoming solar radiation across the globe (Hayes et al., 1976). Orbital changes alone cannot account for the dramatic climate shifts associated with ice-age cycles. Instead, massive ice sheets wax and wane from feedbacks in the climate system that amplify energy imbalances caused by orbital variations (Imbrie et al., 1993). Although a complete description is beyond the scope of this paper, among the most important feedbacks in the climate system are the ice sheets themselves. The asymmetrical climate cooling from west to east across North America relates to the atmospheric response to the

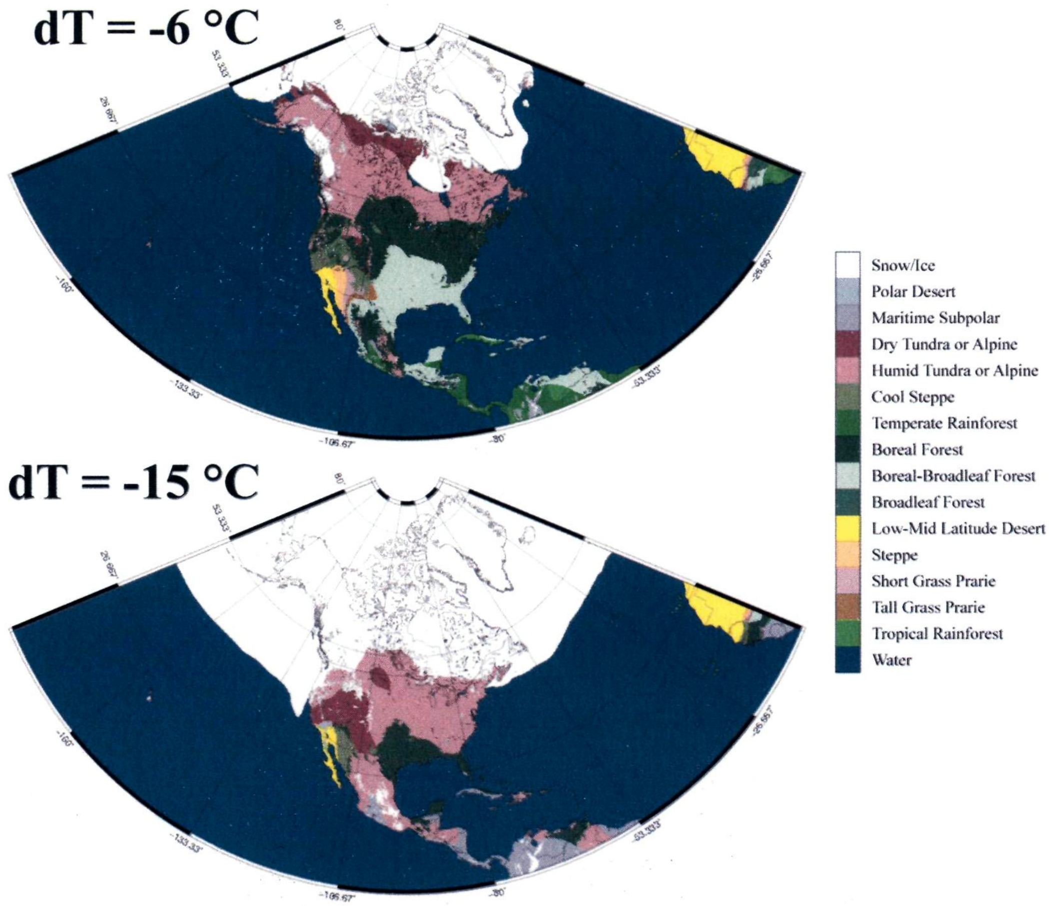


Figure 2.5. Equilibrium biome solutions for North America. Shown are experiments with temperature anomalies of -6 °C (top) and -15 °C (bottom).

orography of the Laurentide Ice Sheet (Ruddiman and Raymo, 1988; Chapter 4 this document) (Figure 2.6).

Having used the UM-ECM to investigate global and continental-scale climate change, the seminar group now shifted focus to a local-scale problem. We wanted to visualize historical and possible future environmental changes across Maine and adjacent areas. Although seminar participants examined several climate fields and made adjustments to multiple input parameters, here only one experiment suite is outlined. Namely, the group investigated changes in biome distribution for temperature anomalies of -1.5, 0, and +1.5 °C. These input parameters grossly characterize preindustrial, modern, and projected postindustrial climate. Figure 2.7 shows a significant northward and vertical shift of forest biomes in response to climatic warming. Particularly interesting is the replacement of tundra with boreal forest in parts of Nova Scotia, Quebec, and on mountaintops in New England (see Figure 2.8 for topography detail).

Finally, after completing global, regional, and local modeling exercises, seminar participants were split into groups in which they worked on developing their own UM-ECM-based climate curriculum for classroom use. During this time, the teachers were encouraged to view a 16-panel laptop display wall configured to cycle through several high-resolution UM-ECM solutions for various parts of the globe.

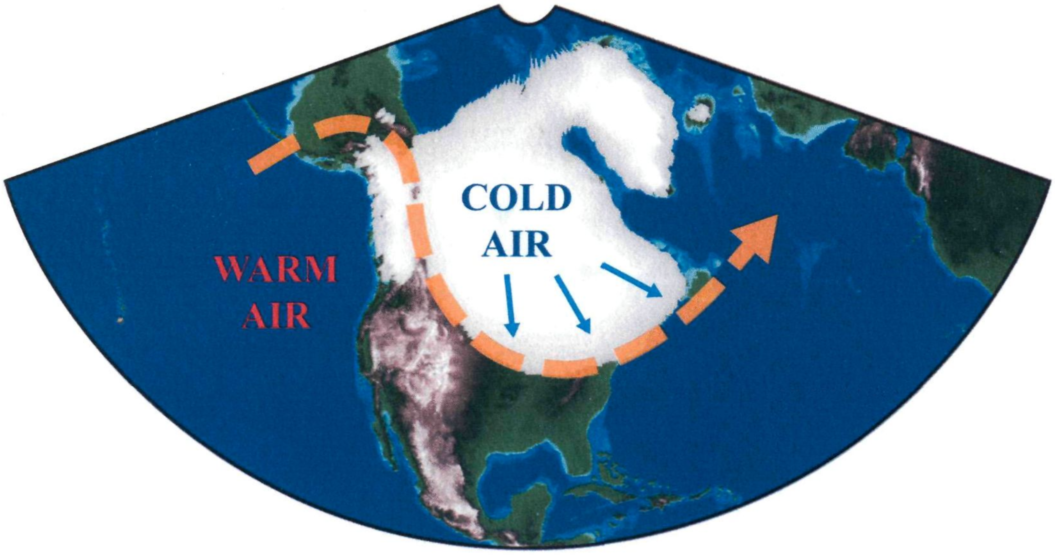


Figure 2.6. UM-ISM reconstruction of North American ice sheets ~20,000 years ago. The dashed orange curve represents the path of the jet stream. One nonlinear change in atmospheric circulation during ice ages is the deep southward displacement of cold air over eastern North America due to orographic forcing by the Laurentide Ice Sheet (indicated by light blue arrows). The ridge of warm air over the west is a feature common to both past and present climate, because it is forced mainly by land-sea contrasts and mountain topography.

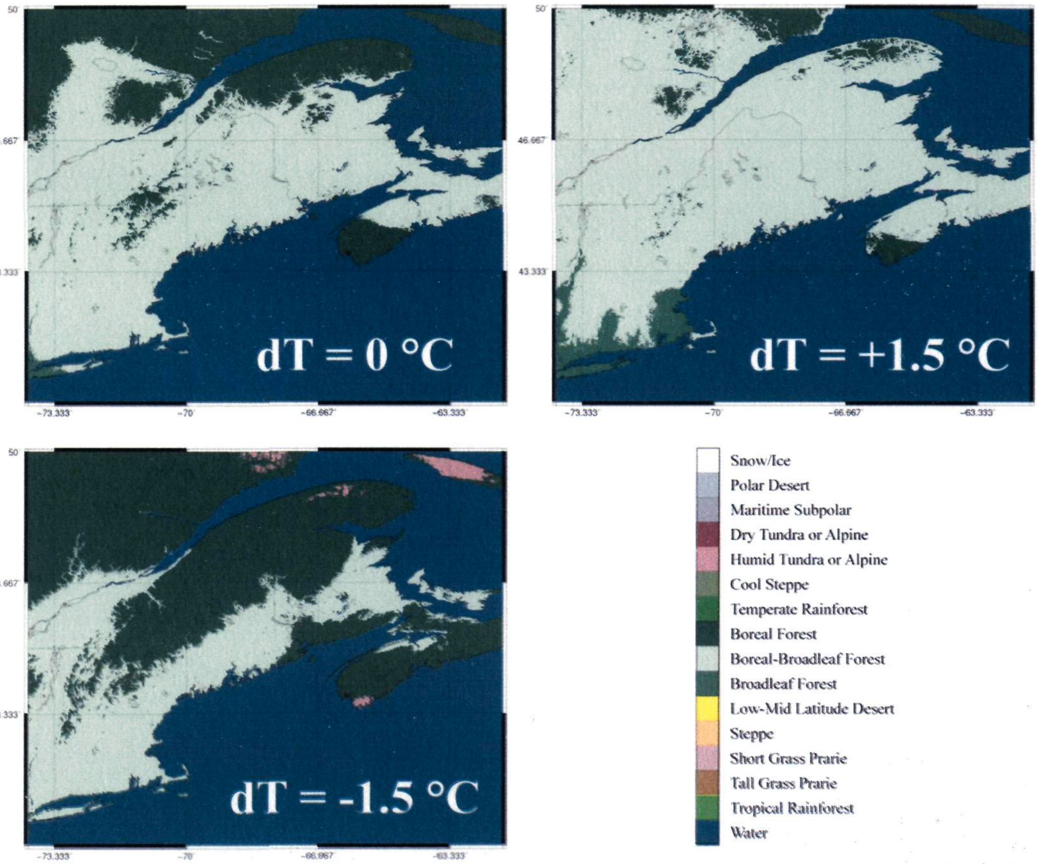


Figure 2.7. Local-scale equilibrium biome solutions. Shown is output for the northeastern U.S. and adjacent Canadian provinces. dT is the change in annual temperature relative to the modern climatological mean (dT = 0 °C). Note significant northward (and vertical) shift of forest biomes and the disappearance of tundra with increasing temperature.

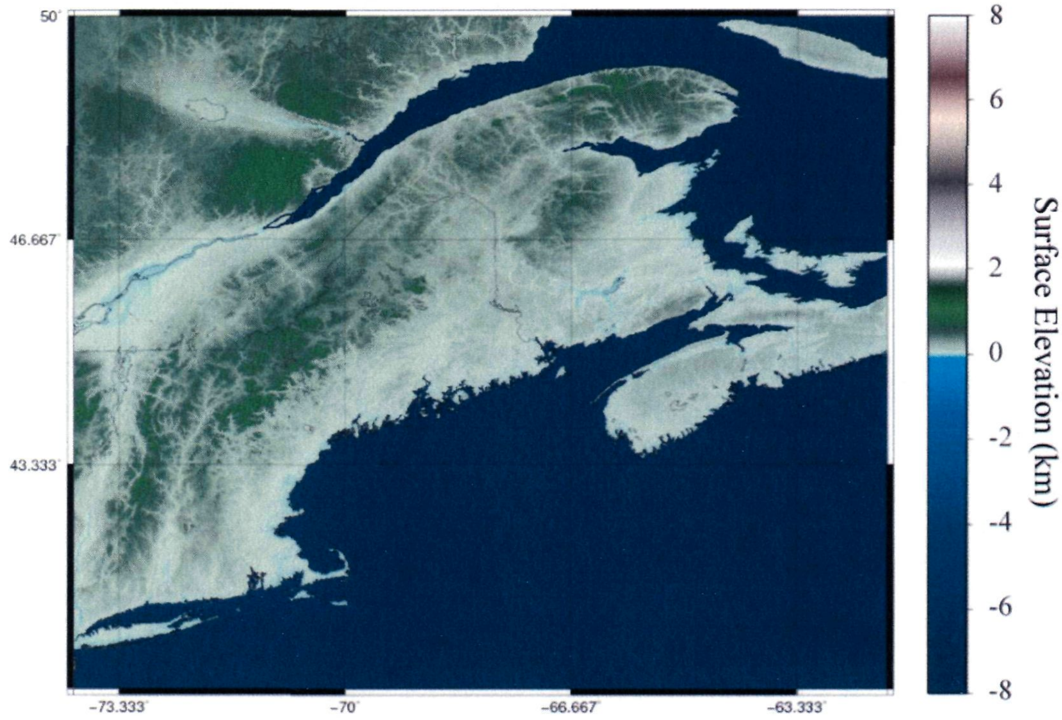


Figure 2.8. Surface elevation map for region shown in Figure 2.7.

2.4 Discussion

The UM-ECM is a flexible tool for examining major components of the global climate system. I have outlined how the model can be used over many spatial scales to investigate the ways in which temperature and precipitation changes can affect environmental conditions. It should be emphasized that the UM-ECM calculates linear differences from input climatology, and that the model itself has no provision for solving complex dynamical equations readily handled by general circulation models (GCMs). The mass balance solver, which produces only equilibrium solutions of net snow/ice accumulation and ablation, also should not be confused with a glacier flow model such as the UM-ISM.

