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

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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, ^{10}Be 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 neoglaciation. 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 neoglaciation, 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 neoglaciation 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 quartzofeldspathic graywacke sandstone (Tables DR1–DR3 in the GSA Data Repository[1]). 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).

[†]Deceased

[1]GSA 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.

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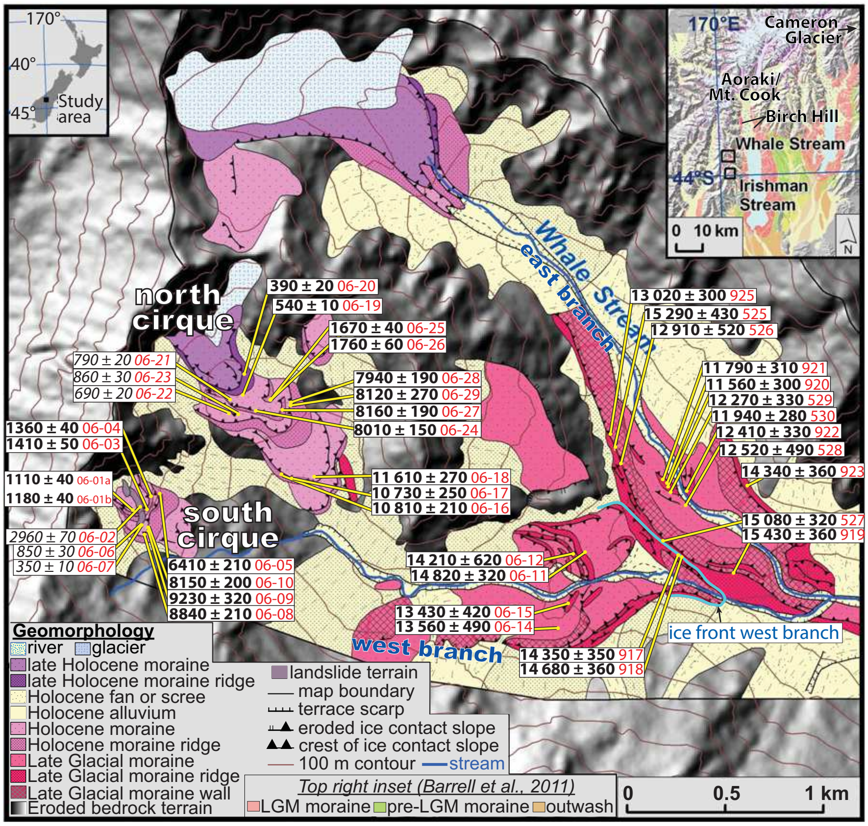

Figure 1. Glacial geomorphology of Whale Stream area, New Zealand (mapped at ~1:10,000 scale), and locations of ^{10}Be ages (outliers are in italics). Light blue line shows maximum Late Glacial extent of west branch glacier. LGM—Last Glacial Maximum. Inset maps at top show location on South Island and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

For selected time slices based on ^{10}Be 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 ^{10}Be 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 ^{10}Be 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, ^{10}Be 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 ^{10}Be 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 ^{10}Be 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 north cirque 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).

