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Northern Hemisphere forcing of the last deglaciation in southern Patagonia

Daniel S. Murray[1], Anders E. Carlson[1,2*], Brad S. Singer[1], Faron S. Anslow[3], Feng He[2,4], Marc Caffee[5], Shaun A. Marcott[6], Zhengyu Liu[2,4], and Bette L. Otto-Bliesner[7]
[1]Department of Geoscience, University of Wisconsin, Madison, Wisconsin 53706, USA
[2]Center for Climatic Research, University of Wisconsin, Madison, Wisconsin 53706, USA
[3]Pacific Climate Impacts Consortium, University of Victoria, Victoria, British Columbia V8P 1A1, Canada
[4]Department of Atmospheric and Oceanic Sciences, University of Wisconsin, Madison, Wisconsin 53706, USA
[5]Departments of Earth and Atmospheric Sciences & Physics, Purdue University, West Lafayette, Indiana 47907, USA
[6]College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA
[7]Climate and Global Dynamics Division, National Center for Atmospheric Research, Boulder, Colorado 80307, USA

ABSTRACT

Although the general patterns of deglacial climate change are relatively well constrained, how, and to what magnitude, large parts of the Southern Hemisphere responded to deglacial forcings remains unknown, particularly for the early part of the last deglaciation. We investigate the timing and magnitude of early deglacial climate change using cosmogenic ^{10}Be surface exposure ages of moraines deposited by glaciers in the Rio Guanaco Valley, adjacent to the Southern Patagonian Ice Field at 50°S. We demonstrate that the beginning of ice retreat from the local last glacial maximum occurred at 19.7 ± 1.1 ka, with significant retreat commencing at 18.9 ± 0.4 ka, concurrent with glacier retreat elsewhere in southern Patagonia and New Zealand and with warming of Southern Hemisphere middle to high latitudes. A third moraine shows that half of the deglacial retreat upvalley had occurred by 17.0 ± 0.3 ka. Equilibrium line altitudes and climate simulations show ~1.5 °C of warming in southern Patagonia between 18.9 ± 0.4 ka and 17.0 ± 0.3 ka, one-third of the total estimated deglacial warming relative to present. The climate model links this warming to retreat of Northern Hemisphere ice sheets ca. 19 ka through changes in ocean circulation that caused a bipolar seesaw response resulting in Southern Hemisphere warming and driving initial deglaciation across southern Patagonia.

INTRODUCTION

The global Last Glacial Maximum (LGM) is defined by a sea-level lowstand lasting from ca. 26 ka to 19 ka and a relatively stable, cold climate, while general global warming with periods of rapid climate change characterized the subsequent deglaciation (Clark et al., 2002, 2009; Shakun and Carlson, 2010). Constraining the timing and nature of ice-mass and climate change across different regions is critical to identifying the forcing and feedback mechanisms involved in the LGM termination and global propagation of the last deglaciation (Imbrie et al., 1993). It is particularly important to establish whether the onset of deglaciation was synchronous between hemispheres, as this has implications regarding atmospheric versus oceanic drivers of deglaciations (Imbrie et al., 1993; Lowell et al., 1995; Alley et al., 2002; Clark et al., 2004, 2009; Sugden et al., 2005; Schaefer et al., 2006; Stott et al., 2007; Huybers and Denton, 2008; Kaplan et al., 2008b; Shakun and Carlson, 2010).

Deglaciations are generally assumed to be triggered by changes in Northern Hemisphere boreal summer insolation that drives ice-sheet retreat, with the signal propagating to the Southern Hemisphere via an oceanic response to ice-sheet melting (Imbrie et al., 1993; Alley et al., 2002; Clark et al., 2004). Alternatively, synchronous retreat of valley glaciers in the middle latitudes of the Northern and Southern Hemispheres that led significant warming in Greenland ice core records may imply a greenhouse gas forcing of deglaciations (Lowell et al., 1995; Denton et al., 1999; Schaefer et al., 2006). Changes in austral spring insolation and attendant retreat of Southern Ocean sea ice with release of CO_2 from the ocean could also cause deglaciations (Stott et al., 2007). A third alternative suggests that increasing austral summer length resulted in Southern Hemisphere deglaciation roughly coincident with that of the Northern Hemisphere (Huybers and Denton, 2008).

