Climatic factors influencing Last Glacial Maximum and modern glacial conditions in the tropical and subtropical Andes

Lauren Vargo

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Joseph Galewsky, Chairperson

Peter Fawcett

Grant Meyer
CLIMATIC FACTORS INFLUENCING LAST GLACIAL MAXIMUM AND MODERN GLACIAL CONDITIONS IN THE TROPICAL AND SUBTROPICAL ANDES

by

LAUREN J. VARGO

B.A. GEOLOGY, THE COLLEGE OF WOOSTER, 2013

THESIS
Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Earth and Planetary Sciences

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I thank Summer Rupper, who provided the model used in this study, and Dylan Ward, both of whom offered insightful comments and valuable help throughout the project.

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ABSTRACT

Geomorphic evidence indicates that the presently unglaciated subtropical Andes (18.5° - 27°S) have previously sustained glaciers. However, the timing of glaciation and the mechanisms driving it are still poorly known. This study uses a full surface energy and mass balance model, driven using general circulation model output, to better understand the potential for past glaciation in the region and to identify the climatic forcings that may drive glaciation in the tropical and subtropical Andes. Model results show average Last Glacial Maximum (LGM) equilibrium line altitude (ELA) depressions to be approximately 600 m in the tropics and 800 m in the subtropics, consistent with studies that suggest the subtropical Andes were glaciated at LGM. While previous studies have found that the subtropical Andes are presently unglaciated due to low precipitation, idealized experiments show that lower LGM temperatures play the largest role in overall lowering of ELAs at that time. Furthermore, results show that shortwave radiation plays a significant role in driving tropical and subtropical ELAs. Results indicate that LGM decreases in shortwave radiation contributed to over 30% of total ELA depressions in the
tropical Andes. In the subtropical Andes, decreases in shortwave radiation are shown to be as important as increases in precipitation during LGM. While previous modeling shows that a 4-5 fold increase in precipitation would have been necessary to glaciate the subtropical Andes, our results suggest that only a 50% increase in precipitation, in conjunction with a decrease in shortwave radiation and decrease in temperatures, would have been sufficient.
PREFACE

This preface outlines the role of each coauthor that contributed to this thesis, which will be submitted as a manuscript to a peer-reviewed journal. In accordance with the Department of Earth and Planetary Sciences’ guidelines, Lauren J. Vargo will be the first author of the manuscript, and has done more than 51% of the research and preparation for publication. Joseph Galewsky provided guidance and feedback on all aspects of this project. Summer Rupper (Brigham Young University) provided the Surface Energy and Mass Balance (SEMB) model that is used for this work, and has provided guidance for using the model and interpreting results. The idea for this project stems from observations of glacial features in the Atacama Desert, made by Joseph Galewsky and Dylan Ward (University of Cincinnati). Dylan Ward has also offered guidance throughout the project, especially in providing a comprehensive overview of the literature for the subtropical Andes, and in interpreting results. Lauren Vargo ran the SEMB model using general circulation model output obtained through the Earth System Grid Federation, analyzed results, and wrote the manuscript, with comments added by Joseph Galewsky, Summer Rupper, and Dylan Ward.
# TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................ viii
LIST OF TABLES ............................................................................................................ ix

1. INTRODUCTION ........................................................................................................1

2. BACKGROUND ..........................................................................................................3

3. METHODOLOGY .......................................................................................................7
   3.1 Surface Energy and Mass Balance Model ..............................................................7
   3.2 General Circulation Models .................................................................................9
   3.3 Modeling Approach .............................................................................................10

4. RESULTS ..................................................................................................................11
   4.1 Climate during the Last Glacial Maximum .........................................................11
   4.2 Modeled ELAs ..................................................................................................13
   4.3 Modeled Ablation ..............................................................................................16
   4.4 Idealized Experiments .......................................................................................17

5. DISCUSSION ...........................................................................................................19

6. CONCLUSIONS .......................................................................................................21

REFERENCES ............................................................................................................22
LIST OF FIGURES

