

Mismatch of glacier extent and summer insolation in Southern Hemisphere mid-latitudes

Alice M. Doughty^{1,2}, Joerg M. Schaefer^{3,4}, Aaron E. Putnam^{2,3}, George H. Denton², Michael R. Kaplan³, David J.A. Barrell⁵, Bjørn G. Andersen^{6†}, Samuel E. Kelley⁷, Robert C. Finkel^{8,9}, and Roseanne Schwartz³

¹Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755, USA

²School of Earth and Climate Sciences and Climate Change Institute, University of Maine, Orono, Maine 04469, USA

³Lamont-Doherty Earth Observatory of Columbia University, 61 Rt. 9W, Palisades, New York 10944, USA

⁴Department of Earth and Environmental Sciences, Columbia University, New York, New York 10027, USA

⁵GNS Science, 764 Cumberland Street, Dunedin 9016, New Zealand

⁶Department of Geosciences, University of Oslo, 0316 Oslo, Norway

⁷Department of Earth and Environmental Sciences, Waterloo, Ontario N2L 3G1, Canada

⁸Department of Earth and Planetary Sciences, University of California–Berkeley, Berkeley, California 94720, USA

⁹CAMS, Lawrence Livermore National Laboratory, Livermore, California 94550, USA

ABSTRACT

Here we address a long-standing puzzle of ice-age climate called the “fly in the ointment of the Milankovitch theory.” Using geomorphic mapping and ¹⁰Be surface-exposure dating, we show that five moraine belts were formed during maxima of the last ice age by the Pukaki glacier in New Zealand’s Southern Alps. They afford ages of 41.76 ± 1.09 ka, 35.50 ± 1.26 ka, 27.17 ± 0.68 ka, 20.27 ± 0.60 ka, and 18.29 ± 0.49 ka. These five maxima spanned an entire precessional cycle in summer insolation intensity at the latitude of the Southern Alps. A similar mismatch between summer insolation and glacier extent also characterized the Chilean Lake District in the mid-latitudes of South America. Thus, in apparent contrast to northern ice sheets linked by Milankovitch to summer insolation at 65°N latitude, the behavior of southern mid-latitude glaciers was not tied to local summer insolation intensity. Instead, glacier extent between 41.76 ka and 18.29 ka, as well as during the last termination, was aligned with Southern Ocean surface temperature and with atmospheric carbon dioxide.

INTRODUCTION

A prominent version of the Milankovitch (1941) theory of climate is that changes in summer insolation at high northern latitudes, induced by variations in Earth’s orbit, controlled the extent and volume of Pleistocene ice sheets. In support, Roe (2006) showed a zero-lag, anti-phased relation between variations of summer insolation intensity at 65°N latitude and the rate of volume change of these sheets at the precession and obliquity frequencies. However, a long-standing conundrum is that despite summer intensity being anti-phased between the Southern and Northern Hemispheres, during the latter part of the last ice age the Patagonian Ice Field and the southern sector of the Laurentide Ice Sheet varied almost in concert (Mercer, 1984; Denton et al., 1999a, 1999b). The finding of similar climate changes in the two hemispheres was dubbed “a fly in the ointment of the Milankovitch theory” (Broecker, 1978; Mercer, 1984).

Here, we evaluate possible factors controlling glacier extent in the mid-latitude Southern Hemisphere by comparing a ¹⁰Be surface-exposure moraine chronology in the Southern Alps of New Zealand that extends well back into the most recent glaciation with the local orbitally induced signature of summer insolation, Southern Ocean sea-surface temperatures (SSTs), and variations of atmospheric carbon dioxide.