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

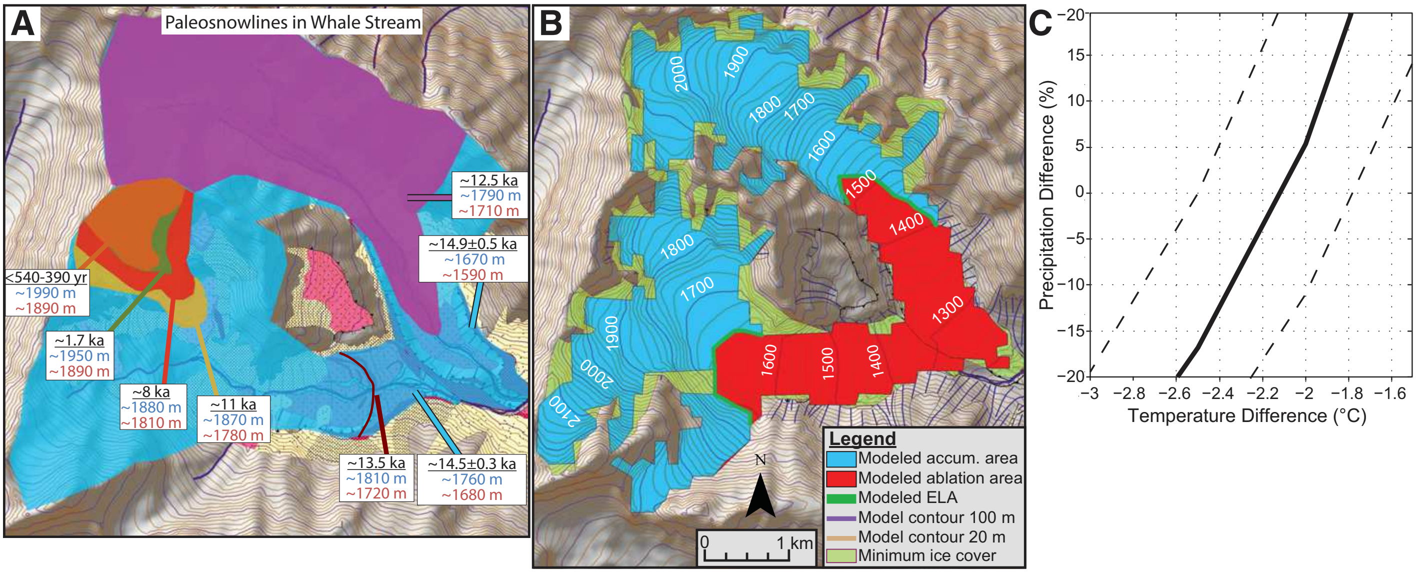

Figure 2. A: Maximum ice cover reconstructions and corresponding snowline values (m) based on maximum (blue) and minimum (red) methods (ablation area ratio = 0.66; Fig. DR5 [see footnote 1]). B: Modeled glacier when it was at Late Glacial moraine, and for comparison, minimum ice cover glacier reconstruction (green). ELA—equilibrium line altitude; accum.—accumulation. C: Modeled Δ*T* and ΔP (temperature and precipitation) combinations that simulate glacier shown in B. Solid and dashed lines represent best fit and range of values, respectively, obtained with sensitivity tests (Fig. DR7). Location same as in Figure 1.

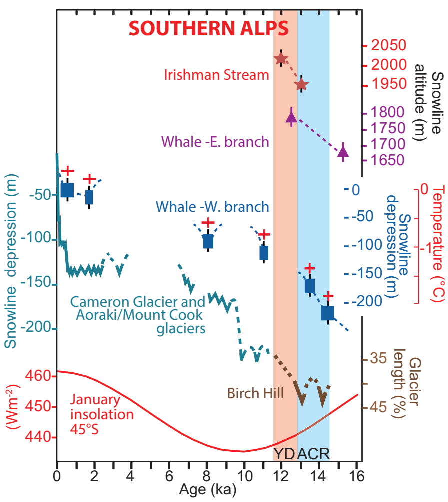

Figure 3. Evolution of snowline in Southern Alps (New Zealand) since Late Glacial time based on [10]Be-dated moraines. In essence, we are comparing climate at culminations of dated advances. For Whale Stream west (W.) branch, snowline and temperature depression are relative to late Holocene values (Fig. DR6 [see footnote 1]); Cameron Glacier–Aoraki/Mount Cook compilation of snowline relative to A.D. 1995 (Schaefer et al., 2009; Putnam et al., 2012); Birch Hill glacier length relative to Last Glacial Maximum (LGM) extent (Putnam et al., 2010a); Irishman Stream is from Kaplan et al. (2010). Insolation is from Berger and Loutre (1991). YD—Younger Dryas; ACR—Antarctic Cold Reversal.

the Late Glacial, is evidently not represented at Irishman Stream. We infer that as the east branch large moraine loop formed, it served as a dam that encouraged further vertical moraine accretion, thereby protecting older Late Glacial ridges from being overridden and/or destroyed (Fig. 1). By ca. 12 ka, the east branch glacier had withdrawn to low moraines inside the loop (Fig. 1). The west branch glacier retreated from the composite moraine loop by ca. 13.5 ka, and had shrunk back into the cirques by 11 ka.