Compared to GCMs, the UM-ECM holds significant advantages in terms of accessibility, speed, and resolution. GCMs most often run on supercomputers at resolutions measured in degrees. Global solutions can days or weeks to processes. In contrast, the UM-ECM is available by web browser at 1 km resolution and performs in seconds to minutes. Perhaps the most viable GCM for classroom use is EdGCM, a 3-degree global model adapted to run on a personal computer (Chandler et al., 2005).

At least two improvements could expand the functionality of the UM-ECM. First, past climates could be simulated with more realism by including general circulation model grids for the last glacial maximum. In this case, climate could be defined in the model as some fraction of modern and glacial end members depending upon user-input parameter

settings. This is opposed to past climate defined by linear departures from modern climatology. A second improvement to the UM-ECM could be made by incorporating topography and climatology for the last glacial cycle as predicted in UM-ISM simulations (e.g., Chapter 4 of this dissertation). In either case, this would afford an extraordinary means to examine environmental changes across the globe over different time and spatial scales.

2.5 Conclusions

- The UM-ECM generates high-resolution (up to 1 km) equilibrium climate simulations from existing climatology grids and user-defined parameter input. Primary model output is local-global biome distribution and snow/ice mass balance.

- Ability of the UM-ECM to operate at high resolution over local-global spatial scales makes the model well suited for inquiry-based exploratory exercises in classroom settings.

- The UM-ECM is available freely online, and solutions can be visualized either through the web interface, or in Google Earth™ using a KML-file output feature. The model impact can be enhanced by viewing solutions through a multi-monitor display wall, such as the type under development at the University of Maine as part of ITEST/IDEAS.

- Ongoing work will increase the educational breadth of the UM-ECM. The first improvement is to incorporate GCM solutions of the last glacial maximum, and the second is to integrate UM-ISM solutions for the last complete glacial cycle.

CHAPTER 3: GLACIOLOGICAL RECONSTRUCTION OF THE PLEISTOCENE WIND RIVER ICE CAP

3.1 Introduction

3.1.1 Purpose

The purpose of this analysis is to produce a glaciological reconstruction of the Pleistocene ice cap of the Wind River Range, Wyoming, and to test the sensitivity of that ice cap to several climate regimes. This modeling exercise is supplemental to a University of Maine field research program documenting worldwide glacier recession during the last termination (e.g., Putnam et al. in press). One additional benefit of this study is that it affords a test of the high-resolution capabilities of the University of Maine Ice Sheet Model (UM-ISM) (Appendix A) and Environmental Change Model (UM-ECM) (see Chapter 2), which until now had not been done in a rigorous manner.

3.1.2 Geological Setting

The Wind River Mountains span 200-km in west central Wyoming and constitute one of the largest granite massifs in the intermountain West (Figure 3.1). High peaks lie along a central ridgeline trending NW-SE wherein elevations in some places exceed 4000 m. Modern glaciers and perennial snowfields are found along this ridgeline in cirques generally above 3700 m. The highest concentration of glaciers in the U.S. Rocky

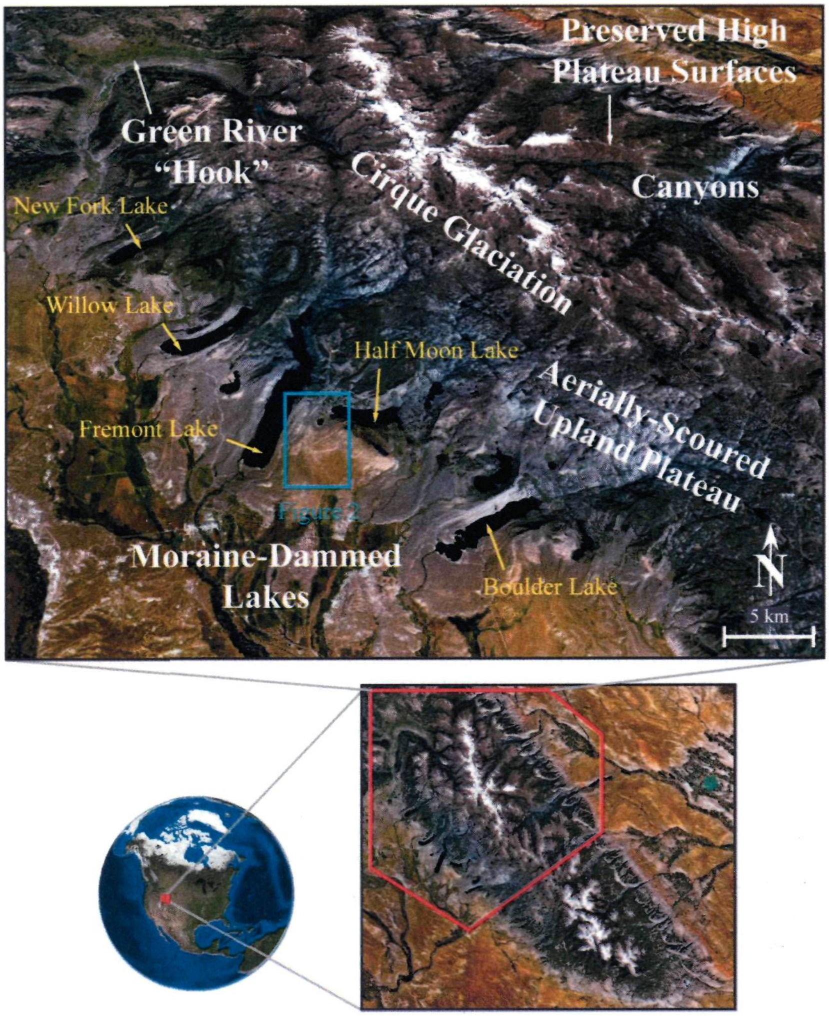


Figure 3.1. Wind River Mountains location map. Important features discussed in the text are labeled in the top panel.

Mountains is found in the northern Wind Rivers in the vicinity of Gannett Peak (Krimmel, 2002). Notable asymmetry in the range is found with respect to the central ridgeline. To the west is a broad glacially scoured upland plateau ~3000 m altitude. To the east is a higher, relatively unweathered plateau 3500-4000 m incised by deep glacial canyons. This relict surface was likely preserved under the cover of thin cold-based ice during past glaciations. Canyons and valleys on both sides of the range drain into lake basins along the mountain front that are rimmed by massive terminal moraines. A particularly striking topographic feature of the Wind Rivers is the "hook" in the Green River valley in the northwest corner of the range. The size of this feature, in addition to flutes and striations indicate that it was a significant Pleistocene ice drainage pathway.

3.1.3 Past Glaciation and Climate

At least six Pleistocene glaciations have been identified from deposits in the Wind River Range (Dahms, 2004). For this study, I am concerned with only the last two glaciations, Pinedale and Bull Lake (marine isotope stages 2 and 6, respectively), which are correlated with other glacial advances in the Rocky Mountains (Gosse et al., 1995a). The footprint of the former ice cap during these stades is easily discernable from terminal moraines (Figure 3.2), and from the limit of areal scour on upland plateau surfaces (e.g., Figures 3.1). Given the greater outward extension of outlet glaciers, the Bull Lake glaciation probably resulted from a slightly cooler and/or wetter climate regime than did the Pinedale glaciation.

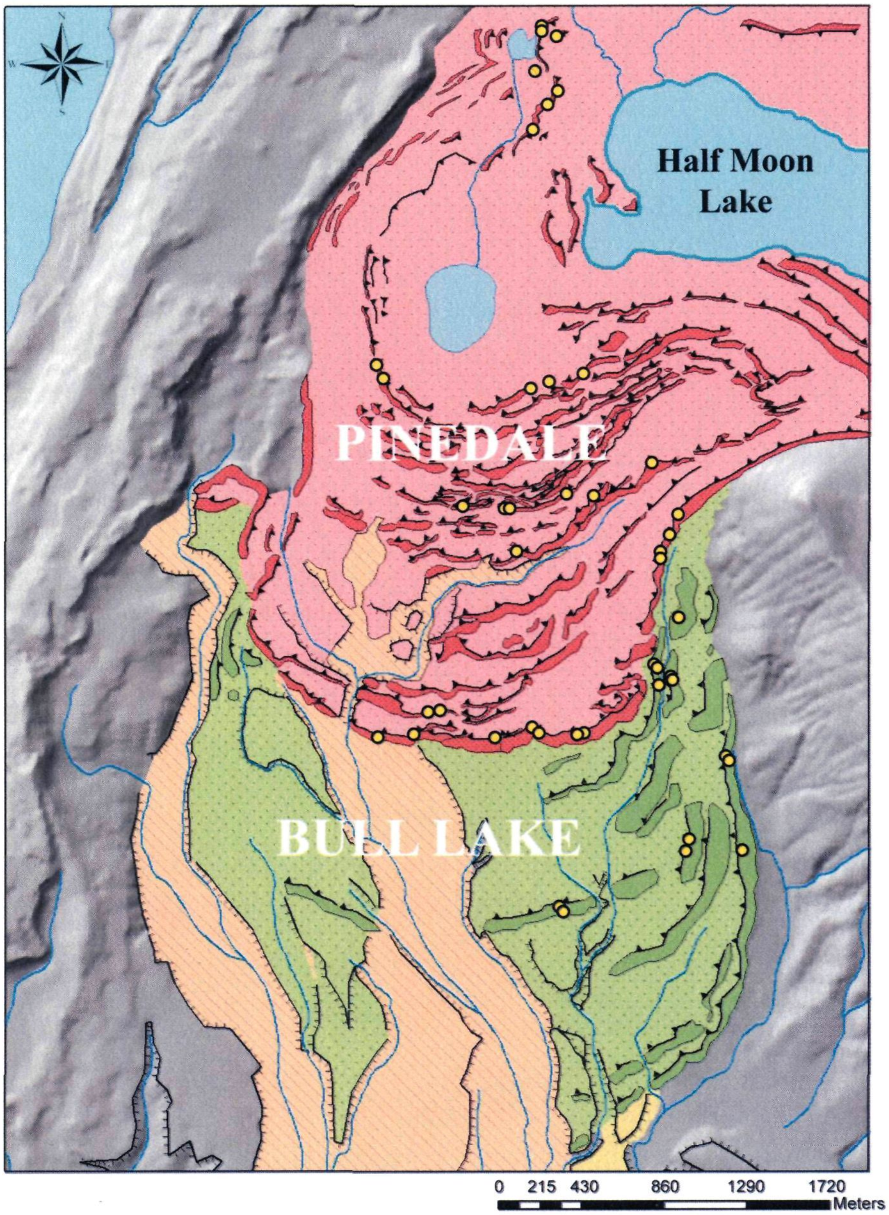


Figure 3.2. Glacial geomorphic map. Shown are Pinedale (red) and Bull Lake (green) moraine complexes deposited by the Half Moon outlet glacier. The yellow circles mark University of Maine boulder sample collection sites for cosmogenic surface-exposure dating. Map courtesy of A. Putnam.

A third glacial deposit identified in the Wind Rivers, Temple Lake, provides information about the deglaciation of the ice cap following the Pinedale maximum. In many cirques throughout the range, including near Temple Lake and in Titcomb Basin, a prominent weathered moraine belt can be found down valley of existing glaciers and historical-age moraines. Radiocarbon and ^{10}Be age determinations for this glacial deposition range 11-14 kyrs BP, indicating that the Wind River Ice Cap collapsed rapidly following the Pinedale maximum ~17 kyrs BP (Zielinski, 1989; Gosse et al., 1995a; Gosse et al., 1995b). It also suggests that late glacial climate in the region was comparable to modern, in contrast to severe cold conditions registered across the North Atlantic region around the same time during the Younger Dryas (e.g., Denton et al., 2005).

Under what climate regime did the Wind River Ice Cap form, and how sensitive was the ice cap to changes in temperature and precipitation? It is understood from paleo snowline reconstructions that the seasonal thermal cycle over much of the West may have been 4-6 °C lower during the last glacial maximum compared to the late Holocene (Broecker and Denton, 1989). Furthermore, from the existence of large pluvial lakes, most notably Lake Bonneville in Utah and Lake Lahontan in Nevada, it has been hypothesized that western U.S. climate was wetter during glacial stades due to southward-displacement of the North American storm track induced by the Laurentide Ice Sheet (Antevs, 1948; Benson and Thompson, 1986). General circulation modeling studies have demonstrated the physical plausibility of the latter situation (e.g., Kutzbach et al., 1998). Moreover, at least one mass balance study has shown probable development of ice caps in Wyoming,

Utah, and Colorado given a 3.5-5.5 °C summer temperature depression in addition to a doubling of annual precipitation (Leonard, 2007).

Here I examine the formation, deglaciation, and climatic sensitivity of the Wind River Ice Cap in several scenarios using the UM-ISM in conjunction with the UM-ECM. Results of this experimentation are consistent with previous interpretations: 1) The modeled Pinedale and Bull Lake ice caps attain equilibrium with a cooling of 5-6 °C coupled with at least a twofold precipitation increase relative to modern conditions; 2) In an extreme deglaciation scenario, the Pinedale stade ice cap disappears within 90 years when subjected to modern temperature and precipitation fields, indicating the Pleistocene ice cap would have been very sensitive to climatic perturbation.