Figure 1. Grayscale DEM with locations of modern glaciers (shown in black) in the tropical and subtropical Andes (0° – 30°S) edited from the World Glacier Inventory [WGMS, and National Snow and Ice Data Center, 1999, updated 2009]. Areas within the subtropics that have been previously glaciated, based on Jenny et al. [1996], Ammann et al. [2001], and Ward et al. [in review], are marked with boxes. ..............................................................2

Figure 2. Modern austral summer (December, January, February) (A) temperature (°C), and (B) precipitation (m/yr) taken as the 30 year average (December, 1984 – February, 2014) from ERA-Interim reanalysis data [European Centre for Medium-Range Weather Forecasts, 2009]. Western South America coast line is in gray ........................................................................................................5

Figure 3. Modern austral summer (A) shortwave radiation (W/m²), and (B) cloud fraction (%) taken as the 14-year average (December, 2000 – February, 2014) from CERES EBAF data [Loeb et al., 2009]. Western South America coast line is in gray ........................................................................................................6

Figure 4. Change in austral summer (A) temperature (°C), (B) accumulation (%), and (C) shortwave radiation (W/m²) for LGM compared to modern based on CCSM4 [Blackmon et al., 2001; Shin et al., 2003]. Western South America coast line is in gray, positive contours are solid lines, negative contours are dashed lines, and the zero contour is bold........................................................................................................12

Figure 5. Grayscale DEM of the tropical and subtropical Andes for the (A) modern and (B) Last Glacial Maximum, showing where the topography intersects modeled ELAs. Previously glaciated areas within the subtropics are marked with boxes...15

Figure 6. Relationship between percent of ablation due to melt and (A) mean annual temperature at the ELA (°C), (B) total annual precipitation (m/yr), and (C) mean annual shortwave radiation (W/m²) for each LGM CCSM4 grid point between 0° and 30°S with an elevation greater than 1,500 m .................................................................17
LIST OF TABLES

Table 1. Modeled ELA depression during LGM compared to modern......................14
Table 2. Relative importance of different climatic forcings in the tropical Andes.........18
Table 3. Relative importance of different climatic forcings in the subtropical Andes.....19
1. Introduction

While the subtropical Andes (18.5° - 27°S) are unglaciated today, geomorphic evidence suggests the presence of past glaciers in the region, including in the El Tatio area (22.5°S) [Graf, 1991; Ammann et al., 2001] and on the Chajnantor Plateau (23.0°S) [Ward et al., in review] (Figure 1). However, the timing of glaciation is uncertain, with some studies finding evidence for late glacial times (15-12 ka) [Kull and Grosjean, 2000; Ammann et al., 2001], and others the global Last Glacial Maximum (LGM; 21 ka) [Grennon, 2007; Ward et al., in review].

In addition to timing, the climatic forcings controlling glaciation in the subtropical Andes are not well understood. The influences of temperature and precipitation on past and present glaciation of the Andes have been the focus of several studies, all of which conclude that the arid subtropical Andes are most sensitive to precipitation [Klein et al., 1999; Ammann et al., 2001; Sagredo et al., 2014]. However, the influence of shortwave radiation in this region has received less attention. This is despite previous studies of low-latitude African glaciers that found shortwave radiation is one of the most important climatic parameters in determining glacial mass balance [Kruss and Hastenrath, 1987; Mölg et al., 2003a; Mölg et al., 2003b].
Figure 1. Grayscale DEM with locations of modern glaciers (shown in black) in the tropical and subtropical Andes (0° – 30°S) edited from the World Glacier Inventory [WGMS, and National Snow and Ice Data Center, 1999, updated 2009). Areas within the subtropics that have been previously glaciated, based on Jenny et al. [1996], Ammann et al. [2001], and Ward et al. [in review], are marked with boxes.