SETTING

During ice-age maxima, the Pukaki glacier, located at 44°S latitude, flowed southward from the highest sector of the Southern Alps to deposit moraines, kame terraces, and outwash outboard of the glacier trough now

occupied by Lake Pukaki (Barrell et al., 2011). This moraine-outwash complex has been divided into several stratigraphic units (Barrell and Read, 2014), but here we consider only the moraines depicted in red (local Last Glacial Maximum) in Figure 1. In our study area, along the southeastern sector of the left-lateral margin of the Pukaki glacier trough, these moraines compose four successive belts (Figs. 1 and 2). The moraine morphology is well preserved, with little erosion by outwash streams. Glaciers in the Southern Alps are sensitive to the effects of summer temperature (Anderson and Mackintosh, 2012), and thus we use glacier extent derived from mapped moraine belts as a temperature proxy. Glaciological modeling indicates that a snowline ~900 m lower than today, corresponding to atmospheric temperatures 6.25 ± 0.5 °C cooler than present, was sufficient for the Pukaki glacier to expand to these moraine belts (Golledge et al., 2012).

CHRONOLOGY

Quartzofeldspathic sandstone (greywacke) boulders are the predominant lithology in the Pukaki moraines and are well suited for exposure dating. These boulders are sourced from bedrock in the Pukaki catchment and were transported southward by glacier flow. We carried out ¹⁰Be exposure dating on samples from large boulders well rooted in moraine tops and hence unlikely to have been rotated since deposition. Samples were collected and then processed at the Lamont-Doherty Earth Observatory Cosmogenic Dating Laboratory (Columbia University, New York, USA) following our standard procedures (Schaefer et al., 2009). ¹⁰Be/⁹Be ratios were determined at Lawrence Livermore National Laboratory (California, USA). A locally established production rate for ¹⁰Be was used in the age calculations (Putnam et al., 2010). All processing and measurement details are given in Tables DR1–DR3 in the GSA Data Repository¹.

Morphological relations, including truncation of outer moraine belts by inner moraine belts, combined with dating allow discrimination of four moraine belts in our study area, which is centered on a small distributary outlet of the former glacier, known as the Maryburn lobe. Our chronology (Fig. DR1 in the Data Repository) indicates construction of the oldest moraine belt (*a* in Figs. 1 and 2), comprising three subdued ridges, at 35.50 ± 1.26 ka (*n* = 3; all ages given are the arithmetic mean age and 1σ uncertainty, and correspond to the “Lm” production-rate scaling scheme given in Table DR2; Balco et al., 2008). The next inboard belt (*b* in Figs. 1 and 2) yields an exposure age of 27.17 ± 0.68 ka (*n* = 7, one outlier excluded). The outer limit is a prominent moraine ridge; the remainder of the belt shows less-prominent ridges. The third belt (*c* in Figs. 1 and 2)

¹GSA Data Repository item 2015144, explanation of the CO₂ record, Figure DR1, and Tables DR1–DR3, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

