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Sensitivity of glaciation in the arid subtropical Andes to changes in temperature, precipitation, and solar radiation

L.J. Vargo[a,*], J. Galewsky[b], S. Rupper[c], D.J. Ward[d]

[a] Antarctic Research Centre, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
[b] Dept. of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM, USA
[c] Dept. of Geography, University of Utah, Salt Lake City, UT, USA
[d] Dept. of Geology, University of Cincinnati, Cincinnati, OH, USA

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ABSTRACT

The subtropical Andes (18.5–27 °S) have been glaciated in the past, but are presently glacier-free. We use idealized model experiments to quantify glacier sensitivity to changes in climate in order to investigate the climatic drivers of past glaciations. We quantify the equilibrium line altitude (ELA) sensitivity (the change in ELA per change in climate) to temperature, precipitation, and shortwave radiation for three distinct climatic regions in the subtropical Andes. We find that in the western cordillera, where conditions are hyper-arid with the highest solar radiation on Earth, ELA sensitivity is as high as 34 m per % increase in precipitation, and 70 m per % decrease in shortwave radiation. This is compared with the eastern cordillera, where precipitation is the highest of the three regions, and ELA sensitivity is only 10 m per % increase in precipitation, and 25 m per % decrease in shortwave radiation. The high ELA sensitivity to shortwave radiation highlights the influence of radiation on mass balance of high elevation and low-latitude glaciers. We also consider these quantified ELA sensitivities in context of previously dated glacial deposits from the regions. Our results suggest that glaciation of the humid eastern cordillera was driven primarily by lower temperatures, while glaciations of the arid Altiplano and western cordillera were also influenced by increases in precipitation and decreases in shortwave radiation. Using paleoclimate records from the timing of glaciation, we find that glaciation of the hyper-arid western cordillera can be explained by precipitation increases of 90–160% (1.9–2.6× higher than modern), in conjunction with associated decreases in shortwave radiation of 7–12% and in temperature of 3.5 °C.

1. Introduction

Understanding the sensitivity of glaciers to changes in climate provides insight into the climatic drivers of past glaciations, as well as how the cryosphere may respond to future climate variability. (Oerlemans et al., 1998). The South American Andes are ~7000 km long, and the full length of the range is glaciated, or has been glaciated as recently as the late Pleistocene. Glaciers in the Andes therefore exist, or have existed, in a broad range of climatic settings (Sagredo and Lowell, 2012). Between ~18 and 27 °S in the subtropical Andes there are glacial deposits but no modern glaciers, even at altitudes > 6000 m (Casassa et al., 2007; WGMS and NSIDC, 1999, updated, 2012), making it an especially interesting area to investigate the relationship between glaciers and climate.

The subtropical Andes are influenced by multiple large-scale climate patterns, including the Inter-Tropical Convergence Zone (ITCZ), the South American Summer Monsoon (SASM), El Niño Southern Oscillation (ENSO), and a high-pressure system referred to as the Bolivian High. They are also located between the tropical easterly winds to the north, and the westerly winds to the south. Shifts in these climate patterns, including a southward shift of the ITCZ (Placzek et al., 2006), or the intensification or southward shift of the SASM, would enhance precipitation in the subtropical Andes (Cruz Jr et al., 2005; Quade et al., 2008). For the region to have been glaciated, previous works have noted that higher precipitation, lower temperatures, or a combination of both would have been necessary (Klein et al., 1999; Kull et al., 2008). However, few studies have noted the importance of incoming shortwave radiation reaching the surface of Earth (referred to herein as shortwave radiation) on past glaciation in the subtropical Andes.

Recent surface exposure dating of glacial deposits in the subtropical Andes has better constrained the timing of glaciation (Blard et al., 2009; Smith et al., 2009; Zech et al., 2009; Blard et al., 2013; Ward et al., 2015; Martini et al., 2017; Ward et al., 2017; Zech et al., 2017).

* Corresponding author.
E-mail address: lauren.vargo@vuw.ac.nz (L.J. Vargo).

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Maximum glaciation occurred at different times across three distinct sub-regions: 1) the northern Altiplano region ~18 and 20 °S, 2) the hyper-arid western cordillera ~21–25 °S, and 3) the more humid eastern cordillera ~22–25 °S. The out-of-phase timing of glaciation across these three regions is likely due to the differences in climate. While temperatures are similar, the western cordillera is drier and receives more shortwave radiation than the other regions (Vuille and Keimig, 2004; Rondanelli et al., 2015).

In this work, we investigate glacial sensitivity to climate by modeling equilibrium line altitudes (ELAs), the altitude at which a glacier would be in mass and energy balance in a year. We then run idealized model experiments to quantify ELA response and sensitivity in each region to changes in climate, including temperature, precipitation, and shortwave radiation. We use a surface energy and mass balance model driven using reanalysis data. ELA sensitivity is compared between the Altiplano, the western cordillera, and the eastern cordillera to better understand the influence of climate, including shortwave radiation, on tropical and subtropical glaciers. We then use the quantified ELA sensitivities in conjunction with surface exposure dates of glacial deposits from the region and paleoclimate data to explore the changes in climate that would have been required for glaciation in the subtropical Andes.

2. Field area and previous work

2.1. Modern climate

Climate variability of the subtropical Andes is influenced by several large-scale atmospheric circulation systems. In the central Andes, most (> 50%, up to 90% in some areas) of the annual precipitation falls during the austral summer (December through March) (Vuille and Keimig, 2004; Vera et al., 2006). The ITCZ and its associated precipitation shifts seasonally, with the southernmost position in February through April (Barry and Chorley, 2009) enabling increased moisture transport towards the central Andes (Garreaud et al., 2009). However, the majority of precipitation in the subtropical Andes is due to austral summer development of the SASM. In addition to the increase in moisture during the SASM, an associated increase in cloud cover occurs, both of which are linked with reduced shortwave radiation (Garreaud et al., 2009; Martini et al., 2017). Wet periods in the central Andes also correspond with a southward shift and intensification of the Bolivian high. This shift is characterized by enhanced easterly flow, which brings additional moisture to the subtropical Andes from the interior of the continent (Lenters and Cook, 1997; Vuille, 1999).