3.2 Methods

Detailed descriptions of the UM-ISM and UM-ECM are provided in Appendix A and Chapter 2 of this dissertation. Important ice sheet model considerations are high-resolution bedrock topography and climatology input grids, which are both prepared in the UM-ECM. On the first point, I use a 0.8 km resolution map of the Wind Rivers downsampled from 30 m elevation data from the National Elevation Dataset (Gesch, 2007). This resolution is sufficient to resolve valleys and cirques across the range. On the second point, I use 30 arcsecond (~1 km) monthly climatology from the PRISM climate mapping system (Daly et al., 1994) scaled to match the dimensions and resolution of the model bedrock topography input (Figure 3.3). The climatology grids are used by

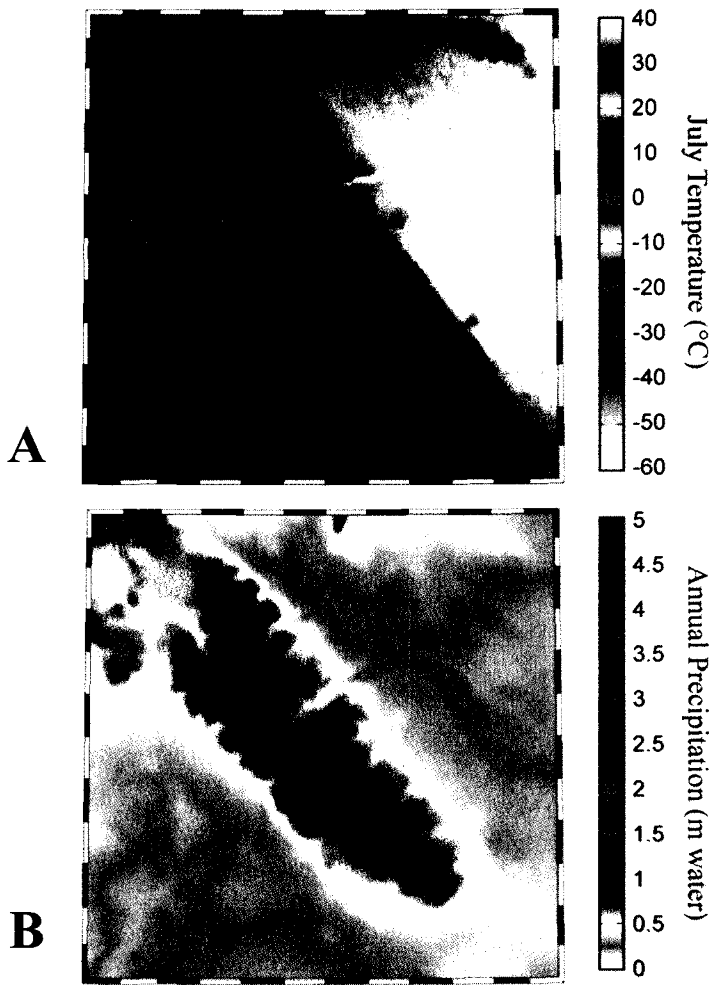


Figure 3.3. Sample PRISM climatology input to the ice sheet model. A) Mean July temperature. B) Mean annual precipitation. Note that at 0.8 km resolution individual valleys are well resolved.

the UM-ISM to calculate surface mass balance. PRISM itself is a model that reproduces temperature, precipitation, and other parameters using point data and an interpolation scheme that considers the effect of orography in producing rain shadows and temperature inversions. I chose to use PRISM in this study because it is the most robust gridded climatology presently available.

As noted in Appendix A, the ice-flow solver in UM-ISM is based on the Shallow Ice Approximation method (Hutter, 1983). Models of this sort neglect longitudinal stresses that would otherwise be considered in full Stokes equations for the momentum balance of ice flow. Although, shallow-ice models are typically used for studying the behavior of continental ice sheets, they can also be used for examining plateau glaciers and ice caps. Solution validity is dependent upon a low aspect ratio of the modeled ice mass (ice thickness should not exceed flowline length), and the normalized bedrock surface slopes being less than about 0.2 (Hindmarsh, 2004; Le Meur et al., 2004; Schäfer et al., 2008). For the purposes of this study, I assume that UM-ISM produces reasonable solutions in the Wind Rivers problem domain, especially when the ice cap is large and most of its surface covers low gradient plateau surfaces. Further support for our assumption is that outlet glacier termini are impacted strongly by surface mass balance (Schäfer et al., 2008). I feel that the latter implementation is particularly robust.

3.3 Results

I devised several UM-ISM experiments to test the climate conditions necessary for Pinedale and Bull Lake stade ice caps to develop, and to examine sensitivity of the ice cap system to climate change. First, I ran equilibrium simulations lasting 1000 years for different temperature and precipitation forcing combinations (Figure 3.4). Specifically, temperature anomalies (dT) of -4 °C, -5 °C, and -6 °C were tested separately with precipitation percentages (P) of 100%, 150%, 200%, and 250% relative to modern climatology. Two important observations are that 1) an equilibrium ice cap could develop within 300 to 800 years, and 2) the change in ice area and volume effected by a 1 °C change in temperature could be compensated roughly by a 50% precipitation step. For example, the ice area and volume signals are similar for dT=-4 °C + P=250%, dT=-5 °C + P=200%, and dT=-6 °C + P=150%.

By comparing model ice-surface reconstructions to geomorphic features, our "best-pick" climates under which the Pinedale and Bull Lake ice caps could have formed are dT=-5 °C + P=250% and dT=-6 °C + P=200%, respectively (Figures 3.5 and 3.6).

In a second experiment, I ran a 2500-year simulation meant to capture a plausible cycle of Pinedale (i.e., dT=-5 °C + P=250%) ice cap evolution (Figure 3.7). For this test, temperature and precipitation signals were coupled such that precipitation increased (or decreased) linearly as temperature decreased (or increased); the temperature signal is a sine function modified to include a 500-year cold period in which the ice cap could attain

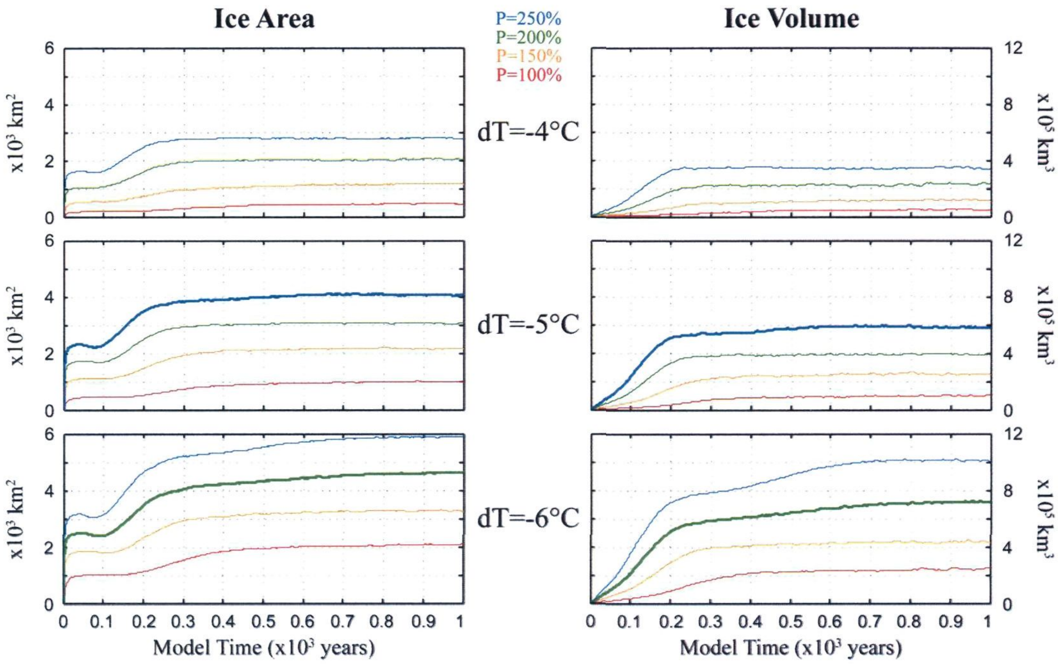


Figure 3.4. UM-ISM Equilibrium solutions for prescribed climate regimes. Each experiment starts with modern topography and no model ice. Experiment suites are grouped horizontally by temperature anomaly (dT), and vertically by output type (ice area or ice volume). The colored lines in each panel represent different precipitation percentages (P) relative to modern: 100% (red), 150% (orange), 200% (green), 250% (blue). Bold lines indicate parameter settings used in the Pinedale and Bull Lake solutions shown in Figure 3.6. Note that the ice cap attains equilibrium within 300 to 800 years depending upon the scenario.

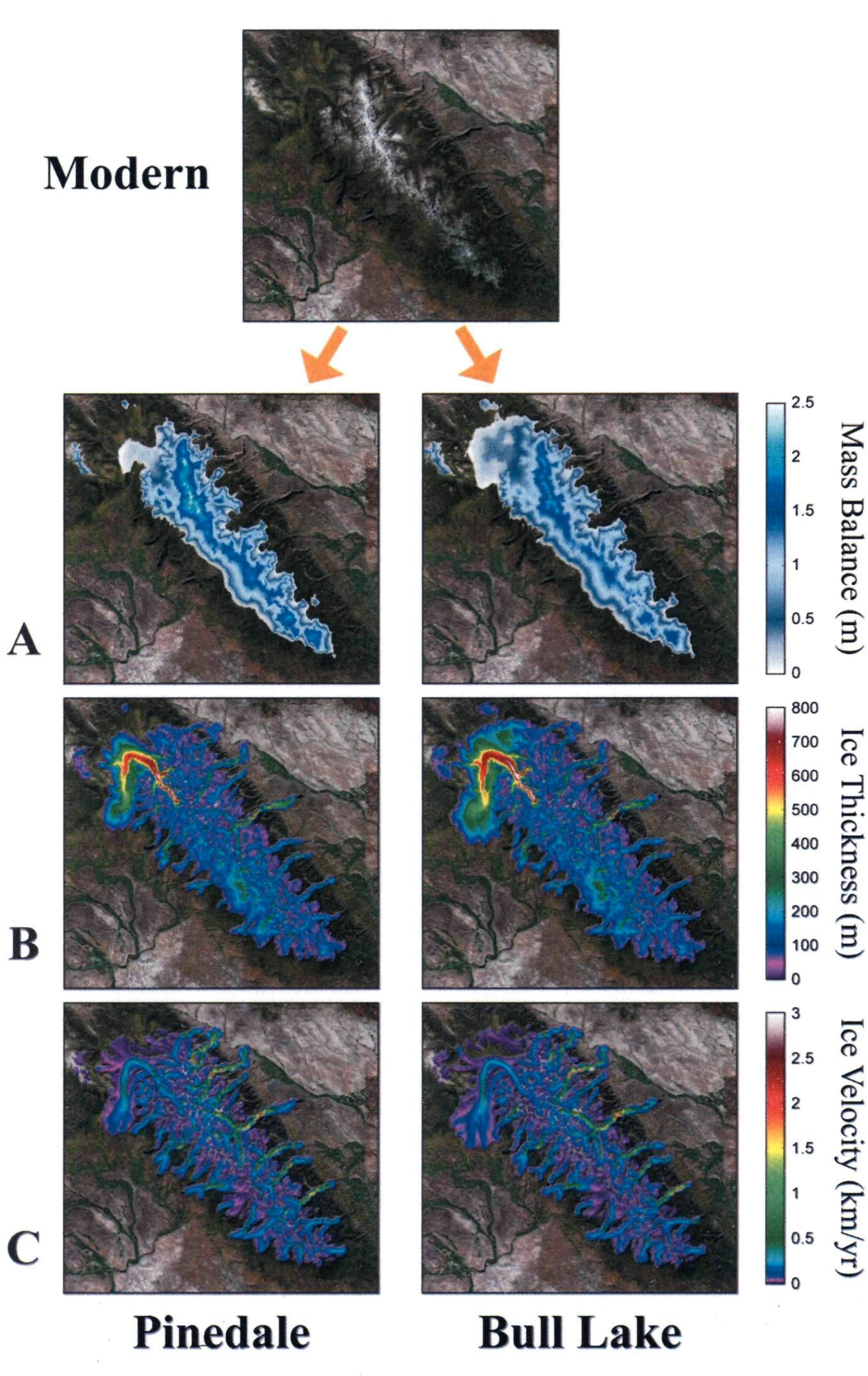


Figure 3.5. UM-ISM Wind River Ice Cap reconstructions. Shown are A) mass balance, B) ice thickness, and C) ice velocity fields for the Pinedale (dT=-5 °C, P=250%) and Bull Lake (dT=-6 °C, P=200%) glaciations. A striking feature of the ice cap system is the "hook" and piedmont lobe of the Green River outlet glacier (top left of each frame).

