The anatomy of long-term warming since 15 ka in New Zealand based on net glacier snowline rise

Michael R. Kaplan1, Joerg M. Schaefer1,2, George H. Denton3, Alice M. Doughty4, David J.A. Barrell5, Trevor J.H. Chinn6, Aaron E. Putnam1,2, Bjorn G. Andersen7, Andrew Mackintosh4, Robert C. Finkel8, Roseanne Schwartz1, and Brian Anderson4

1Division of Geochemistry, Lamont-Doherty Earth Observatory, Palisades, New York 10964, USA
2Department of Earth and Environmental Sciences, Columbia University, New York, New York 10027, USA
3Department of Earth Sciences and Climate Change Institute, University of Maine, Orono, Maine 04469, USA
4Antarctic Research Centre and School of Geography, Environment and Earth Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
5GNS Science, Private Bag 1930, Dunedin 9054, New Zealand
6Alpine and Polar Processes Consultancy, Lake Hawea 9382, New Zealand
7Department of Geosciences, University of Oslo, 0316 Oslo, Norway
8Department of Earth and Planetary Sciences, University of California–Berkeley, Berkeley, California 95064, USA

ABSTRACT

The timing and magnitude of postglacial climatic changes around the globe provide insights into the underlying drivers of natural climate change. Using geomorphologic mapping of moraines, 10Be surface-exposure dating, snowline reconstructions, and numerical modeling, we quantified glacier behavior during Late Glacial (15–11.5 ka) and Holocene (the past ~11.5 k.y.) time in the Ben Ohau Range, New Zealand. Glaciers were more extensive during the Antarctic Cold Reversal (ACR), than subsequently, and the margins underwent a punctuated net withdrawal over the Holocene. Numerical modeling experiments that achieve the best fit to the moraines suggest that air temperature during the ACR was between 1.8 °C and 2.6 °C cooler than today, with similar (~±20%) prescribed precipitation. After the ACR, a net snowline rise of ~100 m through the Younger Dryas stadial (12.9–11.7 ka) was succeeded by a further “long-term,” or net, rise of ~100 m between ~11 k.y. and ~500 yr ago. Glacier snowline records in New Zealand show generally coherent Late Glacial and Holocene climate trends. However, the paleoclimate record in the southwest Pacific region shows important differences from that in the Northern Hemisphere.

INTRODUCTION

An important goal of paleoclimatology is to understand the reasons behind climate contrasts between the Northern and Southern Hemispheres. Changes since the Late Glacial are particularly important because they provide a recent geologic context for present climate behavior. General features of Northern Hemisphere Late Glacial to Holocene climate are the cold Younger Dryas (YD), followed by an interval when conditions were mostly unfavorable for mountain glaciers (ca. 11–7 ka; the warm altithermal concept of Porter and Denton, 1967), which was succeeded by the colder neoglacial. From a broad perspective, although the early Holocene is inferred to be a period of time not favorable for mountain glaciers in the Northern Hemisphere, climate changes during this period exhibited diversity and at least some regions underwent cold episodes and ice growth (Kaufman et al., 2004; Davis et al., 2009; Schimmelpfennig et al., 2012). After the early Holocene, some Northern Hemisphere regions underwent a relatively marked, or gradual, transition into the neoglacialization, which culminated in the Little Ice Age (LIA). During the LIA, glaciers were at, or very close to, their maximum Holocene extents (e.g., Grove, 2004; Holzhauser et al., 2005; Schimmelpfennig et al., 2012). It remains unclear, however, whether Northern Hemisphere expressions of the YD, altithermal, and neoglacialization are applicable in the Southern Hemisphere.

The glacier records of New Zealand’s Southern Alps, situated in the southwestern Pacific region on the opposite side of Earth from the North Atlantic Ocean, are ideal for testing hypotheses of regional and interhemispheric paleoclimate patterns. To deepen our understanding of past climate change in this region, we studied a well-preserved sequence of moraines at Whale Stream, in the Ben Ohau Range. Glaciers in the mid-latitude temperate maritime setting of South Island respond relatively quickly to variations in temperature and precipitation (Oerlemans, 2010). Both theoretical and empirical climate-glacier studies have shown that New Zealand glacier mass depends more upon atmospheric temperature than on amounts of precipitation, on time scales greater than decades (Anderson and Mackintosh, 2006; Anderson et al., 2010).