Southern South America preserves the longest terrestrial latitudinal transect in the hemisphere (Fig. 1A) and is ideal for assessing deglacial climate change for this part of the globe (Mercer, 1983). Patagonian glaciers are sensitive to austral winter precipitation and summer temperatures, with glaciers on the eastern side of the Andean Cordillera having greater temperature sensitivity due to an arid rain shadow (Hulton et al., 1994). Using ^{10}Be surface exposure ages, we date glacier retreat in the Rio Guanaco Valley, Argentina, adjacent to the Southern Patagonian Ice Field at 50°S (Fig. 1B), as a terrestrial proxy for regional climate change at the end of the LGM.

METHODS AND RESULTS

The Rio Guanaco Valley is located in a mountainous pre-Cordilleran interfluve, and is flanked to the north and south by the Lago Viedma and Lago Argentino Valleys (Fig. 1B), which drain Southern Patagonian Ice Field outlet glaciers. The glaciers and associated moraines in the Rio Guanaco Valley are not linked directly to the Southern Patagonian Ice Field (Wenzens, 1999); their small sizes make them more sensitive recorders of fluctuations in climate than the larger adjacent outlet glaciers. The main Rio Guanaco Valley contains five separate moraines from the last glacial period (Fig. DR1 in the GSA Data Repository[1]). The La Sofia end moraine reflects ice stability during the local LGM with the San Jorge moraine ~1.5 km upvalley (Fig. 1B; Wenzens, 1999). The Cerro Pintado recessional moraine is ~12 km upstream in the Rio Manga Norte tributary valley, approximately one-half the distance between the valley headwall and the San Jorge moraine, and represents a more recent period of ice stability (Fig. 1B).

We collected 21 samples from the uppermost 2 cm of flat-topped quartz-bearing rhyolitic boulders along the moraine crests (Fig. 1B), and analyzed for in situ ^{10}Be. The ^{10}Be ages were calculated using the reference production rate for the southern middle latitudes of New Zealand and South America (Putnam et al., 2010; Kaplan et al., 2011). We include the effects of 1.4 mm k.y.$^{-1}$ of surface erosion in our age calculations, as determined by Douglass et al. (2006) for southern Patagonia, shifting ages 0.3–0.4 k.y. older, which is within the uncertainty of the mean and does not affect our conclusions. We do not include an exposure correction for

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*E-mail: acarlson@geology.wisc.edu.

[1] GSA Data Repository item 2012186, boulder sample field and laboratory data, geologic setting, paleo–equilibrium line altitude determination, and climate model information, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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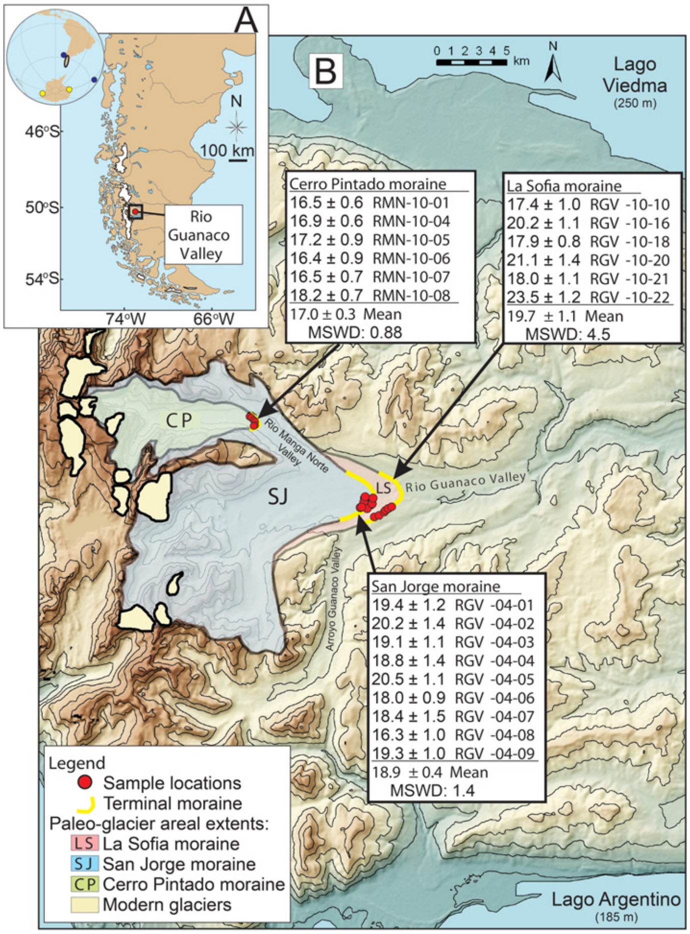