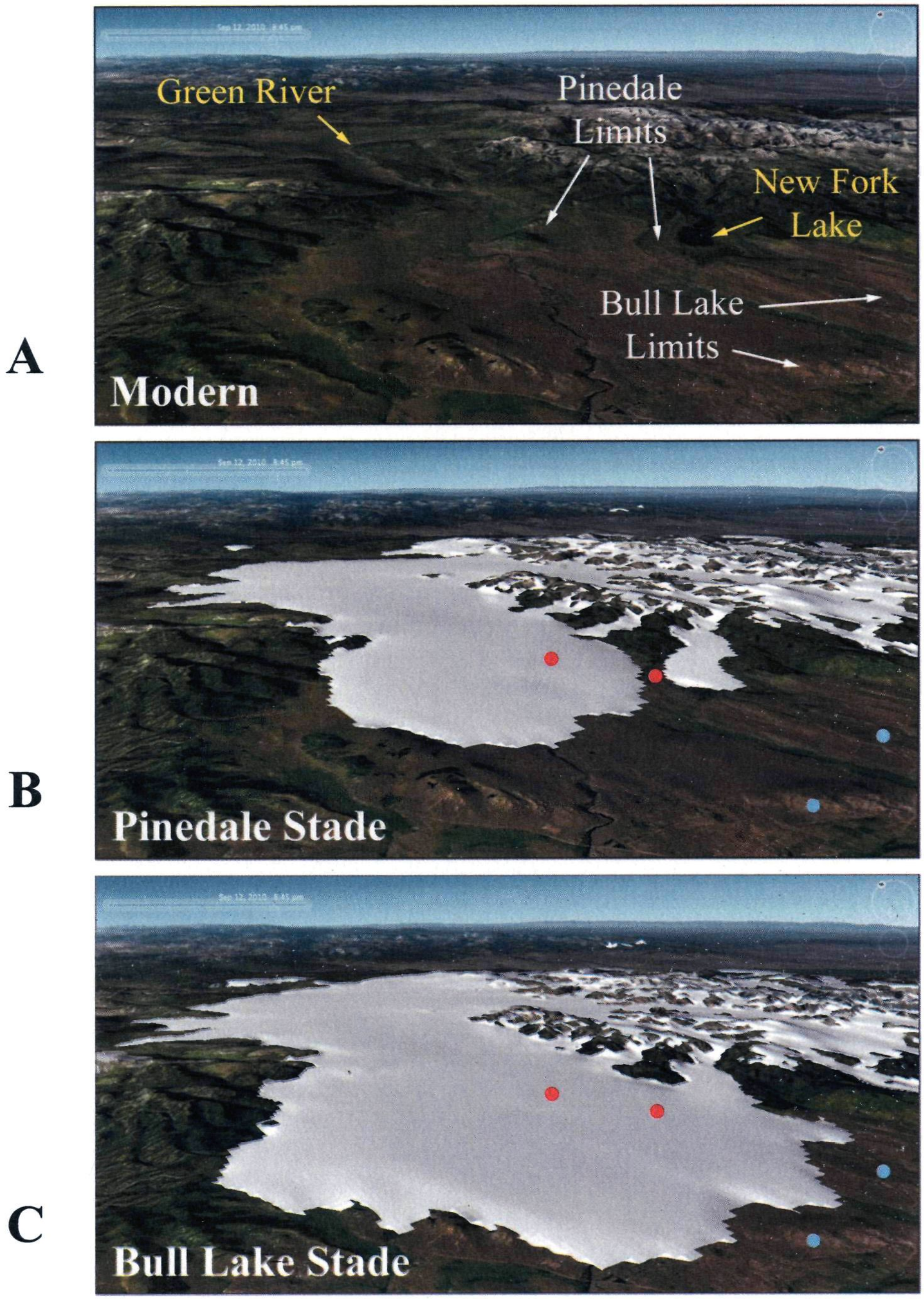


Figure 3.6. The upper Green River valley. A) Modern. B) Pinedale stade. C) Bull Lake stade. Here UM-ISM ice surfaces are visualized in Google Earth™. Pinedale and Bull Lake outer deposits are identified in panel A, and marked with corresponding red and blue dots in panels B and C for comparison. Modeled ice extent is generally consistent with these geomorphic boundaries.

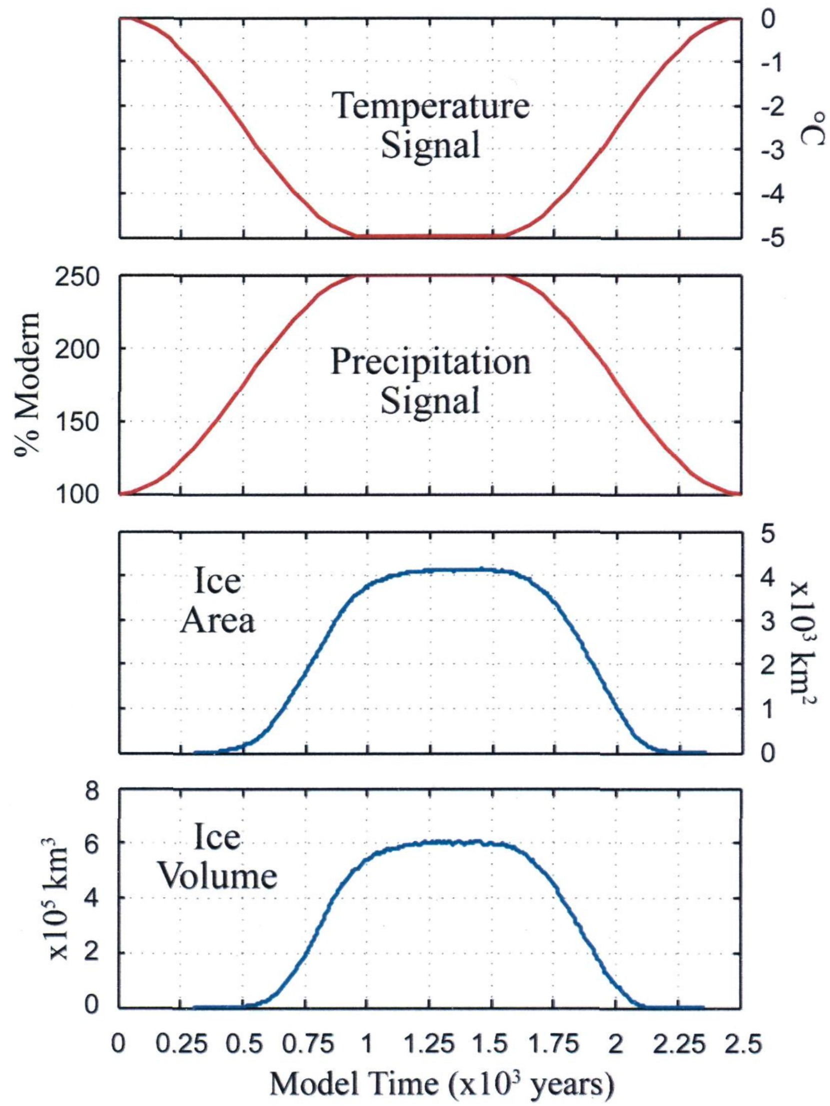


Figure 3.7. UM-ISM 2500-year cycle experiment. The top two panels show temperature and precipitation signals input to the model. The bottom two panels show ice area and ice volume model output. This experiment affords a Pinedale maximum ice cap (dT=-5°C and P=250%). It is evident that ice measureable ice accumulation does not begin until ~500 years into the simulation when dT=-3 and P=175%. Beyond this limit, snowline drops below the upland Plateau, enabling rapid ice cap growth. Following the simulation cold phase, the ice cap contracts with most rapid recession occurring at ~1900 years.

equilibrium before the onset of terminal warming. It is apparent from ice area and volume output that the sensitivity of the Wind River mountains to ice cap glaciation is about -3 °C and 175% precipitation relative to modern climatology. Moreover, once established, the ice cap size and volume is coupled very closely to the climate forcing. This is evident from the deglaciation phase shown in Figure 3.7 in which ice recession begins synchronously with the onset of climatic amelioration.

In supplement to the second experiment, I ran a final simulation in which the Pinedale stade ice cap was subjected to sustained modern climate. I found that the ice cap is indeed sensitive to climatic perturbation: in this scenario it disappears completely within 90 years.

3.4 Discussion

My overall assessment of the first experiment group, based on comparison of model surface extents to glacial geomorphic features, is that the most favorable Pinedale and Bull Lake ice caps form when dT=-5 °C or -6 °C, and P=200% or 250%. It is not possible to say which combination of temperature and precipitation is the "best" in each case, because the moraines are indeed close to one-another, and the model ice margin is not a perfect fit to geomorphic features everywhere around the mountain range. However, given the enormity of the piedmont lobe of the Green River outlet glacier during Bull Lake time compared to Pinedale, it seems reasonable that the ice cap footprint anomaly could result from a climate difference on the order of 1 °C or 50% precipitation.

An important point learned from the second experiment is that the ice cap glaciation threshold for the Wind Rivers is approximately dT =-3 C and P=175%. Beyond these conditions snowline intersects the upland plateaus, resulting in a rapid increase in ice area and volume. During deglaciation the major factor leading to rapid ice decline likewise relates to snowline and ice cap geometry. In this case, disappearance of the ice cap results from snowline rising above the broad, relatively thin ice accumulation areas that cover the plateaus, thereby increasing the melt area nonlinearly.

It seems improbable that the Wind River Ice Cap could have formed without a significant increase in annual precipitation across the region. The most likely scenario is that the polar jet stream and North American storm track was shifted southward due to Laurentide Ice Sheet orography during the Pinedale and Bull Lake stades (e.g., Antevs, 1948). Given this linkage to large-scale circulation, the ice cap would have been exceptionally vulnerable to far-field climatic shifts during the termination. This is emphasized in the extreme deglaciation experiment wherein a modern climate forcing disintegrates the ice cap within 90 years. The latter result supports the suggestion that the Wind River glacier system disappeared rapidly during the first phase of the termination (Gosse, 1995b).

Finally, given evidence of only cirque glaciation following the initial ice-cap collapse, then climate over the Wind Rivers during the late glacial was only moderately cooler than it is now (or during preindustrial times). If the ice cap glaciation threshold I suggest above is realistic, then the numeric value for mean-annual thermal field cooling relative

to present is 3 °C. In all, this suggests that the Wind River Ice Cap and probably other glacier systems in the western U.S. were maintained by a thin margin during the glacial period, and they were exceptionally sensitive to perturbations stemming from large-scale climate processes.

3.5 Conclusions

- The Wind River Range was covered by an ice cap several times during the Pleistocene, but now supports only small cirque glaciers. This study is an effort to reconstruct the former ice cap using the UM-ISM and UM-ECM, and to examine ice-cap response to different temperature and precipitation regimes.

- I find that the Pinedale and Bull Lake ice caps could have formed with a 5-6 °C cooling in conjunction with a doubling of annual precipitation relative to modern climatology. The ice cap of Bull Lake time was slightly larger than that of Pinedale, indicating a relative climate either 1 °C cooler or 50% wetter, or some combination of the two parameters.

- As suggested by previous workers, dramatic precipitation changes over the range are likely due to a southward shift of the polar jet stream and North American storm track due Laurentide Ice Sheet orography forcing.

- The Wind River glacier system is exceptionally sensitive to climate change. For example, the threshold for ice cap glaciation appears to be approximately -3 °C and 175% precipitation relative to modern climatology. The threshold is linked to snowline altitude with respect to the upland plateaus. In terms of deglaciation, the maximum ice cap could disappear in as little as 90 years if subjected to modern conditions.

- Given the model results and evidence of only cirque glaciation following the termination ice-cap collapse, then climate over the Wind Rivers during the late glacial was only ~3 °C cooler than it is now. In all, this study concludes that the Wind River Ice Cap and probably other glacier systems in the western U.S. were exceptionally sensitive to perturbations stemming from large-scale climate processes during glacial times, and during the termination.

CHAPTER 4: THE ROLE OF THE LAURENTIDE ICE SHEET IN DRIVING GLACIAL CYCLES

4.1. The Problem

Glacial cycles of the late Quaternary period follow a saw-toothed pattern of ice buildup and decay wherein major deglaciations, or terminations, occur approximately every 100 kyrs (Emiliani, 1955; Broecker and van Donk, 1970). The precise origin of this pattern remains an important unsolved problem in paleoclimatology. Spectral analyses of marine oxygen isotope records reveal that glacial cycles are linked to variations in Earth's axial tilt, equinox geometry, and orbit eccentricity (Hayes et al., 1976). The global ice volume signal bears striking resemblance to that of northern high-latitude summer insolation, indicating that orbital parameters are amplified by the Northern Hemisphere ice sheets (Imbrie et al., 1993). In particular, the Laurentide Ice Sheet, which is by far the most important contributor to global ice-volume and sea-level change, is thought to be a primary amplifier due to its orography, high albedo, and readily exchangeable freshwater reservoir (Clark et al., 1999).

Several physical processes for propagating insolation anomalies from the Laurentide to the rest of the globe have been identified in climate models. These mechanisms, all influenced by ice-sheet orography, include formation of anticyclones above the ice sheet surface, southward displacement of the middle latitude jet stream, reorganization of storm tracks, promotion of sea-ice formation across the North Atlantic Ocean from cold

Laurentian airmasses, and alteration of the hemispheric hydrological cycle (Shinn and Barron, 1989; Manabe and Broccoli, 1985; Bromwich et al., 2005; Romanova et al., 2006). It is likely that these mechanisms are tied in some fashion to changes in greenhouse gases, which would lend additional feedback (Paillard, 2001; Cheng et al., 2009).