SETTING AND METHODS

Whale Stream drains from two main headwater valleys, which we refer to informally as the east and west branch (Fig. 1). Our detailed glacial geomorphology map of both branches (Fig. 1) is based on the regional-scale approach in Barrell et al. (2011). Emanating from the east branch and abutting the mouth of the west branch is a prominent, well-preserved, 60–80-m-tall moraine loop (Fig. 1). The east branch moraine loop, the crest of which ranges in altitude from ~1200 to ~1500 m above sea level (asl), comprises several adjoining frontal and lateral ridges. Inside this loop, several low moraine ridges are on the valley floor. A glacier flowing from the west branch abutted the outer margin of the east branch moraine loop (Fig. 1). As the west branch glacier withdrew upvalley, it formed moraines ranging from ~1300 to 1600 masl. Subsequently, moraine sets formed in the north and south cirques of the west branch. In contrast, there is no succession of moraines in the upper east branch, but rather a single large moraine complex that was not investigated in this study. The general geological and climatic setting of the Ben Ohau Range was described in Kaplan et al. (2010) and Putnam et al. (2010a).

Our chronology is based on 42 samples from boulders composed of hard quartzfeldspathic graywacke sandstone (Tables DR1–DR3 in the GSA Data Repository1). Of the samples, 18 came from the lower reaches of the east and west branches (Fig. 1), while 24 samples were collected from the west branch cirque moraines, 14 from the north cirque and 10 from the south cirque. Samples were processed in the Lamont-Doherty Earth Observatory Cosmogenic Nuclide Laboratory (New York) and measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory (California). For details of the cosmogenic dating method employed in this study, see Schaefer et al. (2009) and Putnam et al. (2010b).

1GSA Data Repository item 2013245, supplemental text, figures, and tables, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Numerical modeling results suggest that a mean annual temperature of 2.2 ± 0.4 °C cooler than today is required to simulate a glacier to the Late Glacial moraine loop (Fig. 2). The uncertainty estimate is only indicative, and is calculated by rerunning the model under varying precipitation totals (±20% relative to modern), and by systematically varying model parameters (such as the snow albedo) within their expected ranges under a constant precipitation regime (see Fig. DR7). The Late Glacial model glacier extent and snowline altitude accord remarkably well with the hand-drawn minimum glacier reconstruction (Fig. 2B), especially considering uncertainties in both approaches (Kaplan et al.; 2010; Doughty et al., 2012; Putnam et al., 2012).

DISCUSSION AND CONCLUSIONS

Whale Stream contains a record of past climate change since the Late Glacial interval, augmenting the known glacier history of the Tasman River–Pukaki drainage basin (Fig. 3; Barrell et al., 2011; Kirkbride and Winkler, 2012). Whale Stream glaciers established Late Glacial positions by ca. 15 ka. The youngest Late Glacial advances in Whale Stream overlap in age with the 13 ka moraines at nearby Birch Hill and Irishman Stream (Fig. 1). There is also a ca. 14 ka moraine deposit at Birch Hill (Fig. 3). The Whale Stream ca. 15–14 ka ice limit, during

Figure 1. Glacial geomorphology of Whale Stream area, New Zealand (mapped at ~1:10,000 scale), and locations of 10Be ages (outliers are in italics). Light blue line shows maximum Late Glacial extent of west branch glacier. LGM—Last Glacial Maximum. Inset maps at top show location on South Island and sites mentioned in text.

For selected time slices based on 10Be ages, we reconstructed the geometries of former glaciers, including maximum and minimum ice-cover scenarios (Kaplan et al., 2010), and we estimated associated snowline elevations using the accumulation to ablation area ratio (AAR) method (Fig. 2). We emphasize relative amounts of change in snowlines, which are independent of the AAR assumed or method of reconstruction, rather than absolute values (Fig. 2; Fig. DR6 in the Data Repository).

We quantified possible mean annual temperature and precipitation change combinations during Late Glacial time by using a coupled two-dimensional ice-flow approximation model with an explicit time step and an energy-balance model (Fig. 2; Fig. DR7). The energy-balance model is driven by present-day climate input data in the form of 30 yr monthly means (1981–2010; Doughty et al., 2012). Our modeling methods are similar to those in Doughty et al. (2012), except that we employed a 100 m horizontal grid resolution, and the model simulations were run for 300 model years. All simulations began from ice-free conditions, and a 300 yr running time was ample for the model glaciers to reach equilibrium with the prescribed steady-state climate. Additional model sensitivity tests with slightly different parameter values, and determination of uncertainties specific to this study, are shown in Figure DR7.