Figure 1. Glacial map of Rio Guanaco Valley, Argentina. A: Regional map, Rio Guanaco Valley (in box), and locations of ice cores (yellow) and marine (blue) records. B: Rio Guanaco Valley digital elevation model; shaded regions show glacier extents; modern glaciers provide equilibrium line altitude of 1750 ± 200 m (±1σ, n = 12). MSWD—mean square of weighted deviates.

snow cover, due to the short-lived and minimal snow pack in this arid region (Douglass et al., 2006). Using Chauvenet's criterion, we conclude that there are no statistical outliers for any of the moraines. Because the standard deviations of the mean sample ages are equivalent to or larger than the analytical uncertainties, we calculate each moraine age by taking the mean of the dates and its one standard error uncertainty.

The calculated ages are interpreted to reflect the time elapsed since the boulders became exposed due to ice retreat from the moraine. Deposition of the La Sofia moraine ended at 19.7 ± 1.1 ka (n = 6), whereas the adjacent San Jorge moraine is more precisely dated at 18.9 ± 0.4 ka (n = 9; Fig. 2A). Deposition of the Cerro Pintado moraine ended significantly later, at 17.0 ± 0.3 ka (n = 6). The La Sofia and San Jorge moraine cosmogenic ages date the onset of ice retreat at 19.7 ± 1.1 ka; more significant retreat at 18.9 ± 0.4 ka marks the end of the local LGM. Ice retreated ~12 km upvalley to the Cerro Pintado moraine before 17.0 ± 0.3 ka, and renewed retreat occurred 17.0 ± 0.3 ka.

TIMING OF REGIONAL DEGLACIATION

The timing of the end of the local LGM in the Rio Guanaco Valley at 18.9 ± 0.4 ka agrees well with the termination of the local LGM elsewhere in southern Patagonia and New Zealand (Fig. 2B). The ^{14}C dates are calibrated using IntCal09 (http://calib.qub.ac.uk/calib/), whereas ^{10}Be exposure dates are recalculated using the reference production rate for the southern middle latitudes (Putnam et al., 2010; Kaplan et al., 2011). ^{14}C dates from the Chilean Lake District (41°S) indicate that ice retreat occurred prior to 18–17 ka (Denton et al., 1999); this is in agreement with adjacent marine proxies that suggest enhanced ablation and delivery of terrestrial sediment to the ocean 19–17 ka (Lamy et al., 2004; Muratli et al., 2010). ^{10}Be-dated moraines near Lago Buenos Aires (46.5°S) indicate the end of the local LGM at 18.7 ± 0.6 ka (Douglass et al., 2006); ^{10}Be ages at Lago Pueyrredon (47°S) and Lago San Martin (49°S) date the onset of deglaciation before 17.8 ± 2.0 ka (Hein et al., 2010) and 15.0 ± 0.5 ka (Glasser et al., 2011), respectively. Deglaciation at Torres del Paine (51°S) began prior to 16.3 ± 0.4 ka (Moreno et al., 2009), and prior to ca. 17.7 ka just south of Torres del Paine (52°S), in the Strait of Magellan (53°S), and in Tierra del Fuego (55°S) (Heusser, 1989; McCulloch et al., 2005; Kaplan et al., 2008a; Sagredo et al., 2011). In New Zealand, at 44°S, ^{10}Be ages date the end of the local LGM at 18.9 ± 0.1 ka (Schaefer et al., 2006; Putnam et al., 2010).