[†]Deceased

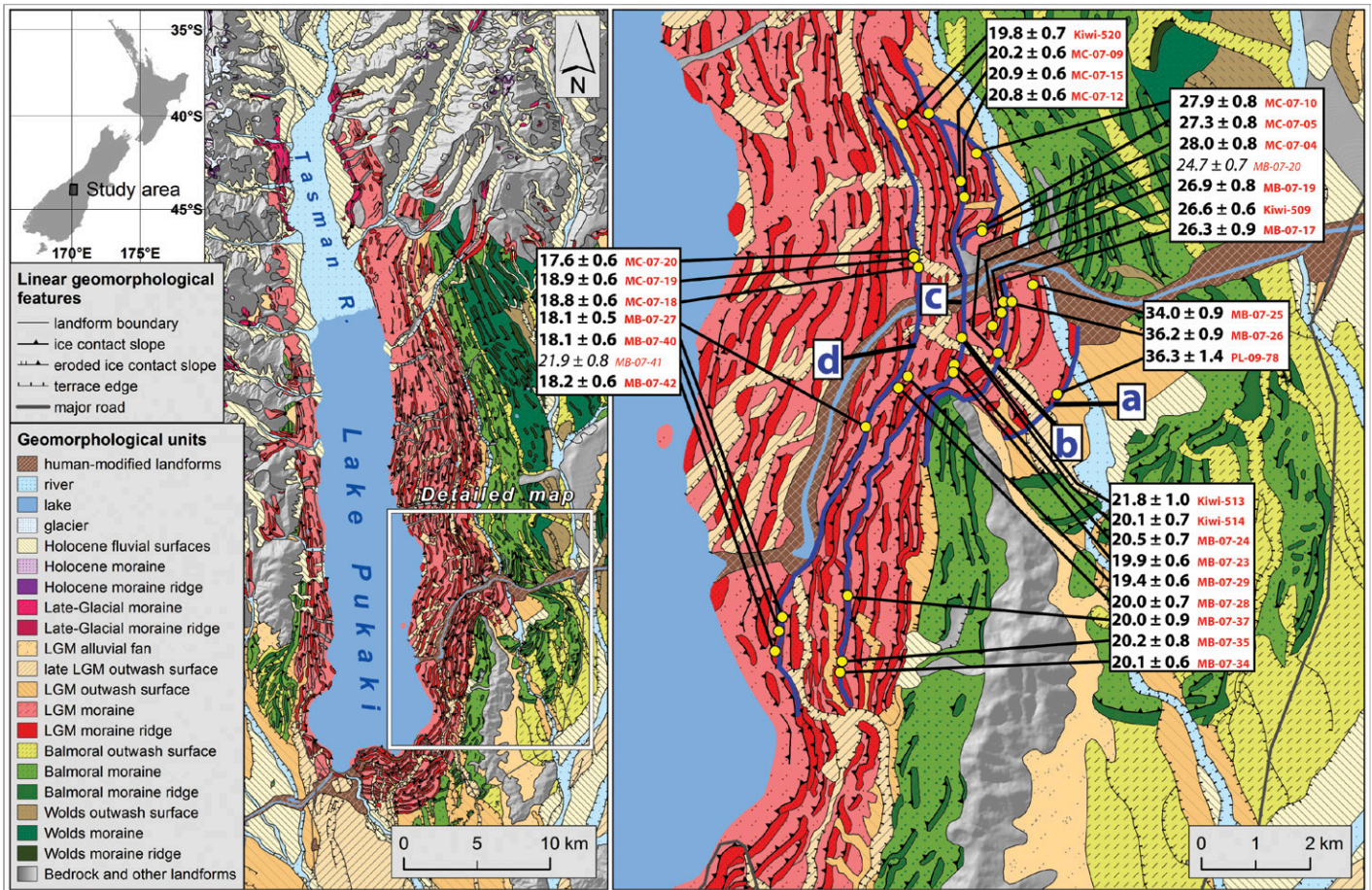


Figure 1. Glacial geomorphology of study area, New Zealand (after Barrell et al., 2011), showing sample sites (yellow) and ¹⁰Be ages (ka; see Table DR3 [see footnote 1]). Outliers are in italics. Blue lines mark outer limits of moraine belts a–d. LGM—Last Glacial Maximum.

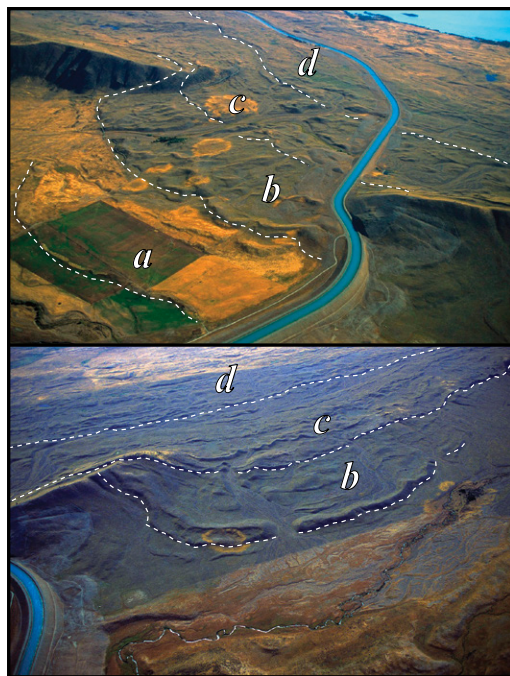


Figure 2. Aerial views of moraines in study area (South Island, New Zealand), looking southwest (top) and south (bottom). White dashed lines depict outer limits of moraine belts a–d. Canal is 50 m wide.