CHRONOLOGY

The east branch moraine loop samples have 10Be ages of 15.4 ± 0.4 ka to 12.9 ± 0.5 ka (n = 6) (Fig. 1; Lm age in Table DR2). The low moraines on the valley floor inside the east branch moraine loop have consistently younger 10Be ages of between 12.4 ± 0.3 and 11.6 ± 0.3 ka (mean = 12.1 ± 0.4 ka; n = 6). Samples from moraines in the lower reaches of the west branch have ages of 14.8 ± 0.3 to 13.4 ± 0.4 ka (n = 4) that are consistent with their morphostratigraphic positions. Collectively, the results demonstrate a Late Glacial age for these moraines.

In the west branch north cirque, 10Be ages (n = 14) cluster at 11.1 ± 0.5 ka (n = 3), 8060 ± 100 yr (n = 4), 1710 ± 70 yr (n = 2), and 540–390 yr (~500 yr) (n = 2), and each moraine ridge provides statistically distinct distributions (Figs. DR2 and DR4). Three boulders with ages of 690–860 yr are close to, but outboard of (beyond), older moraine ridges. In retrospect, we noted that the three boulders are on a deposit that is noticeably more weathered than the boulders and lacks moraine crests (Figs. DR2A and DR3E). We consider that these boulders fell from nearby cliffs and came to rest on an older deposit; we do not include their ages in further discussion.

In the west branch south cirque, the southern sector of the outer moraine ridge returned 10Be ages from 9230 ± 320 yr to 8150 ± 210 yr old (n = 3), while one boulder on the northeastern sector of this ridge yielded an age of 6410 ± 210 yr. The ridge’s northeastern sector is lighter in color (i.e., less weathered) than the southern sector (Fig. DR2B). The color contrasts and range of ages indicate that this ridge may be of composite age. Inboard of the outermost ridge are two distinct crests with 10Be ages of ~1400 yr (n = 2) and 1140 yr (n = 1), respectively; these boulders have little or no surface oxidation. Since collection, we realized that boulders WS-06–02, WS-06–06, and WS-06–07 are on a rock avalanche runout track that overprints and postdates the moraine, and we exclude their ages from further discussion (Figs. DR3F and DR2B).

SNOWLINES AND MODELING

We reconstructed glacier geometries and AAR-based snowlines for the following dated Late Glacial and west branch moraines: ca. 15–14 ka, ca. 12 ka, ca. 11 ka, ca. 8 ka, ca. 1.7 ka, and ca. 500 yr ago (Fig. 2; Fig. DR4). A net snowline rise of ~100 m occurred between ca. 15 and ca. 12 ka, with a further rise of ~100 m between ca. 11 ka and 500 yr ago. This equates to a long-term (net) snowline rise of ~200 m between ca. 15 ka and 500 yr ago.

Numerical modeling results suggest that a mean annual temperature of 2.2 ± 0.4 °C cooler than today is required to simulate a glacier to the Late Glacial moraine loop (Fig. 2). The uncertainty estimate is only indicative, and is calculated by rerunning the model under varying precipitation totals (±20% relative to modern), and by systematically varying model parameters (such as the snow albedo) within their expected ranges under a constant precipitation regime (see Fig. DR7). The Late Glacial model glacier extent and snowline altitude accord remarkably well with the hand-drawn minimum glacier reconstruction (Fig. 2B), especially considering uncertainties in both approaches (Kaplan et al.; 2010; Doughty et al., 2012; Putnam et al., 2012).
Based on 10Be-dated moraines. In essence, Alps (New Zealand) since Late Glacial time

Figure 3. Evolution of snowline in Southern

The findings for the Southern Alps that are collated in Figure 3 reveal important differences from glacier and climate trends in the Northern Hemisphere. Out-of-phase climate changes during Late Glacial time were discussed in prior studies (Fig. 3). In general, in the early to middle Holocene, ocean temperatures were relatively warm, and conditions were mostly unfavorable for glaciers in the Northern Hemisphere (e.g., Davis et al., 2012).
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