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Patagonian and southern South Atlantic view of Holocene climate

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ABSTRACT

We present a comprehensive ^{10}Be chronology for Holocene moraines in the Lago Argentino basin, on the east side of the South Patagonian Icefield. We focus on three different areas, where prior studies show ample glacier moraine records exist because they were formed by outlet glaciers sensitive to climate change. The ^{10}Be dated records are from the Lago Pearson, Herminita Península-Brazo Upsala, and Lago Frías areas, which span a distance of almost 100 km adjacent to the modern Icefield. New ^{10}Be ages show that expanded glaciers and moraine building events occurred at least at 6120 ± 390 (n = 13), 4450 ± 220 (n = 7), 1450 or 1410 ± 110 (n = 18), 360 ± 30 (n = 5), and 240 ± 20 (n = 8) years ago. Furthermore, other less well-dated glacier expansions of the Upsala Glacier occurred between ~1400 and ~1000 and ~2300 and ~2000 years ago. The most extensive glaciers occurred over the interval from ~6100 to ~4500 years ago, and their margins over the last ~600 years were well within and lower than those in the middle Holocene. The ^{10}Be ages agree with ^{14}C-limiting data for the glacier histories in this area.

We then link southern South American, adjacent South Atlantic, and other Southern Hemisphere records to elucidate broader regional patterns of climate and their possible causes. In the early Holocene, a far southward position of the westerly winds fostered warmth, small Patagonian glaciers, and reduced sea ice coverage over the South Atlantic. Although we infer a pronounced southward displacement of the westerlies during the early Holocene, these conditions did not occur throughout the southern mid-high latitudes, an important exception being over the southwest Pacific sector. Subsequently, a northward locus and/or expansion of the winds over the Patagonia-South Atlantic sector promoted the largest glaciers between ~6100 and ~4500 years ago and greatest sea ice coverage. Over the last few millennia, the South Patagonian Icefield has experienced successive century-scale advances superimposed on a long-term net decrease in size. Our findings indicate that glaciers and sea ice in the Patagonian-South Atlantic sector of the Southern Hemisphere did not achieve their largest Holocene extents over the last millennium. We conclude that a pattern of more extensive Holocene ice prior to the last millennium is characteristic of the Southern Hemisphere middle latitudes, which differs from the glacier history traditionally thought for the Northern Hemisphere.

1. Introduction

In pioneering work, Mercer (1968) inferred that during the Holocene glaciers in Patagonia may have been larger before the last millennium. He reasoned that, if correct, then such glacier behavior

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must be related to climates far from Northern Hemisphere influences, where he assumed that Holocene maxima occurred during the European Little Ice Age. In Europe, over the last ~1000 years glaciers were at, or very close to, their maximum Holocene extents (e.g., Grove, 2004; Holzhauser et al., 2005; Davis et al., 2009; Schimmelpfennig et al., 2012), and the conventional wisdom is that this period contained generally the most persistent cold conditions of the epoch (Davis et al., 2009; Kaufman et al., 2009). However, it still remains unclear (e.g., IPCC, 2014) whether the Southern Hemisphere contains different expressions of Holocene glacier-climate from that in the Northern Hemisphere.

In Patagonia, as elsewhere, hypotheses such as Mercers' have been difficult to test robustly, because glacier deposits are difficult to date. ^{14}C dating is commonly used to construct Quaternary glacier chronologies. Although invaluable, this approach often only provides minimum-limiting, and less commonly maximum-limiting, ages for glacier landforms because they typically lack fossil matter. Moreover, when trying to resolve decadel-multidecadal glacier fluctuations over the last ~500 years, global ^{14}C variations may not permit assignment of unique ages, increasing the uncertainty of the dating approach (e.g., Stuiver, 1978; Porter, 1981).

To this end, we obtained >80 ^{10}Be surface exposure ages that are used to reconstruct Holocene fluctuations of South Patagonian Icefield outlet glaciers (Figs. 1 and 2). We use recent advances in the ^{10}Be method (Schaefer et al., 2009) to date directly for the first time the exposure ages of moraine boulders and thus former glacier positions in Patagonia throughout the Holocene, including those that are <500 years old. We targeted the Lago Argentino area for study for several reasons. First, prior efforts documented which specific glaciers are particularly sensitive to climate and have left the most thorough landform and stratigraphic archives (e.g., Mercer, 1968; Strelin et al., 2014). Earlier studies carried out detailed mapping, stratigraphic studies, and ^{14}C based reconstructions (Mercer, 1968; Aniya, 1995, 2013; Aniya and Sato, 1995; Aniya et al., 1997; Malagnino and Strelin, 1992; Strelin et al., 2011, 2014). This study differs in approach from these valuable prior efforts, as we focus primarily on dating directly moraine boulders throughout the basin with ^{10}Be. In particular, we build on the recent work of Strelin et al. (2011, 2014), which demonstrated that in the Lago Argentino basin two independent dating approaches can indeed be used, ^{14}C and ^{10}Be, totaling the confidence and information obtained using both chronologies (Figs. 2–5). For example, combining both approaches allows 1) information on times of glacier expansion (^{10}Be) and retraction (^{14}C); 2) replication of glacial-event ages within a given valley, including knowledge of the bounds of limiting ^{14}C ages; and 3) additional tests of the apparent similarities and differences between valleys.