Previous modeling studies have explored the relationship between glaciers and climate, either in identifying climatic controls behind glacier fluctuations, or explaining glacial response to changes in climate [e.g. Braithwaite and Zhang, 2000; Kull and Grosjean, 2000; Kaser, 2001; Rupper and Roe, 2008; Rupper et al., 2009; Sagredo et al., 2014]. This study uses a surface energy and mass balance (SEMB) model [Rupper and
Roe, 2008] to calculate equilibrium line altitudes (ELAs), the elevation of the glacier surface where annual accumulation is equal to annual ablation. In general, the ELA lowers as a glacier advances and rises as a glacier retreats. Numerical modeling of ELAs makes it possible to explore the relationship between regional climate and glacial conditions. The goal of this study is to use the SEMB model driven by general circulation model (GCM) output in order to better understand past glaciation of the subtropics, as well as explore the climatic forcings driving glaciation in both the tropical and subtropical Andes.

2. Background

Temperature and precipitation are directly related to accumulation and ablation, and therefore are important to the energy and mass balance of a glacier. In the northern Andes, austral summer (December, January, February) temperatures drive ablation, and austral summer precipitation, the wet season for this region, is closely related to accumulation [Francou et al., 2003]. Modern temperatures in the tropical and subtropical Andes are comparable, with temperatures in the unglaciated subtropical Andes being as cold as temperatures in parts of the glaciated tropical Andes (Figure 2a). However, there is a large difference in precipitation between the two regions. The tropical Andes, where summertime precipitation is greater than 0.3 m in the many areas, are significantly wetter than the arid subtropical Andes, where summertime precipitation is below 0.05 m in many areas [Vuille and Keimig, 2004; European Centre for Medium-Range Weather Forecasts, 2009].
These cold and arid conditions have led previous studies to focus mainly on the importance of temperature and precipitation on glaciation of the subtropical Andes, with other possible climatic forcings receiving less attention. Ammann et al. [2001] conclude that because the 0°C isotherm today lies below the summit of many peaks, past glaciation would have required an increase in precipitation and humidity. Klein et al. [1999] also point out that modern snowlines in the presently arid Andes are above the 0°C isotherm, and explain glaciation in the region by wetter conditions in conjunction with a decrease in temperatures. Sagredo et al. [2014] focus on modern ELA sensitivity in the Andes, and find that glaciers in the arid subtropics are most sensitive to changes in precipitation, while glaciers in the tropical Andes are less sensitive to changes in precipitation and more sensitive to changes in temperature.
Figure 2. Modern austral summer (December, January, February) (A) temperature (°C), and (B) precipitation (m/yr) taken as the 30 year average (December, 1984 – February, 2014) from ERA-Interim reanalysis data [European Centre for Medium-Range Weather Forecasts, 2009]. Western South America coast line is in gray.

In conjunction with low precipitation, the subtropical Andes also receive significantly higher levels of shortwave radiation than the tropical Andes (Figure 3a). In fact, the highest downwelling solar radiation on Earth, over 300 W/m², is located within the subtropical Andes (24° - 25°S) due to low values of water vapor, cloud cover, ozone, and aerosols together with high elevations and low latitudes [Rondanelli et al., 2015]. High levels of shortwave radiation are due in part to the low percentage of cloud cover in the subtropical Andes (Figure 3b), which is tied to the low precipitation in the region (Figure 2a).
**Figure 3.** Modern austral summer (A) shortwave radiation (W/m$^2$), and (B) cloud fraction (%) taken as the 14-year average (December, 2000 – February, 2014) from CERES EBAF data [Loeb et al., 2009]. Western South America coast line is in gray.

The importance of shortwave radiation on low-latitude glaciers, and the connection between shortwave radiation, cloudiness, and precipitation, have been shown in previous studies. Kruss and Hastenrath [1987] find that high levels of shortwave radiation play a key role in ablation of African glaciers, with cloudiness identified as the most important factor in reducing incoming radiation. Further modeling results indicate that drier conditions and decreases in cloud cover in east Africa since 1880 have led to increased shortwave radiation, which is shown to be the main climatic parameter contributing to glacial retreat on Kilimanjaro [Mölg et al., 2003a; Mölg et al., 2003b].
the Andes, *Vuille et al.* [2008] acknowledge that cloudiness, and the associated incoming radiation, are among the climatic forcings controlling tropical glaciers. *Kull and Grosjean* [1998] show that humid conditions and decreases in summertime shortwave radiation during late glacial times coincide with the expansion of paleolakes and glacial advances. *MacDonell et al.* [2013] find that ablation of one subtropical Andean glacier (29°S) is dominated by sublimation, which is strongly influenced by incoming shortwave radiation. Despite findings highlighting the importance of shortwave radiation on low-latitude glaciers, previous studies that have discussed why the subtropical Andes are presently unglaciated have not focused on the influence of high levels of shortwave radiation in the region.