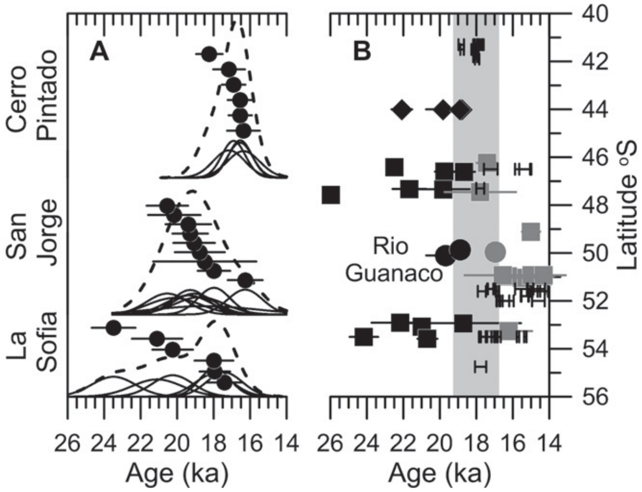

Figure 2. Southern Hemisphere deglacial chronologies. A: Probability density curves of ^{10}Be Rio Guanacao surface exposure ages (dashed line—summed moraine probability, solid line—individual boulder probability, circles—individual dates). B: Glacial chronologies for southern South America (squares) and New Zealand (diamonds). Symbols are ^{10}Be dates (black—local Last Glacial Maximum, gray—recessional); black bars are ^{14}C dates (±1σ); circles are Rio Guanaco Valley. Gray bar is deglaciation in Rio Guanaco Valley.

The general agreement between ice margin retreat in the Rio Guanaco Valley and the rest of southern Patagonia from 41 to 55°S implies that the ice retreat was in response to broad Southern Hemisphere climate change. The onset of significant ice retreat in the Southern Hemisphere middle latitudes is concurrent with initial deglacial warming in Antarctic ice cores at 18.3 ± 0.7 ka (Stenni et al., 2011), in the southeast Pacific ca. 19 ka (Lamy et al., 2004), and in the South Atlantic ca. 18 ka (Barker et al., 2009) (Figs. 3E and 3F). The coeval multiproxy-based timing of climate change indicates that middle- to high-latitude Southern Hemisphere LGM conditions terminated between ca. 19.3 and 17.5 ka and more likely between ca. 19 and 18 ka, slightly earlier than some previous estimates of 17.5–17.0 ka (Sugden et al., 2005; Schaefer et al., 2006; Kaplan et al., 2008b), but overlapping with other estimates of 20.0–16.5 ka (Clark et al., 2009), which may reflect our use of a regionally calibrated ^{10}Be production rate. The relatively synchronous timing of glacier retreat across the Southern Hemisphere also suggests that shifts in the southern westerly winds (Kaplan et al., 2004; Sugden et al., 2005; Douglass et al., 2006) played less of a role in driving initial deglaciation.

SOUTHERN PATAGONIAN DEGLACIAL CLIMATE CHANGE

We estimate the climate conditions that caused the glacier extents in the Rio Guanaco Valley by calculating paleo-equilibrium line altitudes