The three regions, the Altiplano, eastern (Oriental) cordillera, and western (Occidental) cordillera (Fig. 1) have distinct climates. All are characterized by cold temperatures, with mean annual temperatures below 0 °C at high elevations (e.g. Giovanelli et al., 2001; Hardy et al., 2003). However, annual precipitation in the western cordillera is 0–0.3 m y^{-1}, while precipitation in the Altiplano is slightly higher at 0.05–1 m y^{-1}, and precipitation in the eastern cordillera is 0.5–1.5 m y^{-1} (Giovanelli et al., 2001; Vuille and Keimig, 2004; Dee et al., 2011). The hyper-aridity of the western cordillera, and the aridity of the Altiplano, is primarily due to subsidence of dry air associated with Hadley cell circulation, and upwelling of the Humboldt current leading to cold sea surface temperatures offshore (Hartley, 2003; Rondanelli et al., 2015). The difference in precipitation between the eastern and western cordilleras has led previous studies to conclude that glaciation in the arid western cordillera is most sensitive to changes in precipitation, and that an increase in moisture relative to the present-day would have been necessary to support glaciers (Klein et al., 1999; Ammann et al., 2001; Kull et al., 2008).

Compared with precipitation and temperature, the influence of shortwave radiation on paleo-glaciation in the subtropical Andes has received far less attention. This is despite the subtropical Andes receiving the highest levels of shortwave radiation on Earth, with locations within 24–25 °S receiving an annual average of over 300 W m^{-2} (Loeb et al., 2009; Rondanelli et al., 2015) (mean global shortwave radiation is ~190 W m^{-2} (Stephens et al., 2012)). These high values are due to high elevations and low-latitudes, as well as low amounts of water vapor, cloud cover, ozone, and aerosols. The low percentage of cloud cover in the subtropical Andes is also tied to the low precipitation in the region.

Previous studies have shown the importance of shortwave radiation for low-latitude glaciers in the Andes and in Africa. High shortwave radiation plays a key role in ablation of African glaciers, with cloudiness identified as an important factor in reducing shortwave radiation (Kruss and Hastenrath, 1987; Mölg et al., 2003a,b). In the modern Andes, high shortwave radiation and the associated low cloud cover influence the energy balance of low-latitude glaciers (Vuille et al., 2008; MacDonell et al., 2013). Late-Holocene glacial advances in the tropical Andes were found to be coincident with solar minima, and considerably sensitive to small changes in shortwave radiation (Polissar et al., 2006). Furthermore, over the past 20 ka in the subtropical Andes, increases in cloud cover and subsequent decreases in summertime shortwave radiation coincided with the expansion of paleolakes and glacial advances (Kull and Grosjean, 1998). These studies suggest the potential importance of shortwave radiation on low-latitude glaciers, highlighting the need to quantify the influence of shortwave radiation on glaciation of the subtropical Andes.

2.2. Paleoclimate

Paleoclimate records and modeling experiments provide insight into climate conditions when the subtropical Andes were glaciated. Last glacial maximum (LGM; ~21–23 ka) temperatures were likely 5–7 °C lower than modern (e.g. Klein et al., 1999; Kull et al., 2008) and late glacial (~13–18 ka) temperatures were likely 3–4 °C lower than modern (e.g. Kull and Grosjean, 2000; Kull et al., 2008). In addition to lower temperatures, for glaciers to have existed in the arid western cordillera of the subtropical Andes, an increase in moisture in the region was likely also required (Klein et al., 1999; Kull et al., 2008).

Proxy records suggest that precipitation was generally similar to modern during the LGM, and that precipitation was significantly higher than modern during late glacial. Rodent middens from northern Chile indicate increased winter precipitation during the LGM through the late glacial (17–24 ka) and increased annual precipitation during the late glacial (14–17 ka) (Maldonado et al., 2005). A separate midden record shows that annual rainfall was 2× modern values during part of the late glacial (~16.3–17.5 ka) (Latorre et al., 2006). Organic deposits from 24.5 °S show evidence for elevated groundwater levels occurring within the late glacial (13.8–15.9 ka) (Quade et al., 2008), and deposits from 21 °S suggest the presence of perennial rivers within the late glacial (14.2–17.6 ka) (Gayo et al., 2012).

These wet periods generally coincide with the presence of LGM and late glacial paleolakes on the Bolivian Altiplano (Fig. 1) (Baker et al., 2001; Placzek et al., 2006; Blard et al., 2011). Results from a hydrologic budget model suggest that paleolake Tauca (14–18 ka) would have required increases in precipitation of > 100%, while paleolake Sajsi (20.5–24 ka) could have been supported by little to no increase in rainfall (Placzek et al., 2013). In association with the higher precipitation and resulting increases in cloud cover, there was likely also a decrease in shortwave radiation in the subtropical Andes at the end of, and following, the late glacial (10–14 ka) (Kruss and Hastenrath, 1987; Kull and Grosjean, 1998).

2.3. Glacial history

Previous studies have investigated when the subtropical Andes were glaciated, with results showing that maximum glaciation occurred within the late glacial (~13–17 ka) in the Altiplano (Blard et al., 2009; Smith et al., 2009), before ~25 ka in the western cordillera (Blard et al., 2014; Ward et al., 2017), and during the global LGM (~23 ka) in