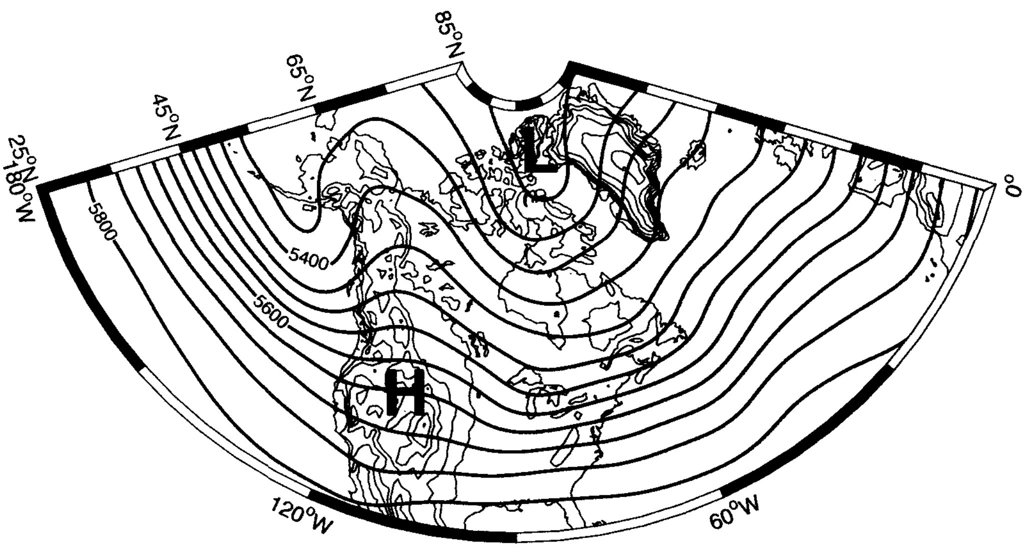
It is conceivable that glacial cycles are in a sense "driven" by the dynamic response of the Laurentide Ice Sheet to insolation changes. In that vein, many authors have suggested that terminations result from a gravitational collapse of the ice sheet following attainment of a critical mass (Hughes et al., 1977; MacAyeal, 1979; Denton and Hughes, 1981; Raymo, 1997; Clark et al., 1999; and others). One mode of instability is manifested by enhanced calving along marine ice margins in areas of severe isostatic depression (e.g., Hughes et al., 1977; Denton and Hughes, 1981). A second mode of instability is enhanced ice-stream flow due to thawing of underlying sediments, particularly in the Hudson Strait region. This mechanism has been proposed to explain Heinrich events (MacAyeal, 1993). Similarly, the Laurentide Ice Sheet southern margin could become unstable and collapse after expanding to its maximum over a thawed bed of deformable sediments flanking the Canadian Shield (Clark et al., 1999).

If one thing is clear, it is that understanding the origin of 100-kyr glacial cycles involves disentangling multiple nonlinear systems. Here, I attempt to simplify the problem by supposing most of the ice age signal results from the orographic evolution of the Laurentide Ice Sheet. In order to evaluate this hypothesis, I reconstructed the last 126 kyr

glacial cycle over North America using an insolation-driven glaciological model with provisions for ice-sheet instability and atmospheric feedback to changes in ice extent. Other ice sheet models lack atmospheric feedbacks, and forgo using insolation to change climate in favor of environmental proxies derived from ice core records (e.g., Marshall et al., 2000; Zweck and Huybrects, 2005). One important find from the formulation here is that the Laurentide could sustain itself under Holocene insolation by orography feedbacks, provided the ice sheet was not already rendered susceptible to mechanical collapse. From a sea level perspective, this implies that glacial climate is maintained by the presence of Laurentide orography. Thus, these results reinforce the supposition that Laurentide Ice Sheet dynamics afford a dominant means of amplifying northern summer insolation and translating the signal to other parts of the globe.

4.2. The North American Stationary Wave

Before introducing the ice sheet model, it is necessary to provide a discourse on the basis for incorporating an atmospheric feedback into the experimental framework of this study. In the present climate, a mean-annual stationary wave forms in the middle-latitude westerlies (including the jet stream) due to differential surface heating and diversion of flow around the Rocky Mountains (Charney and Eliassen, 1949; Bolin, 1950; Sutcliffe, 1951; Manabe and Terpstra, 1974) (Figure 4.1). The wave pattern exhibits a northward meander of warm air in a ridge over the western highlands, and a southward meander of cold air in a trough over the eastern lowlands. This circulation is most pronounced in winter when a steep equator-pole thermal gradient leads to vigorous westerly flow and



500 mb Geopotential Height (m)
May 1st 1960–1990 Average

Figure 4.1. 500 mb geopotential heights for May 1st averaged over 1960-1990. This image shows a ridge-trough atmospheric flow pattern across North America. Upper-level high (H) and low (L) pressure centers driving this pattern are labeled. Data from NCEP Reanalysis (Kalnay et al., 1996).

high amplitude waves; it also exists during summer when surface heating weakens the circulation, and sees the trough-axis shifted northeastward over Hudson Bay and the Canadian coastal waters (Lamb, 1972).

The environmental impact of the North American stationary wave is readily apparent across multiple systems including snow and ice cover, configuration of the boreal forest biome, and the northern tree limit (Figure 4.2). Existence of a cold circulation anomaly over the east is evident particularly over Hudson Bay (51°N to 64°N), where extensive sea ice is supported on average for eight months out of the year (Parkinson and Cavalieri, 2008). The latter, of course, is part of a feedback between large-scale atmospheric flow, and the thermal inertia of sea ice and cold ocean water (e.g., Lamb, 1972). Geomorphic maps indicate that the orography-induced planetary wave also had a profound influence on the nucleation and growth of Pleistocene ice sheets (Figure 4.3).

Previous workers have already pointed out the importance of the North American circulation pattern in glacial onset over eastern Canada (e.g., Andrews and Barry, 1978). To that end, Ruddiman and Raymo (1988) examined the problem from a tectonic evolution standpoint. They suggested that uplift of the Tibetan Plateau and the North American cordillera have gradually altered westerly flow, which has cooled the northern landmasses and increased their sensitivity to insolation changes. The authors linked the initiation and intensification of Northern Hemisphere glaciation during the Quaternary period to these atmospheric changes, citing wave-amplification as a robust mechanism for expanding polar ice sheets into the middle latitudes. Most notable is the expansion of

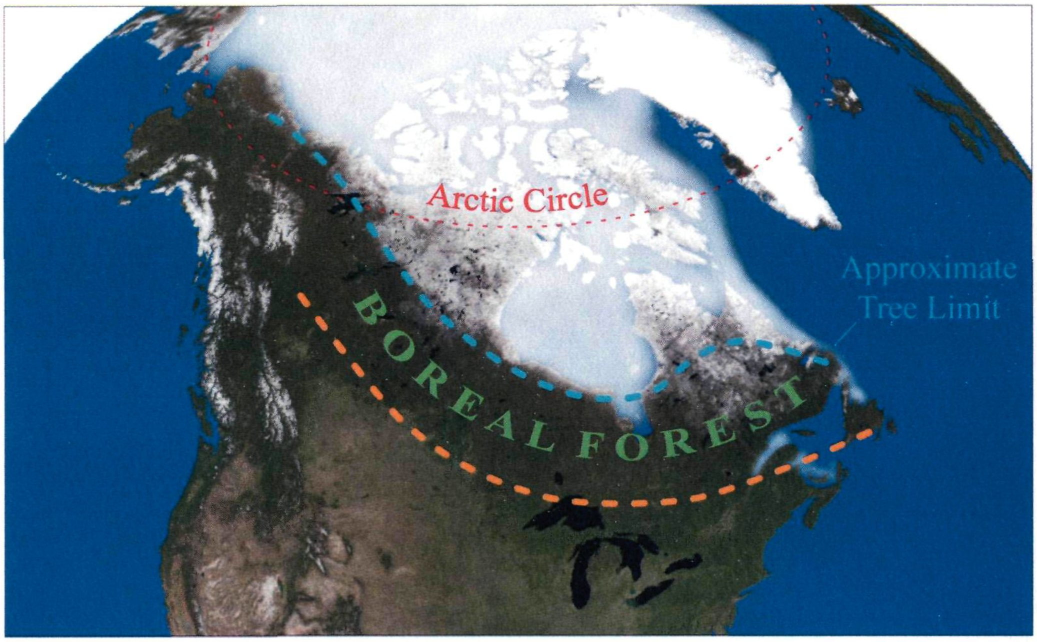


Figure 4.2. Environmental impact of the North American stationary wave. The boreal forest biome limits, and snow and ice cover all reflect the dominant ridge-trough pattern induced by large-scale atmospheric circulation. Base image modified from NASA WorldWind imagery. Snow and sea-ice distribution is representative of conditions typical for early June.

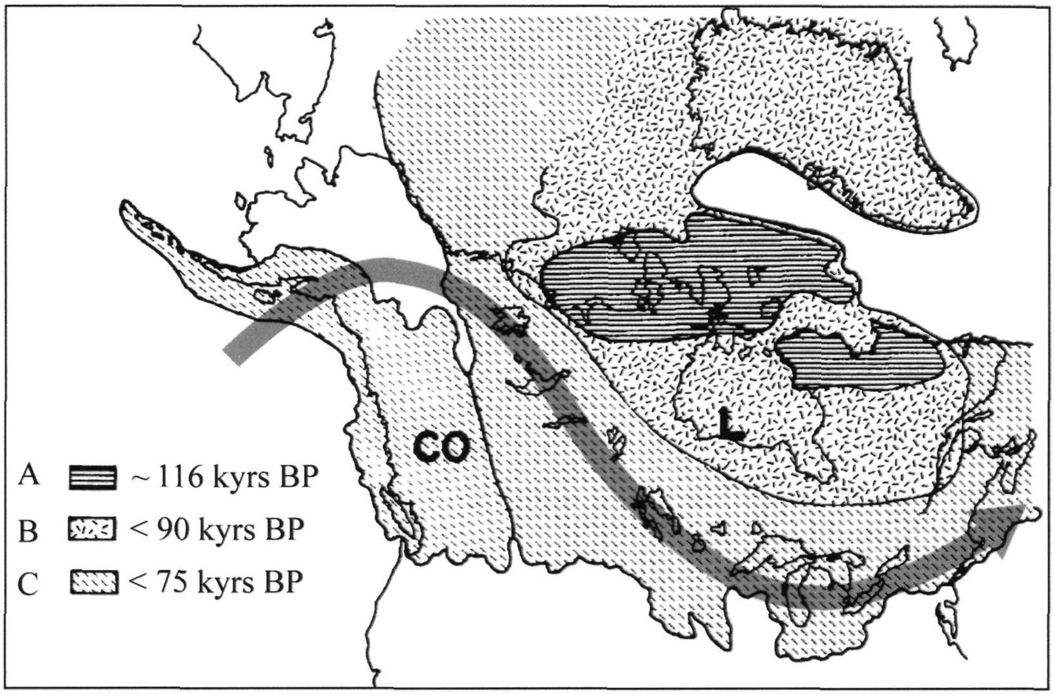


Figure 4.3. Schematic diagram of the Laurentide Ice Sheet during three main development phases. The zones depicted represent regions of A) instantaneous glacierization ~116 kyrs BP, B) stable core development and persistence from ~90 kyrs BP until the termination, and C) periphery ice advance during severe stadials after ~75 kyrs BP. Also shown is the inferred position of the middle latitude jet stream in summer during the last glacial maximum (sinusoidal wave with arrow). The Cordilleran Ice Sheet (CO) lies beneath an atmospheric ridge, and the Laurentide Ice Sheet (L) lies beneath a trough. Note the distribution of great lakes along an arc centered on Hudson Bay. We presume the lakes reflect a former ice margin and influence of the North American stationary wave. Adapted from Andrews and Barry (1978).

the Laurentide Ice Sheet under the Canadian cold trough. Indeed, several modeling studies have shown that ice sheets influence planetary waves much like cordillera, and that changes in ice-sheet size and shape can lead to multiple climate equilibria with significant far-field impacts (Manabe and Broccoli, 1985; Shinn and Barron, 1989; Roe and Lindzen, 2000; Romanova et al., 2006). At least one study suggests that a positive feedback loop between ice growth and local atmospheric cooling could be a critical factor for the evolution of an ice sheet such as the Laurentide (Lindeman and Oerlemans, 1987).

4.3. Methods

4.3.1. The Ice Sheet Model

In order to test the wave-amplification hypothesis, I use the University of Maine Ice Sheet Model (UM-ISM) (Appendix A). Bedrock topography supplied to the model is a map of North America downscaled to 40 km resolution from ETOPO1 elevation data. The base surface mass-balance input consists of NCEP Reanalysis (Kalnay et al., 1996) monthly mean temperature and precipitation grids averaged over 1950-2000. For this study, I developed a mass balance scheme in which the input climatology is modified as a function of ice area and summer insolation anomaly. The purpose for this scheme is to provide a means for the cold air trough over eastern Canada to expand and contract in a feedback with changes in ice orography (Appendix B). Also for this study, I use the existing model calving parameterization that is necessary in deglaciation experiments for instability and collapse of marine-based ice domes.