In this study we explore the influence of climatic forcings on glaciation of the tropical and subtropical Andes during the Last Glacial Maximum, including incoming shortwave radiation, temperature, and precipitation.

### 3. Methodology

#### 3.1 Surface Energy and Mass Balance Model

A full surface energy and mass balance (SEMB) model presented in *Rupper and Roe* [2008] is used to explore the relationship between ELAs in the tropical and subtropical Andes and climate. Model inputs include monthly mean atmospheric pressure, relative humidity, downwelling shortwave radiation, surface temperature, atmospheric emissivity, and wind speeds, as well as annual accumulation and adiabatic temperature lapse rate. Atmospheric emissivity is calculated using downwelling longwave radiation and surface temperature, and the lapse rate is calculated based on the
difference between the temperature one geopotential height above the surface and the surface temperature. The model uses two nested algorithms involving surface energy balance and mass balance to calculate the ELA, i.e., altitude at which a glacier would be in mass and energy balance over the annual cycle.

The energy balance algorithm solves for the surface temperature resulting in a surface energy balance equaling zero. If the resulting surface temperature is less than zero, and the atmospheric vapor pressure is less than the saturation vapor pressure of the surface, sublimation occurs. If the resulting surface temperature is greater than or equal to zero, the surface temperature is reset to zero, the energy balance is recalculated, and the excess energy is used to calculate the total melt. Total ablation is equal to the sum of sublimation and melt. The mass balance algorithm seeks the elevation at which the mean annual air temperature results in total annual ablation that is equal to total annual accumulation. Thus the ELA is the altitude at which both an energy and mass balance is achieved over the annual cycle.

The model assumes that all precipitation at the ELA is snow, which maximizes accumulation. Model parameters, including annual albedo, roughness lengths, and ice and firn density are the same as in Rupper and Roe [2008]. Sensitivity analysis, presented in Rupper and Roe [2008], show that modeled equilibrium line altitudes are most sensitive to albedo. Annual albedo of two subtropical Andean glaciers (29°S) has been shown to range between approximately 0.2 and 0.95 [Abermann et al., 2014]. In general, albedo ranges between 0.35 for pure ice and 0.85 for fresh snow [Cuffey and Paterson, 2010]. For this study we set albedo to 0.6, the intermediate between the two values, for both LGM and modern simulations.
Other methods of modeling ELAs include using a positive degree-day (PDD) model for ablation, which assumes that the total snow and ice that is melted is directly related to temperature [e.g. Braithwaite, 1995]. However, in reality ablation is due to the net heat input into the system. Therefore, modeling ELAs using surface heat fluxes is preferred over the simpler PDD approach, especially in regions, like the subtropical Andes, where sublimation dominates ablation [Rupper and Roe, 2008; Rupper et al., 2009].

3.2 General Circulation Models

The surface energy and mass balance model [Rupper and Roe, 2008] used in this study is driven using a suite of general circulation models (GCMs; Table 1) that are part of the third phase of the Palaeoclimate Modeling Intercomparison Project (PMIP3) [Braconnot et al., 2012] and the fifth phase of the Coupled Model Intercomparison Project (CMIP5) [Taylor et al., 2012]. CMIP5 provides protocol for climate model experiments, and PMIP3 is an initiative that focuses on simulations of past climate and falls within this protocol. From each of the four GCMs, we use pre-industrial control experiments to simulate modern glaciation, and 21 ka experiments to simulate LGM glaciation. The pre-industrial control experiment is an unforced control run with pre-industrial conditions, and is consistent with CMIP5 requirements. The 21 ka experiment is consistent with both CMIP5 and PMIP3, and sets variables including trace gases, ice sheet extent, land surface elevation, ice sheet mass balance, mean ocean salinity, and insolation to Last Glacial Maximum conditions.
3.3 Modeling Approach