cross-cuts the adjacent, older belt, and affords an age of 20.27 ± 0.60 ka ($n = 13$). It consists of a sharp, well-delineated outer ridge backed by several subsidiary ridges. Finally, the outer ridges of the youngest belt (*d* in Figs. 1 and 2) afford an exposure age of 18.29 ± 0.49 ka ($n = 7$; one outlier excluded). Across the whole data set, just two samples were designated as outliers because they gave ages that are morphostratigraphically out of place.

An additional maximum of the Pukaki glacier is represented by a lateral moraine belt that is preserved between 6 km and 14 km north of the detailed map area in Figure 1 (Kelley et al., 2014). Boulders from this belt yielded an exposure age of 41.76 ± 1.09 ka ($n = 13$; four outliers excluded). This belt is not present in our study area because it is cut out, and thus either eroded or buried, by the moraine belt dated to 27.17 ± 0.60 ka. The five maxima of the Pukaki glacier are well separated in time and span an interval of as much as 25 k.y., between 18.29 ± 0.49 ka and 41.76 ± 1.09 ka (Fig. DR1). Terminal moraine belts at adjacent Lake Ohau formed at 32.52 ± 0.97 ka and 22.51 ± 0.60 ka (Putnam et al., 2013b), but these moraines were not preserved at Lake Pukaki. Collectively, seven episodes of full-glacial ice maxima have been identified in the Pukaki and Ohau moraine sequences.

DISCUSSION

A plot of surface-exposure ages of the seven moraine belts of the Pukaki and Ohau glaciers alongside orbital-scale variations of summer insolation intensity for 44°S latitude, which is dominated by precession (Fig. 3), shows no obvious relation between glacier maxima and insolation intensity minima. Indeed, glacier maxima were spread through an entire