4.3.2. Experiment Setup

The ice sheet model was configured to run three 126-kyr glacial cycle simulations (gcycle1, 2, and 3) with different ice-area amplification sensitivities (low, medium, and high). For the calving parameter, a uniform value was chosen from several test runs that produced the extension of ice margins to the edges of continental shelves at the glacial maximum, and ice-margin retreat into the continental interior without mechanical collapse. In other words, a calving parameter value was chosen that enabled marine ice sheets to melt as though they were based on land. After running the three base experiments for a full glacial cycle, three subset experiments were run for the Marine Isotope Stage (MIS) 2 deglaciation starting at -18 kyrs and ending at 0 kyrs. In these final three simulations, the calving sensitivity was increased, again to a uniform value, in order to enable instability over marine ice sectors. Experiment gcycle2 and sub-solution 2b constitute the "best fit" simulations discussed below.

4.3.3. Results

Figure 4.4 shows model output compared against the insolation anomaly forcing function and a marine isotope ice-volume proxy. The mean annual temperature, ice area, and ice volume outputs all reveal distinct peaks and troughs translated from the summer insolation signal. Ice volume and ice area show gradual intensification from MIS 5e to MIS 2 consistent with the pattern evident in the global proxy record. In gcycle2, ice

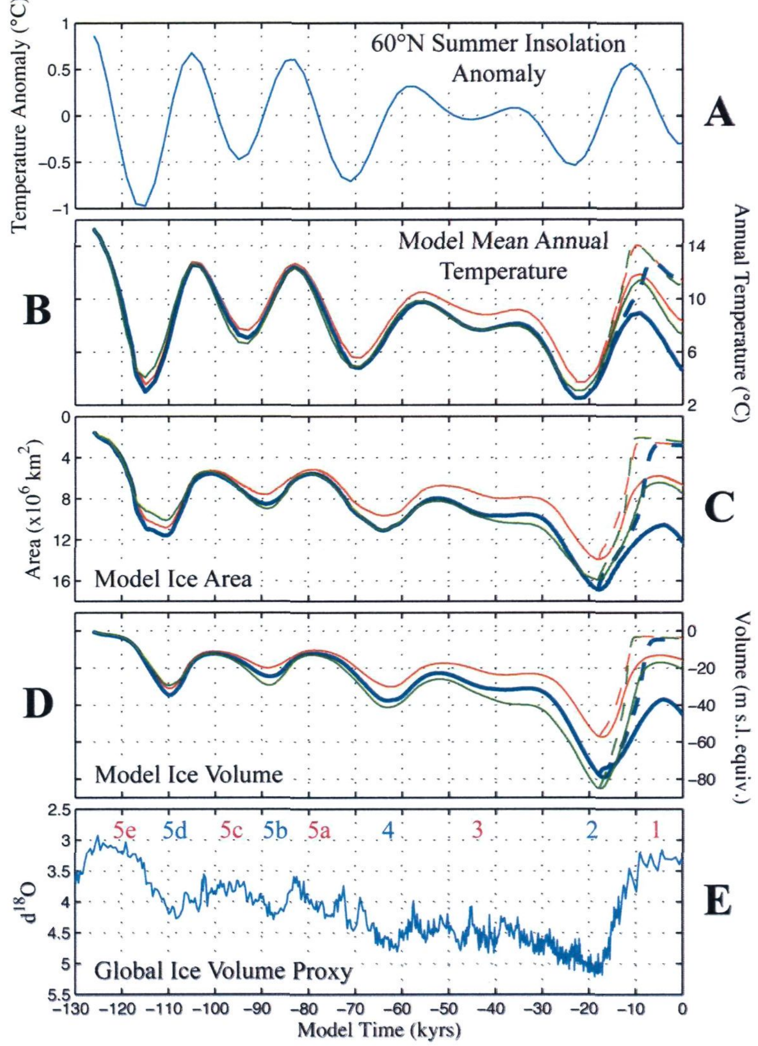


Figure 4.4. Plot stack showing UM-ISM input and output. Shown are A) normalized 60°N June insolation anomalies input to the model (Berger and Loutre, 1991), B) calculated mean-annual surface temperature averaged across the model map plane, C) model ice area, D) model ice volume, and E) a benthic oxygen isotope record taken as a proxy for global ice volume and sea level (Shackleton et al., 2000). The model solutions are for gcycle1 (orange), gcycle2 (heavyset blue), and gcycle3 (green). Only gcycle2 is discussed in the text; the other solutions are shown for comparison. Dashed lines indicate deglaciation sub-simulations in which calving sensitivity was increased to ensure ice-sheet collapse. MIS 1-5 are labeled in panel E, wherein red text denotes interstades and blue text denotes stades.

volume increases from 0 m to a maximum of 80 m sea level equivalence (s.l. equiv.) relative to modern baseline. The time lag between insolation forcing, and the ice-volume and area response is about 6 kyrs. This delay affords favorable temporal alignment of the features in the model output and proxy data. The low frequency waves in the marine isotope signal are stades and interstades. The MIS 2 ice-volume maximum occurs in response to a mean annual temperature forcing of 2 °C across the map plane, which is equivalent to a 13 °C cooling from modern conditions. Deglaciation following the MIS 2 maximum is characterized by a marked decline in ice volume until about -5 kyrs, after which there is a volume increase in response to decreasing insolation. At 0 kyrs the model ice volume is sufficient to depress global sea level ~40 m relative to the present. In contrast, gcycle2b exhibits a terminal deglaciation due to ice-sheet collapse, wherein near-modern sea level is attained by -7 kyrs with no appreciable change thereafter.

Figures 4.5 and 4.6 show model ice surface, mass balance, and mean annual air temperature maps for the interstades and stades labeled in Figure 4.4. The glacial cycle begins with nucleation of the Laurentide Ice Sheet over Baffin Island and Foxe Basin in response to the first major summer insolation decline during MIS 5e. By -116 kyrs, ice is expanded over Hudson Bay and much of eastern Canada, with the Quebec-Labrador ice dome having established itself rapidly due to high precipitation input along the North Atlantic storm track. The ice sheet proceeds to contract and expand in interstades and stades in response to insolation changes. Interstades encompass a Greenland-size ice sheet extending across Hudson Bay and the Canadian Archipelago, and stades encompass ice extending across the Canadian Shield. The glacial cycle culminates during MIS 2, at

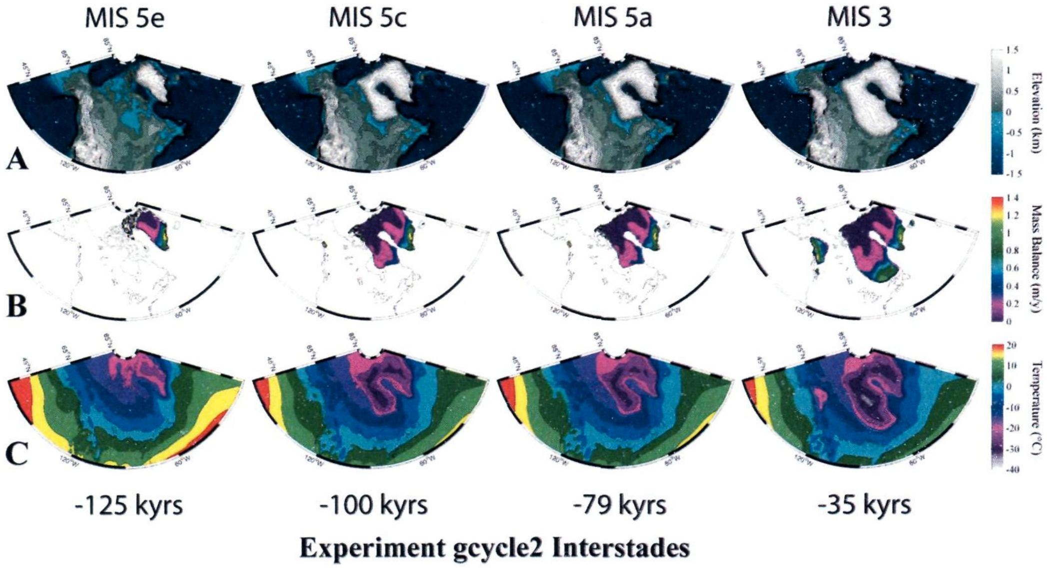


Figure 4.5. Interstade conditions for experiment gcycle2. Rows are A) surface elevation, B) net surface accumulation, and C) mean annual temperature. Each column is a different timeslice.

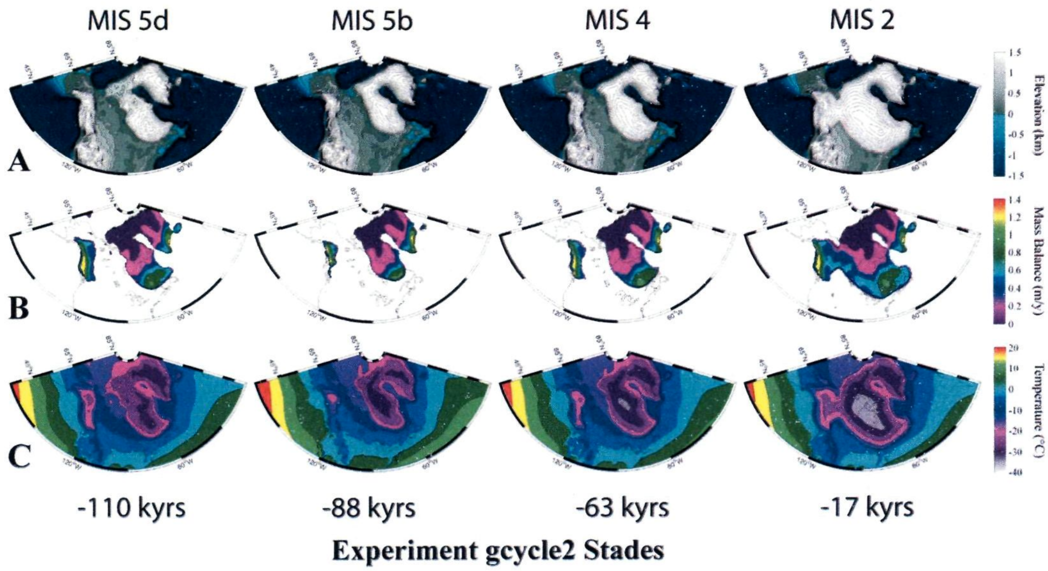


Figure 4.6. Stade conditions for experiment gcycle2 organized in the same manner shown in Figure 4.5.

which time Laurentide ice is expanded across Canada and coalescent with the Cordilleran Ice Sheet. The results of deglaciation in gcycle2 and gcycle2b are shown in Figs. 7 and 8. In gcycle2, with the absence of an instability mechanism, the Laurentide Ice Sheet contracts somewhat from its maximum configuration, but then stabilizes over Hudson Bay. At 0 kyrs the ice sheet covers nearly all of the Canadian Shield, following marked expansion throughout the latter half of the Holocene. The thermal field at present time in this simulation is stadial in character. In contrast to gcycle2, the instability mechanism in gcycle2b results in ice-sheet collapse into Hudson Bay between -9 and -8 kyrs, and a complete deglaciation by mid Holocene. It is noteworthy that collapse is manifested primarily along the Laurentide southern margin (Figure 4.7). At 0 kyrs the thermal field is modern, as is topography and coastline.

4.4. Discussion

4.4.1. The Glacial Period

To test whether the classic saw-tooth pattern could develop from expansion and contraction of the Laurentide Ice Sheet, simulations of the last glacial cycle were conducted using a model forced by insolation changes with provisions for atmospheric wave amplification and ice-sheet instability. Notable success in the model is the replication of stades and interstades comparable in timing and magnitude to their marine isotope counterparts (Figure 4.4). In addition, the major stades MIS 5d, 4, and 2 in the model become increasingly severe, again matching the comparison dataset. The glacial

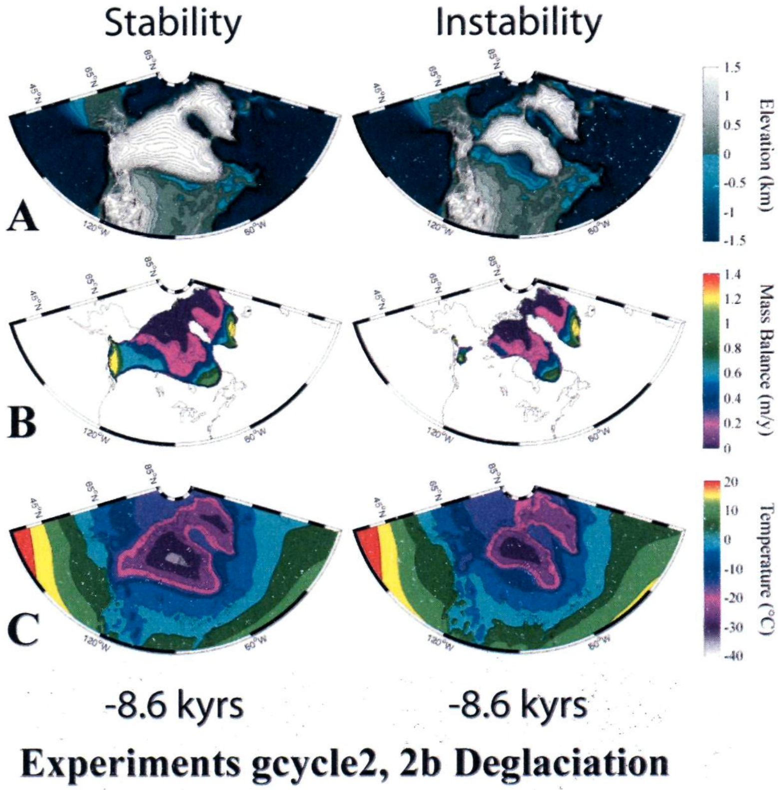


Figure 4.7. Comparison of deglaciation timeslice -8.6 kyrs for gcycle2 and 2b. Note that in gcycle2b the ice sheet is collapsing over Hudson Bay.