The model is first used to estimate ELA depressions during the Last Glacial Maximum using the suite of GCMs. ELA depressions presented are calculated as the mean change in ELA between the LGM and modern for all grid cells with elevations greater than 1,500 meters in the tropical Andes (0° – 18.5°S) and the subtropical Andes (18.5° – 27°S). The model is also used to calculate the fraction of ablation due to melt, making it possible to determine the relationship between different climate parameters and the dominant ablation process.

The SEMB model is then used to gain insight into why the tropical Andes have been continuously glaciated since the LGM [e.g. Thompson et al., 1998] while glaciers no longer exist in the subtropics, and is used to better understand how ELAs may have responded to changes in different climate parameters. We use pre-industrial control output from CCSM4 (Community Climate System Model, version 4) to run idealized experiments with the goal of determining the relative importance of different climate parameters, including shortwave radiation, accumulation, and temperature, on ELAs. As the SEMB model calculates ELAs based on energy fluxes, temperature is directly related to the longwave radiation, shortwave radiation, sensible heat, and latent heat fluxes. In this study, temperature is used as a proxy for these fluxes in order to make results comparable to previous [e.g. Clayton and Clapperton, 1997; Klein et al., 1999; Kull and Grosjean, 2000; Ammann et al., 2001; Sagredo et al., 2014] and future glacial studies, in which temperature and precipitation are the climatic conditions commonly analyzed.
4. Results

4.1 Climate during the Last Glacial Maximum

Because glaciers respond primarily to changes in climate, past climatic conditions of a region can be used to reconstruct former ELAs, and better understand the glacial history of the region. GCM output can be used to analyze how climate changed between the LGM and modern. Figure 4 shows the difference in austral summer (December, January, and February) temperature, precipitation, and shortwave radiation based on CCSM4 [Blackmon et al., 2001; Shin et al., 2003]. Mean temperature depressions at LGM in the tropics and subtropics are comparable, with model output showing both regions were 3° to 4°C colder at LGM (Figure 4a).

Model output shows that tropical Andes were generally slightly drier during the LGM, while the subtropical Andes were wetter, receiving 20 - 40% more precipitation (Figure 4b). This increase in precipitation throughout the subtropical Andes and decrease in precipitation in the tropical Andes at LGM are consistent across three of the four GCMs analyzed in this study (CCSM4, GISS-E2-R, MIROC-ESM). The fourth GCM, MRI-CGCM3, shows an increase in precipitation in the subtropics south of ~27°S, but a slight decrease in LGM precipitation in the northern subtropics. GCM modeled increases in subtropical precipitation are consistent with previous studies that use proxy records to conclude that the subtropical Andes were wetter at LGM [e.g. Bobst et al., 2001; Maldonado et al., 2005; Placzek et al., 2013].

CCSM4 output also shows that the subtropical Andes received less shortwave radiation during the LGM compared to today (Figure 4c), which is likely due, in part, to the increase in precipitation and associated increase in cloudiness. Changes in shortwave
radiation in the tropical Andes are not as straightforward. CCSM4 output shows that the northern tropics received less shortwave radiation during the LGM, while a small region in the southern tropics received more (Figure 4c). The decrease in shortwave radiation in the tropics at LGM is consistent with results from two of the other GCMs used in this study, GISS-E2-R and MIROC-ESM.

![Figure 4](image_url)

**Figure 4.** Change in austral summer (A) temperature (°C), (B) accumulation (%), and (C) shortwave radiation (W/m²), for LGM compared to modern based on CCSM4 [Blackmon et al., 2001; Shin et al., 2003]. Western South America coast line is in gray, positive contours are solid lines, negative contours are dashed lines, and the zero contour is bold.