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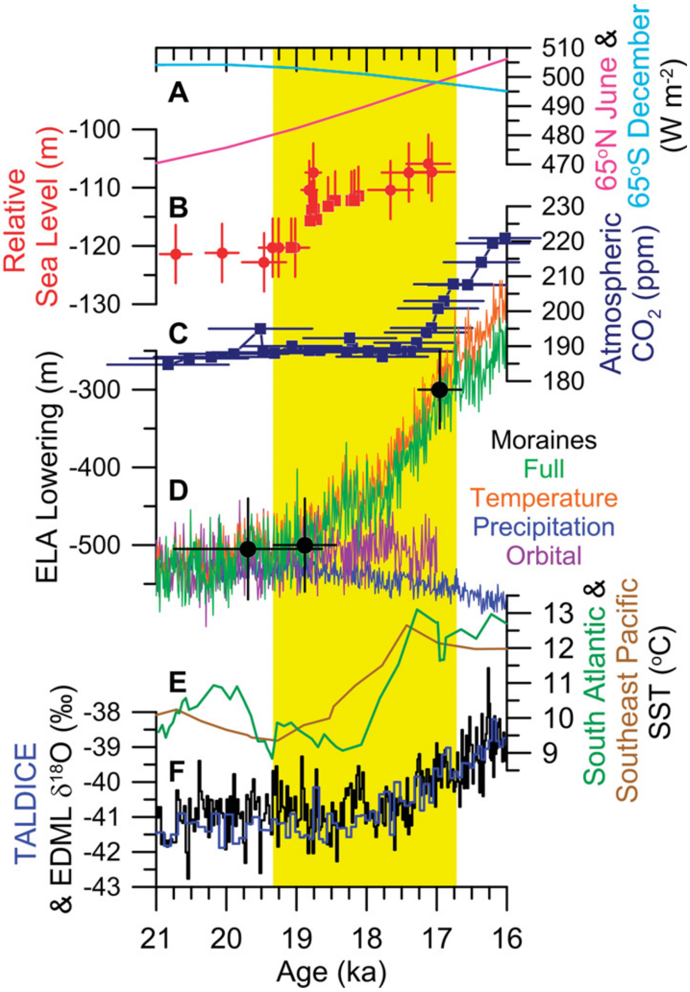

Figure 3. Paleoclimate proxies for onset of last deglaciation. A: June 65°N (pink) and December 65°S (light blue) insolation (Berger and Loutre, 1991). B: Relative sea level (Clark et al., 2009). C: Atmospheric CO_2 (Lemieux-Dudon et al., 2010). D: Estimated change in equilibrium line altitude (ELA): atmosphere-ocean general circulation model ELA change relative to Last Glacial Maximum average (green), temperature only (orange), precipitation only (blue), and orbital only (purple); symbols are reconstructed moraine ELA relative to modern. E: Sea-surface temperatures (SST); alkenone-based southeast Pacific (brown) (Lamy et al., 2004), and foraminifera Mg/Ca southeast Atlantic (green) (Barker et al., 2009). F: Antarctic ice core $\delta^{18}O$ from EPICA Dronning Maud Land (EDML, black; EPICA Community Members, 2006) and Talos Dome ice core (TALDICE; blue; Stenni et al., 2011). Yellow bar is same as in Figure 2.

(ELAs) associated with each moraine using an accumulation area ratio method (see the Data Repository) and assuming that 0.65 ± 0.05 of the total glacier area is in the accumulation zone above the ELA. ELA lowering relative to the present-day ELA of 1750 ± 200 m (Fig. 1B) for the La Sofia and San Jorge moraines is 440–570 m and 440–560 m, respectively (Fig. 3D). Using the present-day lapse rate of 0.008 °C m^{-1} and assuming no change in precipitation, these paleo-ELA estimates suggest 3.5–4.5 °C of cooling relative to present-day temperatures at 19.7 ± 1.1–18.9 ± 0.4 ka. The Cerro Pintado moraine records a paleo-ELA lowering of 250–350 m or 2–3 °C cooler temperatures relative to present at 17.0 ± 0.3 ka. The paleo-ELA rose ~200 m between 18.9 ± 0.4 and 17.0 ± 0.3 ka, implying warming of 1–2 °C.