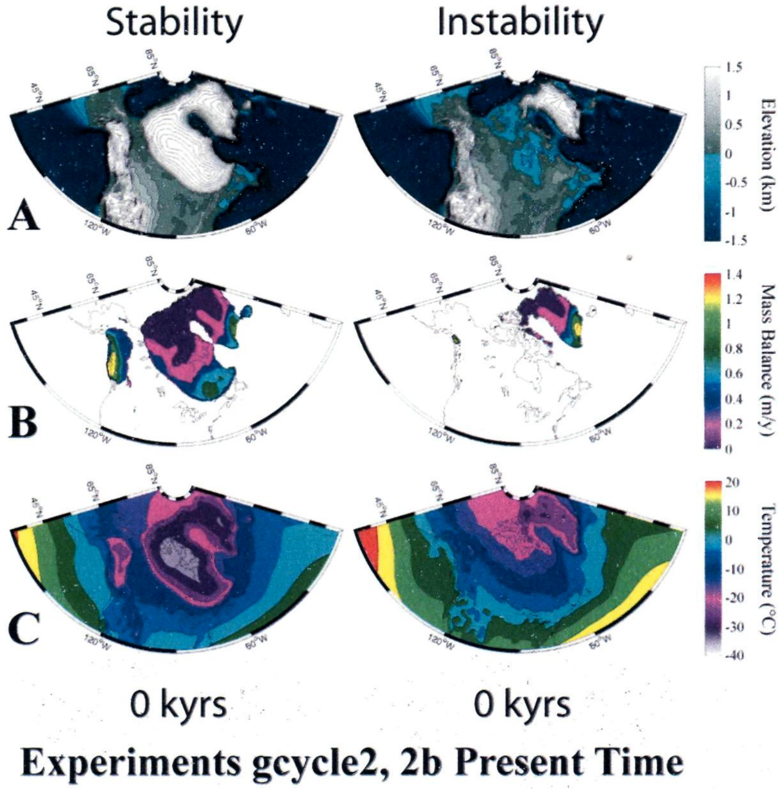


Figure 4.8. Comparison of present conditions for gcycle2 and 2b. The ice sheet configuration in gcycle2 represents a ~40 m sea-level depression relative to present.

termination in gcycle2b is reasonable as well. An important model discrepancy is the steep ice buildup preceding the MIS 2 glacial maximum; a closer fit to the ice volume proxy record would require more model ice to grow at the end of MIS 2, thereby affording greater ice volume during MIS 3 and a shallower MIS 2 buildup. Of course, the marine isotope record is a global composite, and volume contributions of other ice sheets likely introduce measurable departures from the Laurentide signal.

The model surface ice extents shown in Figs. 5 and 6 match available data within reason. Although most geomorphic information is limited to the MIS 2 glacial maximum, it is understood generally that the Laurentide Ice Sheet formed over northern Canada during MIS 5d, and maintained a stable core thereafter over the Foxe Basin and Hudson Bay until the MIS 2 termination (Andrews et al., 1976) (e.g., Figure 4.3). This is demonstrated in the model, with the exception of too much ice at glacial onset, and perhaps too little ice during the MIS 4 stade. The model MIS 2 glacial maximum is favorable overall, especially with the coalescence of the Laurentide and Cordilleran ice sheets and ice-free conditions over central Alaska. However, the southwestern and southeastern Laurentide margins fall shy of the target margins, which are defined loosely by the information in Figure 4.3.

4.4.2. Deglaciation and Holocene Survival

The two deglaciation scenarios depicted in Figs. 7 and 8 differ substantially. Experiment gcycle2b, the model run in which an instability mechanism is introduced, features a full

collapse of the Laurentide Ice Sheet (this could be taken as a termination) and attainment of modern conditions by 0 kyrs. The collapse occurs vigorously between -9 and -8 kyrs along the southern ice-sheet margin where proglacial lakes would have formed in newly uncovered isostatic depressions (Teller, 1987). This result is consistent with suggestions that proglacial lakes could have provided important calving sinks for accelerating Laurentide deglaciation (Pollard, 1983; Marshall et al., 2000). Experiment gcycle2b, on the other hand, does not lead to a termination. In this simulation, the Laurentide contracts from its maximum configuration, but eventually stabilizes over Hudson Bay. The ice sheet then expands for the latter half of the Holocene period in response to declining insolation. By 0 kyrs the ice sheet displaces sea level ~40 m from the modern baseline, and covers the Canadian Shield much as it did during MIS 4 and MIS 3.

The suggestion that the Laurentide Ice Sheet could still cover the Canadian Shield may be met with skepticism at first. However, if one considers that the Greenland Ice Sheet now spans a latitude band comparable to the Laurentide during Pleistocene interstades (60°N to 81°N), the claim becomes more credible. Consider also that the glaciation level (the altitude above which snow can persist year-round) over west Greenland ranges from 1600 m above sea level in the south to 500 m in the north, and that these values are effectively mirrored on the opposite side of Baffin Bay from northern Labrador to northern Ellesmere Island (Figure 4.9). Thus, a broad arc of eastern Canada is, in a sense, as suited for glaciation as Greenland; however, only Greenland now supports an ice sheet.

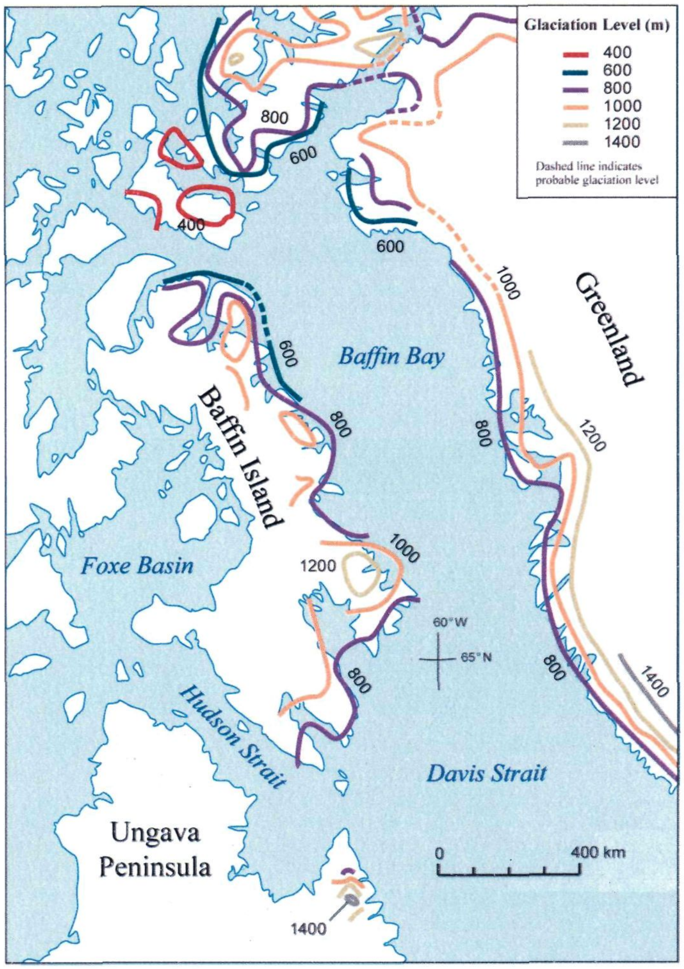


Figure 4.9. Glaciation level estimates for the Baffin Bay region. Adapted from Andrews (2002).

The simplest explanation for this conundrum is that the former Laurentide Ice Sheet collapsed due to a mechanical instability that has not yet devoured the Greenland Ice Sheet (Denton and Hughes, 1981). Indeed, snowline on the Greenland Ice Sheet is above sea level from north to south; this means the ice sheet survives by a surface-height mass-balance feedback, and that it would not reform under present climate if somehow removed from the system (Oerlemans and van der Veen, 1984). The experiments shown here demonstrate that the Laurentide Ice Sheet, if not rendered susceptible to mechanical disintegration, also could have survived the Holocene through feedbacks.

Although it is tempting to ascribe the Laurentide collapse to a specific mode of instability, the model utilizes only a simple parameterization for calving that includes a linear dependence on bed depth. Furthermore, at 40 km resolution, the model may not resolve features sufficiently to capture instabilities in ice streams. The model also excludes any means of changing basal sliding as a function of substrate type. In that vein, the model in its current configuration generates a single-domed MIS 2 maximum ice sheet with a peak altitude of ~4000 m. Future experimentation will examine conditions necessary for Heinrich-like events in which drawdown of interior ice produces distinct domes over Quebec and Keewatin. For now the model demonstrates that instability is a requisite for a complete termination, but the precise nature of the instability remains elusive.

4.4.3. Synthesis

In all, I propose the following synthesis: A glacial cycle develops in a feedback involving insolation, mountain and ice-sheet orography, and the cold air trough over eastern Canada (Ruddiman and Raymo, 1988). Given sufficiently low insolation and cool surface temperatures, the area of the Canadian Arctic north of the present-day tree limit undergoes rapid glaciation (Ives et al., 1975; Andrews and Barry, 1978). Once the Laurentide Ice Sheet is established, the North American stationary wave is amplified by albedo and orography feedbacks, causing a net expansion of the summer-season polar atmospheric cell. This enhanced cold air circulation pattern begins a positive feedback loop in which both the ice sheet and atmospheric trough expand southward in mutual response (Lindeman and Oerlemans, 1987). After the Laurentide reaches sufficient size, it amplifies insolation, "driving" global climate by affecting circulation changes across the North Atlantic region, thereby impacting meridional heat transports and altering the hydrological cycle (e.g., Romanova et al., 2006). The chain of feedbacks undoubtedly involves greenhouse gases (Paillard, 2001; Cheng et al., 2009). The glacial cycle proceeds until the Laurentide grows big enough to become unstable (Raymo, 1997). At this stage, the next appreciable insolation rise triggers peripheral ice-sheet contraction, then collapse, presumably by some mechanism linked to calving in over-deepened embayments along the ice-sheet southern margin (Pollard, 1983; Clark et al., 1999; Marshall et al., 2000), or in Hudson Strait (Hughes et al., 1977; Denton and Hughes, 1981; MacAyeal, 1979).

4.5. Conclusions

- An array of previous work suggests that the ~100-kyr "sawtooth" pattern of late Quaternary global ice-volume change could result from the Laurentide Ice Sheet amplifying summer insolation anomalies through orography feedbacks.

- A basic test of this hypothesis was conducted using an insolation-driven glaciological model that includes a formulation to amplify the North American standing wave over Canada as a function of ice area. The model also includes a marine calving parameterization for ice-sheet instability and collapse.

- The model used here was successful in replicating the low frequency components present in the global ice-volume proxy record. It also produced ice surfaces consistent with existing geomorphological interpretations of ice-sheet extent at various times during the last glaciation.

- It was found that the only way to produce a termination in the model is to increase marine calving sensitivity at the end of Marine Isotope Stage 2, thereby providing a means for the Laurentide to disintegrate mechanically over Hudson Bay. An important find is that if instability is omitted from the model solution, the Laurentide survives Holocene insolation and remains to cover the Canadian Shield, lowering sea level by more than 40 m at present time.

- In conclusion, the model results here emphasize both the importance of the North American stationary wave in the development of the Laurentide Ice Sheet, and the subsequent role of the ice sheet in translating summer insolation to global sea level. Future work could improve upon this study by simulating a Northern Hemisphere glacial cycle in a fully coupled ice sheet-atmosphere-ocean model.

CHAPTER 5: CONCLUSIONS

5.1 Summary

This dissertation is a compilation of work that began as a glaciological investigation of the Laurentide Ice Sheet. The study evolved out of necessity to expand the capability of the existing University of Maine Ice Sheet Model (UM-ISM) to address ice-sheet/climate integration over local and continental scales.

One unintended, but important result of modifying the UM-ISM was development of the University of Maine Environmental Change Model (UM-ECM). The UM-ECM is a web-based climate model that generates equilibrium biome and snow/ice mass balance solutions at high resolution for the entire globe. This model has both research and teaching applications that have been tested in this study. Particularly important aspects of the UM-ECM are 1) the ability to generate local and global climate solutions at up to 1 km resolution, 2) program availability through an intuitive web interface, and 3) the integration of the model with the UM-ISM for topography and climatology input grids.

In Chapter 2 of this dissertation, I examined educational applications of the UM-ECM. In the first example, I reported how participants of the ITEST/IDEAS program conducted experiments to test under what conditions North America might become glaciated in accord with existing geologic data. The group found that linear departure from modern climate was insufficient to produce the known changes, and that glaciation instead must

have arisen from nonlinear changes in global circulation patterns. In a second example, participants examined local-scale equilibrium biome distribution across the northeastern U.S. and Canada in response to mean-annual temperature change. As part of these exercises, the seminar group viewed model results on a multiple-panel display wall. This afforded solution interrogation at high resolution over a broad geographic area, which emphasized the behavior of processes over a range of scales.