Despite the consistency across GCMs, the relationship between precipitation and shortwave radiation in the tropics is the opposite as seen in the subtropics, where more LGM precipitation contributes to less shortwave radiation through an increase in cloudiness. While cloud cover influences shortwave radiation, it is also influenced by
additional factors including orbital configuration, the number of air molecules, ozone, and aerosols [Rondanelli et al., 2015], all of which influence shortwave radiation in the tropics.

4.2 Modeled ELAs

Table 1 shows the modeled equilibrium line altitude depressions during LGM for the tropical (0° - 18.5°S) and the subtropical (18.5° - 27°S) Andes at elevations over 1,500 m. The four GCMs consistently show that between LGM and modern, the change in ELAs in the subtropics is greater than in the tropics. The highest resolution GCM, CCSM4, shows that average ELA depressions in the subtropics are 190 m greater than average ELA depressions in the tropics. ELA depressions calculated from MRI-CGCM3 show only a 40 m difference, while depressions calculated from MIROC-ESM are suppressed in the tropics and greatly enhanced in the subtropics compared to the other GCMs. Modeled ELA depressions presented here are of similar magnitudes as those calculated in previous studies in the northern Andes [Klein et al., 1999; Ammann et al., 2001].
Table 1. Modeled ELA depression during LGM compared to modern

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Resolution</th>
<th>ΔELA (m): Tropics (0° - 18.5°S)</th>
<th>ΔELA (m): Subtropics (18.5° - 27°S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM4</td>
<td>0.94° x 1.25°</td>
<td>-620</td>
<td>-810</td>
</tr>
<tr>
<td>[Blackmon et al., 2001; Shin et al., 2003]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GISS-E2-R</td>
<td>2° x 2.5°</td>
<td>-430</td>
<td>-970</td>
</tr>
<tr>
<td>[Schmidt et al., 2006]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>2.8° x 2.8°</td>
<td>-270</td>
<td>-1590</td>
</tr>
<tr>
<td>[Watanabe et al., 2011]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>1.125° x 1.125°</td>
<td>-650</td>
<td>-690</td>
</tr>
<tr>
<td>[Yukimoto et al., 2012]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 shows a high-resolution digital elevation model (DEM) with colors indicating the extent to which modeled ELAs intersect the topography, or where glaciers are likely to exist. Figure 5a shows predicted areas of modern glaciation in the tropical and subtropical Andes. While the SEMB model shows more extensive glaciation in the tropics compared to the subtropics, it does appear to over-predict glaciers, as we know that the Andes between 18.5° - 27°S are presently unglaciated. This over-prediction of glaciers is likely due to several factors. First, the CCSM4 model overestimates precipitation in the subtropical Andes, with modern output showing summer precipitation to be approximately 0.6 m, while ERA-Interim reanalysis data indicates summer precipitation to be less than 0.2 m (Figure 2a). Second, the SEMB model assumes that all precipitation falls as snow at the ELA, which also overestimates the accumulation.

Figure 5b shows the same high-resolution DEM, with predicted glaciers during the Last Glacial Maximum calculated using CCSM4 21 ka output. There is a clear increase in glaciation, including in the subtropical Andes, at LGM. Hollow boxes mark previously glaciated regions within the subtropics, based on Jenny et al., [1996], Ammann...
et al. [2001], and Ward et al. [in review]. There are several locations between 19° and 21°S where glacial moraines have been identified, but the SEMB model indicates minimal LGM glaciation. It is possible that these locations (19° - 21°S) were glaciated either before or after LGM, and were not glaciated at LGM. The SEMB model does indicate significant LGM glaciation at previously glaciated locations throughout the majority of the subtropical Andes (21° - 27°S), and shows minimal to no glaciation in the same regions during the modern.