We compare the reconstructed ELAs with regional ELA changes simulated by a fully coupled atmosphere-ocean general circulation model (AOGCM) transient simulation of the last deglaciation (Liu et al., 2009). The National Center for Atmospheric Research Community Climate System Model Version 3 was forced with realistic meltwater, insolation, and greenhouse gases, and successfully simulated regional climate changes from the global LGM to 14 ka in the North Atlantic, tropics, and high-latitude Southern Hemisphere (Liu et al., 2009). Deglacial Northern Hemisphere meltwater was applied at 19.0 ka when all Northern Hemisphere ice sheets were in retreat and sea level began to rise, ending the global LGM (Clark et al., 2009). Greenhouse gas forcing was initiated at 17.0 ka (Lemieux-Dudon et al., 2010). We convert the AOGCM–predicted changes from the LGM in austral summer temperature and annual precipitation in the Rio Guanaco Valley into changes in ELA using the modern temperature lapse rate of 0.008 °C m^{-1} and the precipitation-ELA relationship of 0.0083 mm day^{-1} m^{-1} (Hulton et al., 1994).

The AOGCM simulates the onset of significant ELA rise ca. 19.0 ka (Fig. 3D) in response to meltwater discharge from rising boreal summer insolation and attendant Northern Hemisphere ice-sheet retreat (Figs. 3A and 3B), which slows the Atlantic meridional overturning circulation redistributing heat to the Southern Hemisphere through the bipolar seesaw mechanism (Figs. 3D–3F; Alley et al., 2002; Clark et al., 2002, 2004, 2009; Barker et al., 2009; Liu et al., 2009; Shakun and Carlson, 2010). The modeled ELA rises 180 ± 20 m by ca. 17.0 ka, in excellent agreement with the ELA rise estimated from the Rio Guanaco moraines. Because simulated precipitation increases, all of this ELA rise is from austral summer temperature warming of ~1.5 °C, implying that changes in precipitation played less of a role in terminating the local LGM in the Rio Guanaco Valley (Fig. 3D), in agreement with inferences from other AOGCM studies (e.g., Kaplan et al., 2008b).

Approximately one-third of the total deglacial warming of southern Patagonia near the Rio Guanaco Valley thus occurred between 18.9 ± 0.4 and 17.0 ± 0.3 ka. Since austral summer insolation declined (Fig. 3A), we infer that initial deglacial warming in southern Patagonia primarily reflects initial retreat of Northern Hemisphere ice sheets at 20–19 ka (Fig. 3B) in response to rising boreal summer insolation (Fig. 3A; Clark et al., 2009) and their attendant effects on ocean circulation redistributing heat to the Southern Hemisphere. This forcing may have also initiated much of the deglacial warming of the middle- to high-latitude Southern Hemisphere, later reinforced by rising atmospheric CO_2 (Clark et al., 2002, 2004, 2009; Schaefer et al., 2006; Shakun and Carlson, 2010). Although the precise timing of the initial rise in atmospheric CO_2 is somewhat uncertain (Fig. 3C; Lemieux-Dudon et al., 2010), the AOGCM shows that this positive feedback is not needed to explain southern Patagonian valley glacier retreat to ca. 17 ka.

We test the ability of austral spring insolation to drive southern Patagonian deglaciation (Stott et al., 2007) by comparing moraine-reconstructed ELAs with the ELA change from the LGM predicted by an AOGCM orbital forcing-alone simulation from 22 to 17 ka. The AOGCM simulates that changes in Earth's orbit can explain ~20 m of the ~200 m of ELA rise that had occurred by ca. 17 ka (Fig. 3D), arguing against austral spring insolation as the driving force behind Southern Hemisphere deglaciation. We also note that the increase in austral summer length (Huybers and Denton, 2008) fails to explain the timing of southern Patagonian deglaciation, because summer length began to increase ca. 26 ka, well before the Southern Hemisphere began to deglaciate ca. 19.3–17.5 ka (Fig. DR2).

CONCLUSIONS

Our findings in the Rio Guanaco Valley demonstrate that at least one-third of the total southern Patagonian deglacial climate warming occurred by 17.0 ± 0.3 ka. AOGCM simulations connect this initial Southern Hemisphere deglaciation to the effects of Northern Hemisphere ice-sheet retreat from rising boreal summer insolation on ocean circulation and heat transport. We thus show with ^{10}Be dates the first terrestrial link between Southern Hemisphere deglaciation and the demise of Northern Hemisphere ice sheets.

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