Early Holocene glacier advances at Whale Stream were more extensive, and thus snowlines lower, than later in the epoch (Fig. 3). Although we do not know the amounts of glacier retreat between recorded advances, the overall pattern of successively smaller advances is documented by progressively younger moraines nested within older moraines. Prior to this study, the Tasman River–Pukaki area lacked evidence of glacier positions between ca. 13 ka and 6.7 ka, possibly because of their absence from this area or burial or erosion by aggrading outwash plains (Barrell et al., 2011; cf. Kirkbride and Winkler, 2012). Studies elsewhere in the Southern Alps indicate times of glacier advance in addition to those identified at Whale Stream, although some of these events remain poorly dated (Kirkbride and Winkler, 2012).

The numerical model provides an annual temperature ~2–3 °C cooler than present ca. 15–14 ka, which overlaps within error with Late Glacial temperature estimates at nearby Irishman Stream (Fig. 1; Doughty et al., 2012). The AAR-derived snowline rise at Irishman Stream during the YD (~75–115 ± 40 m) is also similar to the net ~100 m rise between ca. 15 and 12 ka at Whale Stream (Fig. 3).

We infer a net long-term trend in temperature at Whale Stream over the interval of time shown in Figure 2A. From 11 ka to 500 yr, we estimate ~0.6 °C (~mean annual) of net temperature gain based on the long-term ~100 m rise in AAR-based snowlines (Fig. 2A), assuming an adiabatic lapse rate of ~0.6 °C/100 m and no major deviations in precipitation.

If we assume a modern snowline of ~2100 m (Chinn et al., 2012), we can estimate ranges for long-term temperature rise since the Late Glacial (ca. 14.5 ka) and 11 ka; these are ~2.5–2.0 °C and ~1.9–1.4 °C, based on snowline rises of 420–340 m and 320–230 m (Table DR3), respectively. For Late Glacial time, the temperature estimates derived from the AAR approach and numerical model simulations are similar (between ~2 °C and 3 °C; Fig. 2C).

[10]Be-dated glacier and snowline reconstructions from the Southern Alps together show consistent long-term trends since the ACR (Fig. 3). For example, a long-term snowline rise of ~100 m between 11 ka and 500 yr is also observed at Cameron Glacier, ~100 km to the northeast of Whale Stream (Putnam et al., 2012). Moreover, the South Island glacier record dovetails with marine proxy evidence that the subtropical front was farther north during the early Holocene, and ocean temperatures upwind of the Southern Alps accordingly cooler (Moros et al., 2009).

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 snowlines in the Southern Alps were low, while during the same time interval, conditions were mostly unfavorable for glaciers in the Northern Hemisphere (e.g., Davis et al., 2009; Schimmelpfennig et al., 2012). Although it has long been recognized that Southern Alps glaciers underwent notable advances coinciding with the European LIA (Kirkbride and Winkler, 2012), our study highlights an important dissimilarity; Southern Alps glaciers were even larger in the early and middle Holocene.

The findings in the Southern Alps present a puzzle; namely, what mechanisms caused such interhemispheric differences in long-term glacier trends since ca. 15 ka? At first glance, out-of-phase insolation signals might be invoked to explain the interhemispheric differences in snowline trends. However, a local insolation effect cannot explain salient aspects of the record (Fig. 3). First, a net rise in snowline occurred from ca. 15–14 to 11 ka, and even until 8 ka, despite decreasing mid-summer insolation. Second, insolation changes cannot readily explain millennial and submillennial climatic events. Another possibility involves the effects of Northern Hemisphere and tropical insolation on the intertropical convergence zone (ITCZ). Specifically, data for the past ~11 k.y. are used to infer insolation-driven southward migration of the ITCZ (Haug et al., 2001), expansion of the Western Pacific Warm Pool (Linsley et al., 2010) with attendant southward shifts in major wind belts and sea surface temperature patterns (Moros et al., 2009), and a long-term rise in snowlines in New Zealand (Fig. 3). Moreover, the interplay of insolation and changes in large-scale circulation features, including (equatorward) shifts in major wind belts, could explain short-term Holocene cool episodes (Rojas and Moreno, 2010).

In any event, our findings imply that northern guides for Late Glacial and Holocene glacier behavior (e.g., Grove, 2004) are not entirely applicable to the middle latitudes of the Southern Hemisphere. Any model of hemispheric and global climate change must account for cold ACR temperatures, warming through the YD stadial, and long-term net warming over the Holocene in the New Zealand–Australia region (Fig. 3; Moros et al., 2009). In the past, the long-term pattern of glacier behavior was non-synchronous between the hemispheres.

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