**Figure 5.** Grayscale DEM of the tropical and subtropical Andes for the (A) modern and (B) Last Glacial Maximum, showing where the topography intersects modeled ELAs. Previously glaciated areas within the subtropics are marked with boxes.
4.3 Modeled Ablation

In addition to analyzing modern and LGM ELAs, the relative importance of sublimation and melt to total ablation are calculated within the SEMB model. Figure 6 shows the relationship between the percent of ablation due to melting at the ELA and mean annual temperature at the ELA (a), total annual precipitation (b), and mean annual shortwave radiation (c), at each CCSM4 21 ka grid point with an elevation greater than 1,500 m between 0° and 30°S. Melt dominates the tropical Andes, where temperature is 0°C or greater, precipitation is greater than ~1 m/yr, and shortwave radiation is less than ~250 W/m². Conversely, sublimation dominates the subtropical Andes, where temperature is less than ~5°C, precipitation is less than ~0.5 m/yr, and shortwave radiation is greater than ~275 W/m².

The inverse relationship between precipitation and shortwave radiation is further emphasized when looking at the dominant ablation process related to each climatic forcing. Grid boxes with high precipitation correspond to grid boxes with low shortwave radiation, and ablation is dominated by melting. Grid boxes with low precipitation correspond to those with high shortwave radiation, and ablation is dominated by sublimation.
4.4 Idealized Experiments

To better understand why modeled ELAs show a greater depression in the subtropics during the LGM compared to the tropics, and to understand the relative importance of different climate parameters on ELAs, we now present idealized experiments that calculate the relative importance of each climate parameter on the total ELA depression during the LGM.

First, we calculate LGM and modern mean austral summer temperature, precipitation, and shortwave radiation from CCSM4 pre-industrial control and 21 ka output for regions within the tropical Andes (11° – 13°S, 75° - 76°W) and the subtropical Andes (21° – 24°S, 68°W). The cells used were chosen because they represent average climatic conditions in each region.

Second, we run the SEMB model for the tropical Andes using CCSM4 pre-industrial output and holding all variables constant, but substituting mean austral summer
LGM temperature, precipitation, and shortwave radiation one at a time. The difference between the mean ELA calculated using only CCSM4 pre-industrial output, and ELA calculated when substituting each mean LGM value, is then recorded as the relative change in ELA for the tropics (Table 2) and the subtropics (Table 3).

Temperature depressions, which are tied to energy fluxes through the SEMB model, during the Last Glacial Maximum contribute to the majority of the change in ELA in the tropical Andes (Table 2). As the CCSM4 model shows that precipitation decreased in the tropics during the LGM, these slightly drier conditions would have dampened the ELA depressions. Finally, model results show that the decrease in shortwave radiation by almost 25 W/m² during the LGM contributed to a significant portion, over 30%, of the overall change in ELA at LGM. Again, while an inverse relationship between precipitation and shortwave radiation through cloud cover is seen in the subtropical Andes, the direct relationship between the two in the tropics is likely due to the other factors that influences on shortwave radiation [Rondanelli et al., 2015].

<table>
<thead>
<tr>
<th>Climatic Forcing</th>
<th>LGM Conditions</th>
<th>Modern Conditions</th>
<th>Change in Condition</th>
<th>Relative Change in ELA</th>
<th>% of Total ELA Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>9.52 °C</td>
<td>12.9 °C</td>
<td>-3.38 °C</td>
<td>-602 m</td>
<td>72.9%</td>
</tr>
<tr>
<td>Accumulation</td>
<td>0.948 m/yr</td>
<td>1.049 m/yr</td>
<td>-0.100 m/yr</td>
<td>28.2 m</td>
<td>-3.4%</td>
</tr>
<tr>
<td>Shortwave Radiation</td>
<td>132 W/m²</td>
<td>156 W/m²</td>
<td>-23.3 W/m²</td>
<td>-252.3 m</td>
<td>30.5%</td>
</tr>
</tbody>
</table>
Table 3 shows that in the subtropical Andes, the decrease in temperature during the LGM is responsible for almost 95% of the total ELA depression. Looking at the influence of shortwave radiation and precipitation individually, model results show that lower levels of shortwave radiation during the LGM are slightly more important than the wetter LGM conditions in terms of overall ELA depressions. While glaciers in the arid subtropical Andes have been shown to be sensitive to changes in precipitation [Sagredo et al., 2014], the effects of lower LGM temperatures and shortwave radiation on ablation may have resulted in LGM glaciation of the region, rather than a vast increase in precipitation.