In Chapter 3, I discussed the application of the UM-ISM and UM-ECM to the problem of Pleistocene glaciation in the Wind River Mountains, Wyoming. The purpose of this modeling exercise was in part to compliment my reconstruction of the Laurentide Ice Sheet (reported in Chapter 4), and in part to provide ice cap-climate sensitivity information for a University of Maine field research project investigating worldwide glacier recession during the last glacial termination. Results of this study follow. 1) The former Pinedale and Bull Lake stade ice caps probably formed in response to a 5-6 °C cooling in addition to 200-250% precipitation relative to modern climate. 2) The ice-cap glaciation threshold over the mountain range is approximately a relative cooling of 3 °C cooling in conjunction with 175% precipitation. 3) The maximum ice cap could disappear in under a century if forced by modern climate. 4) Following collapse of the ice cap during the termination, the advance of cirque glaciers and deposition of Temple Lake moraines during late glacial time probably occurred under a climate similar to, but slightly cooler than that of the recent Little Ice Age. In all, this research supports previous hypotheses that the western U.S. was wetter during glacial stades due to a southward-displaced storm track in response to Laurentide Ice Sheet orography, and that

the glacier systems of the western U.S. were exceptionally sensitive to large-scale circulation changes during the termination.

In Chapter 4, I produced a glaciological reconstruction of the Laurentide Ice Sheet over the last glacial cycle, and discussed the role of the Laurentide in driving climate through orography feedbacks. Specifically, I developed and tested a hypothesis that the pattern of global sea level change over the last 140 kyrs could be reproduced in the model by expanding and contracting the cold air trough over eastern Canada as a function of summer insolation anomaly and size of the ice sheet. I also examined the role of glaciological instability during the last deglaciation. The results support the first hypothesis, and show that in the absence of mechanical collapse, the Laurentide could have survived the Holocene period maintaining an ice sheet big enough to lower global sea level by ~40 m at present time. I therefore concluded that the Laurentide Ice Sheet feedback web is a crucial mechanism for translating Northern Hemisphere summer insolation into the basic signal of ice age climate.

5.2 Suggestions for Future Work

This dissertation provides a framework for using the UM-ISM and UM-ECM for climate research and teaching. It also adds to the understanding of key problems pertaining to ice-age cycles and the glaciation of North America. Several avenues of future work that expand upon this study warrant consideration:

- The UM-ECM currently bases biome and mass balance solutions on modern climatology datasets. Climate change is produced in the model by applying linear temperature and precipitation shifts. Thus, the model excludes a means for producing nonlinear circulation changes to input parameters. Although the model is non-dynamical by design, past climates could be simulated with more realism by including general circulation model grids for the last glacial maximum. In this case, climate could be defined in the model as some fraction of modern and glacial end members depending upon user-input parameter settings.

- Although the Wind River analysis demonstrates the high-resolution capability of the UM-ISM, I neglected to perform sensitivity tests on the Shallow Ice Approximation method employed by the model. Although I am confident based on my review of existing literature that the Wind River solutions are robust, it could be a worthwhile venture to compare model output using different bedrock grid resolutions (e.g., 0.5 km, 0.6 km, 0.7 km, and so on). This type of analysis could be done for the Wind Rivers, or for ice cap systems elsewhere. It is conceivable that a future study could employ both UM-ISM, and a three-dimensional full-Stokes ice sheet model, such as one under development at the University of Maine (Sargent, 2009).

- Also in regard to the Wind Rivers, future work could investigate the impact of seasonality on the ice cap system. In the current study, I assume that climate change is distributed equally throughout the annual cycle. However, both the

accumulation of winter snow, and the sum of melting degrees in the mass balance calculation carry a dependence upon monthly temperature. Therefore, strong seasonal temperature and precipitation biases would impact the net surface mass balance, and could in turn impact the glaciological solution in measurable ways. The most likely situation is that thermal seasonality change is minimal, but that glacial precipitation increase is predominantly in winter (e.g., Kutzbach et al., 1998).

- The Laurentide Ice Sheet study could be improved in the future in two important ways. First, the glacial cycle experiment wherein the Canadian cold trough expands in concert with the Laurentide Ice Sheet could be redone in a coupled ice sheet-atmosphere-ocean model. Modern general circulation models include physics that would produce a dynamical atmospheric response to changes in ice cover; thus, a GCM should yield a more robust solution than that possible from the simple parameterization used in this study. In this vein, Ganopolski et al., 2010 report an insolation-driven coupled model of intermediate complexity for the last glacial cycle. It is reassuring that the ice volume signal output from UM-ISM is similar to that from the coupled model. The present study remains unique, because Ganopolski et al. focus on greenhouse gas-insolation feedbacks without explicit discussion on Laurentide Ice Sheet orography feedbacks.

- The second way in which the Laurentide Ice Sheet study could be improved is to refine the calving parameterization. In the current treatment, grounding-line mass

flux is modified on the basis bed depth and a calving parameter tuned to trigger ice-sheet collapse from a Thomas (1979) instability. A more physical formulation would be to vary mass flux as a function of longitudinal stresses at the grounding-line due to thinning of a two-dimensional ice-shelf buttress (Weertman, 1957). Here, the calving parameter would represent buttress strength, and it could be linked to an external climate signal, such as ocean temperature. The usefulness in this approach would be that the calving formulating might work consistently throughout a glacial cycle, instead of having to be turned on only for the termination.

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APPENDIX A: UNIVERSITY OF MAINE ICE SHEET MODEL

The University of Maine Ice Sheet Model (UM-ISM) is a multi-component finite element solution of ice-sheet physics (Fastook, 1993; Fastook and Prentice, 1994; Kleman et al., 2002). Components include mass and momentum conservation for ice dynamics, energy conservation for internal ice temperatures, a hydrostatically supported elastic plate for bed depression and rebound, a conservation of water-based basal water solver, a simple climatology module for surface temperatures and mass balance, and a simple grounding-line ice-thinning (or calving) parameterization for collapsing marine ice domes. The ice-flow solution includes a force balance based on the Shallow Ice Approximation method (Hutter, 1983).

Problem domains are defined in UM-ISM on a spatially distributed quadrilateral grid of nodal points. Required inputs are gridded bedrock topography and climatology, the latter consisting of monthly mean temperature and precipitation. In this study, bedrock and climatology datasets from various sources are prepared for UM-ISM input using the UM-ECM (see Chapter 2).

The existing UM-ISM climatology module was reworked extensively for this dissertation. Modifications include an improved interpolation scheme for scaling temperature and precipitation grids, and a framework for importing high-resolution datasets exported by the UM-ECM. Surface mass balance is found by summing frozen precipitation amounts for months in which the mean temperature is below 0 °C, and then

reducing this amount by the sum of melting degrees (md) divided by either snow or ice melt rates (see Figure 2.2). The melt rates are defined as 0.3 and 0.8 mm/md water equivalence for snow and ice, respectively (e.g., Braithwaite and Olesen, 1989). The snow melt rate is used in the initial ablation calculation; if all snow is melted, and melting degrees remain available to drive further ablation, then the ice melt rate is used for the remainder of the calculation. This method assumes that winter snow accumulates on top of glacier ice. Note that in the mass balance calculation temperature fields are scaled to bedrock and ice topography using a vertical lapse rate of -6 °C/km.

The UM-ISM calving parameterization is used in this dissertation only in Chapter 4. Here, the parameter provides a means to collapse marine-based portions of the Laurentide Ice Sheet by the Thomas instability (Thomas, 1979). In this mechanism, mass flux at the ice grounding-line is increased with a dependence on bed depth and the calving value. The latter varies from 0 (no mass-flux enhancement) to 1 (maximum enhancement). A scale factor is used to tune the calving parameter for individual experiments. The calving treatment employed by UM-ISM is similar to that used in other models (e.g., Marshall et al., 2000; Zweck and Huybrechts, 2005).

APPENDIX B: LAURENTIDE CLIMATOLOGY FORMULATION

One of the most challenging tasks of paleo ice-sheet modeling is developing a climatology scheme that ensures realistic mass balance conditions for both the present and past. The problem can be simplified by viewing past climate as a departure from the present mean, and by defining climate end members, interglacial and glacial. In that vein, I constructed an algorithm to modify the input NCEP temperature and precipitation fields for each month of the year with a dependence on a climate-forcing signal; the forcing signal itself is a function of summer insolation anomaly and ice area. The result is a climate continuum from interglacial (modern temperature and precipitation distribution) to glacial (features a deepened cold trough over eastern Canada) based on insolation and size of the modeled ice sheet.

The anomaly signal serving as the basic input to the climatology scheme is derived from 60 °N summer insolation values from Berger and Loutre (1991) (e.g., Figure 4.4). This curve is translated to a climate forcing through several steps. First, the signal itself is amplified each iteration as a function of total ice area contained within the map plane:

$$A_{mult} = (A_{mult\_max} - 1) * \sin(A_{ice} * 0.5 * pi / A_{ice\_LGM}) + 1$$

$$\text{IF } (A_{ice} > A_{ice\_LGM}) \text{ THEN } (A_{mult} = A_{mult\_max})$$

$$T_{anom} = A_{mult} * (T_{anom} - 1) + T_{anom} - T_{adj} + 1$$

Where A_{mult} is the area amplification term, A_{mult_max} is amount of amplification for Last Glacial Maximum (LGM) ice sheets (4.6), A_{ice} is the current model ice area, A_{ice_LGM} is the area of LGM ice sheets (14×10^7 km^2), T_{anom} is the insolation temperature anomaly, and T_{adj} is the modern insolation anomaly (-0.3634 °C).

The next step is to construct a synthetic thermal field that will be combined with NCEP data in a weighted average. A weighted average is used to allow a gradual transition from modern to glacial climate conditions. The synthetic field, with point values calculated using a horizontal lapse rate and distance from a climate pole situated over Baffin Bay, is tuned to produce a cold anomaly over eastern Canada. The climate pole-based thermal field gains heavier weighting relative to the NCEP field as ice area increases:

$$T_{pole\_xy} = T_{pole} + \text{vlapse} * \text{elev\_xy} - \text{hlapse} * (\text{lat\_xy} - 90\ °\text{lat}) + T_{anom}$$

$$m = (\text{pole\_wt\_LGM} - \text{pole\_wt\_modern}) / (A_{ice\_LGM} - A_{ice\_modern}) * A_{ice\_LGM}$$

$$b = \text{pole\_wt\_LGM} - m * A_{ice\_LGM}$$

$$\text{pole\_wt} = m * A_{ice} + b$$

$$\text{IF (pole\_wt} > \text{pole\_wt\_LGM) THEN (pole\_wt} = \text{pole\_wt\_LGM)}$$

Where T_{pole_xy} is the gridpoint temperature on the synthetic field, T_{pole} is the temperature at the climate pole (0 °C), vlapse is the vertical lapse rate (-6 °C/km), elev_xy is the gridpoint elevation, hlapse is the horizontal lapse rate (0.5 °C/°lat), lat_xy is the gridpoint latitude, pole_wt_LGM is pole weighting for LGM ice cover, pole_wt_modern is pole

weighting for modern ice cover, pole_wt is the pole weighting term, and m and b are the slope and y intercept terms for pole_wt, respectively.

The resultant thermal field is then used as a July datum from which to calculate the remaining monthly temperature fields for later mass-balance determination. To do this, a seasonal cycle is used based on a sine wave with amplitude of 30 °C and maximum temperature of 0 °C. A gridpoint temperature for any given month is found by adding the monthly value to T_{pole_xy}. Note that inclusion of a vertical lapse rate affords the ability to change the surface temperature field due to ice topography.

The next step in the climatology formulation is a modification of the NCEP precipitation input. This transformation is much simpler than that contrived for the temperature fields. Here a linear relationship is made in which the precipitation at each gridpoint caries a temperature-anomaly dependence, and varies by some percentage of the modern input precipitation value:

$$P_{mult} = (P_{mult\_LGM} - P_{mult\_modern}) / (T_{anom\_LGM}) * T_{anom} + P_{mult\_modern}$$

$$P_{xy} = P_{NCEP\_xy} * P_{mult}$$

Where P_{mult} is the precipitation multiplier, P_{mult_LGM} is the LGM precipitation factor (0.625; i.e., when T_{anom} = -6 °C), P_{mult_modern} is the modern precipitation factor (1; i.e., when $T_{anom} = T_{adj}$), P_{xy} is the gridpoint precipitation, and P_{NCEP_xy} is the gridpoint input precipitation.

The precipitation multiplier for the LGM is a best fit derived from a visual comparison of the NCEP annual precipitation field to that of the GENESIS general circulation model of the LGM (Thompson and Pollard, 1995). The GENESIS solution is not incorporated into the climatology formulation for the simplicity of using only one external dataset. Moreover, the GENESIS temperature and precipitation fields reflect glacial maximum ice-sheet topography, which is problematic for growing ice sheets from scratch.

BIOGRAPHY OF THE AUTHOR

Sean Birkel was born in Bangor, Maine on March 16th, 1978. He was raised in his hometown and graduated from Bangor High School in 1996. Sean attended the University of Maine where he graduated with a Bachelor's degree in Geological Sciences in 2002. As an undergraduate, Sean attended a geology field program run by the University of Wyoming. Sean stayed at the University of Maine to pursue a Master's degree through the Climate Change Institute. He participated in field research in Antarctica as part of this program. Sean graduated in 2004 with a focus on Quaternary geology and ice sheet modeling. He is a candidate for the Doctor of Philosophy degree in Earth Sciences from the University of Maine in December, 2010.