We then use the record in Patagonia to ascertain broader patterns of paleoclimate in the middle latitudes, by linking the findings with records from the adjacent, downwind, South Atlantic Ocean. Core TN057-13 is near the southern position reached by the Antarctic Polar front and northern limit of sea ice (Fig. 1). This core thus affords records of sea ice, oceanographic, and climatic conditions also at higher latitudes than just at the drilling site (Kanfoush et al., 2000; Anderson et al., 2009; Divine et al., 2010). By ascertaining similarities between the terrestrial and marine realms, broader hemispheric patterns are reasonably inferred because it can be shown a regional climate change was not only experienced in southern Patagonia. Moreover, we compare our terrestrial-marine based findings with other records in the southern middle latitudes, including of the glacier history in New Zealand, to obtain a hemispheric-wide view.

2. Background and methods

Mountain glaciers respond sensitively to atmospheric change and they are well suited for past climate studies. In particular, glaciers in Patagonia respond directly to atmospheric conditions associated with the globally important Southern Hemisphere Westerly winds and Polar ocean-air climate systems (Fig. 1). 20th/21st century observations document that on timescales of several decades summer temperature dominates glacier history, with precipitation important locally and on the shorter-term (Rignot et al., 2003; Oerlemans, 2005; Rivera and Casassa, 2004; Naruse, 2006; Carrasco et al., 2008; Willis et al., 2012; Casassa et al., 2014). Also, Patagonian glaciers react rapidly to even small changes in climate given the temperate setting. This has led Patagonia to contain some of the fastest waning ice masses in the Southern Hemisphere at present (Rignot et al., 2003; Willis et al., 2012; Casassa et al., 2014).

2.1. Lago Argentino

The regional geology and climate of the Lago Argentino basin,

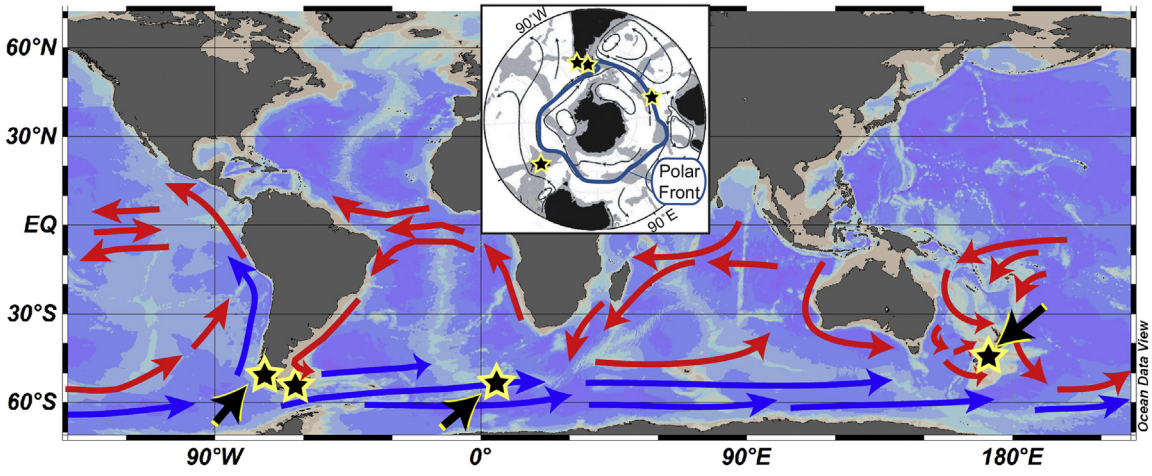

Fig. 1. Setting of places discussed in the text, in a Southern Ocean and Polar context. Sites discussed (stars) include, from left to right, southern Patagonia (Figs. 2 and 3), Isla de los Estados (Fig. 7), TN057-13 (Figs. 6 and 7) and South Island, New Zealand. For simplicity, currents are shown only for the Southern Hemisphere. Patagonia is downwind of the Southeast Pacific, where the cold Humboldt Current flows northward (Fig. 2). The location of TN057-13 is influenced by sub Antarctic climate regimes, being near the Polar front and northern limit of the sea ice influence (see text). Base image from Ocean Data View (ODV), http://odv.awi.de/.