### Table 3. Relative importance of different climatic forcings in the subtropical Andes

<table>
<thead>
<tr>
<th>Climatic Forcing</th>
<th>LGM Conditions</th>
<th>Modern Conditions</th>
<th>Change in Condition</th>
<th>Relative Change in ELA</th>
<th>% of Total ELA Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>3.72 °C</td>
<td>8.27 °C</td>
<td>-4.55 °C</td>
<td>-838 m</td>
<td>94.8%</td>
</tr>
<tr>
<td>Accumulation</td>
<td>0.654 m/yr</td>
<td>0.626 m/yr</td>
<td>0.0273 m/yr</td>
<td>-9.6 m</td>
<td>1.1%</td>
</tr>
<tr>
<td>Shortwave Radiation</td>
<td>262 W/m²</td>
<td>273 W/m²</td>
<td>-10.5 W/m²</td>
<td>-36.8 m</td>
<td>4.2%</td>
</tr>
</tbody>
</table>

### 5. Discussion

Comparing the previously glaciated subtropical Andes with the presently glaciated tropical Andes provides a natural experiment for better understanding changes
in glaciation in these regions, as well as identifying the climatic forcings driving these changes. Previous studies estimate that an increase in precipitation of up to 600%, from 0.2 m to 1.2 m, in conjunction with temperature depressions of 3° – 4°C, would be necessary for areas within the subtropics to have been glaciated [Clayton and Clapperton, 1997; Kull et al., 2002]. CCSM4 21 ka and pre-industrial control output model an increase in precipitation in the subtropical Andes of 20 – 40% during LGM compared to modern (Figure 4b). CCSM4 overestimates precipitation in the subtropics, as modeled precipitation is close to .6 m while measured values are generally less than .15 m [Vuille and Keimig, 2004]. However, accounting for GCM overestimation and increasing precipitation from 0.6 m to 1.2 m still requires a 100% increase in precipitation, while results from this study show a 20 – 40% increase is sufficient to glaciate the subtropical Andes. Furthermore, changes in climatic conditions other than temperature and precipitation have not been fully investigated, leaving the question of what is required to glaciate the subtropical Andes.

We use a full surface energy and mass balance model to reconstruct modern and LGM equilibrium line altitudes in the tropical and subtropical Andes. Our results indicate that the effects of lower LGM temperatures and shortwave radiation on ablation may have been more important to LGM glaciation than large increases in precipitation. Additionally, modeled ELAs calculated using CCSM4 21 ka output suggest that climatic conditions during the global LGM are broadly consistent with the presence of glaciers in the subtropical Andes.
6. Conclusions

The goal of this study was to use a surface energy and mass balance model to investigate glaciation of the subtropical Andes during the LGM, and to explore the climatological processes that influence low-latitude glaciers in the Andes. We found that

1. Modeled ELA depressions calculated from four GCMs are greater in the subtropical Andes than in the tropical Andes during the Last Glacial Maximum compared to the modern. The highest resolution GCM, CCSM4, shows an average depression of 620 m in the tropics and 810 m in the subtropics.

2. Modeled ELAs suggest that the climate during the global LGM could have supported glaciers in the arid subtropical Andes. Additionally, idealized experiments show that temperature depressions are more important to glacial advance than increases in precipitation, further supporting glaciation of the subtropical Andes at LGM due to colder temperatures and slightly wetter conditions.

3. There is a direct relationship between the dominant ablation process and temperature, precipitation, and shortwave radiation. This relationship emphasizes the importance of these climatic forcings on low-latitude glaciers.

4. While glaciers in the arid subtropical Andes are sensitive to changes in precipitation, results of idealized experiments show that effects of lower LGM temperatures and shortwave radiation on ablation may have been more important than a large increase in precipitation to LGM glaciation.
References


Braithwaite, R.J., and Y. Zhang (2000), Sensitivity of mass balance of five Swiss glaciers to temperature change assessed by tuning a degree-day-model, *J. Glaciol.*, 46, 7–14.