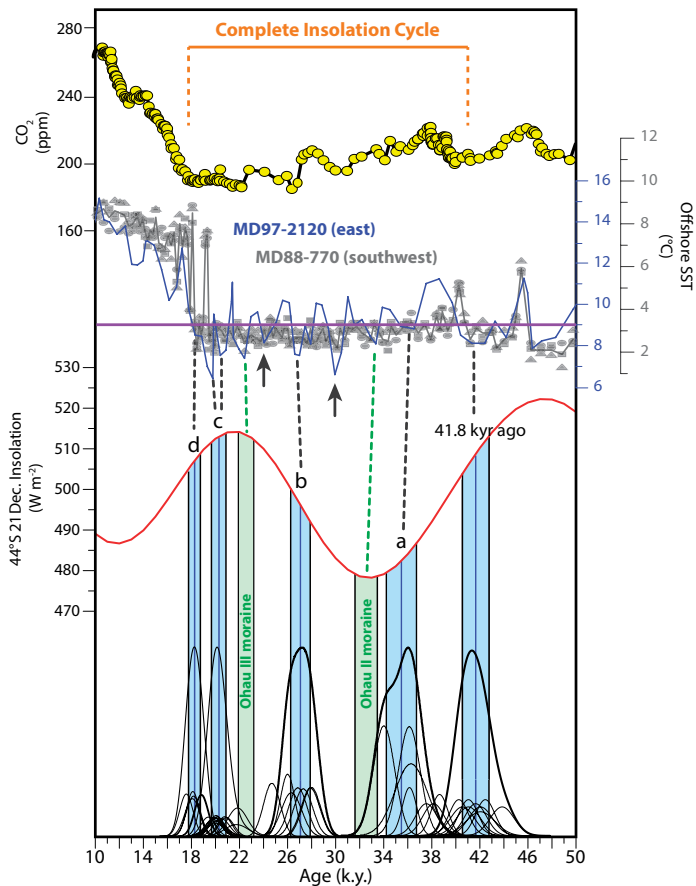


Figure 3. Chronology of moraine belts (a–d and 41.8 ka) constructed at maxima of Pukaki glacier, South Island, New Zealand (probability curves [in black] and notation from Fig. DR1 [see footnote 1]), and moraine belts of nearby Ohau glacier (Putnam et al., 2013b) that have not yet been found at Lake Pukaki. These moraine records are compared with 44°S, 21 December insolation (red curve; Laskar et al., 2004), Southern Ocean sea-surface temperature (SST) records from sediment cores MD88-770 (gray, fauna based; Barrows et al., 2007) and MD97-2120 (blue, Mg/Ca; Pahnke et al., 2003), and atmospheric CO₂ concentrations (yellow; see the Data Repository [see footnote 1]). Being fauna based, the MD88-770 record is bi-modal and illustrates persistent glacial, followed by interglacial, ocean conditions. MD97-2120 shows centennial-scale SST fluctuations comparable to nearby moraine records. Horizontal purple line marks 9 °C in the MD97-2120 core, approximating a maximum threshold for fully expanded ice-age glaciers at Pukaki and Ohau. Of the eight troughs of SST < 9 °C between ca. 18 and ca. 43 ka, only two (arrowed) are not represented by preserved moraines in the Pukaki-Ohau study area.

cycle of precession-forced summer insolation variation, and occurred during times of high, low, and intermediate intensity. In addition, extensive glacier retreat during the last termination, documented in the Pukaki drainage (Schaefer et al., 2006), and in the nearby Ohau and Rakaia drainages (Putnam et al., 2013a, 2013b) accompanied declining summer intensity.

Non-correlation between moraine formation and summer insolation is also demonstrated at 40°–43°S in Chile, where outlet lobes of the Patagonian Ice Field advanced repeatedly into the Llanquihue moraine belt between 34 ka and 18 ka, followed by major recession during the last termination (Denton et al., 1999b). The advances occurred during times of low, high, and intermediate summer insolation intensity, and the termination was coeval with decreasing, not increasing, intensity. Thus in neither Chile nor the Southern Alps was glacier behavior related in any obvious manner to changes in local summer insolation intensity at orbital time scales. This lack of correlation extends back in the most recent glaciation to at least 42 ka.

Barrows et al. (2007) proposed a close link between Southern Ocean SSTs and mid-latitude glacier activity. Due to a lack of well-dated, comprehensive moraine records, Barrows et al. (2007) utilized the Deep Sea Drilling Project (DSDP) Site 594 core of bathyal marine sediments 300 km east of New Zealand to investigate glacier-SST linkage. In that core, changes in the ratio of carbonate and terrigenous sediments have been interpreted as a proxy for glacier extent on the adjacent South Island (Nelson et al., 1993). However, Carter and Mitchell (1987) pointed out that eustatic sea level greatly influences the delivery of sediment to offshore deep-water environments. The DSDP Site 594 record may therefore reflect eustatic sea-level variations, and perhaps other hydrodynamic processes, more than glacier activity on the New Zealand landmass. We consider that times of glacier maximum extents afforded by the Pukaki/Ohau moraine chronology are an unambiguous glacial record that can be compared more confidently with SSTs.

Conditions in the outer sector of the Southern Ocean in the vicinity of New Zealand are illustrated by SST records from sediment core MD88-770 (R/V *Marion Dufresne*), located southwest of Australia at 46°S (Barrows et al., 2007), and sediment core MD97-2120, 300 km east of New Zealand's South Island at 45°S (Pahnke et al., 2003). Both sites lie just south of the modern Subtropical Front and highlight a Southern Ocean temperature as much as 4–5 °C cooler than today during the most recent glaciation. The MD97-2120 Mg/Ca SST record (Pahnke et al., 2003) shows a marked signature of temperature variation, with episodes of temperature minima below ~9 °C corresponding well with episodes of full-glacial ice extent, and moraine formation, at Lakes Pukaki and Ohau. Of note is that a temperature of ~9 °C at sea level corresponds, via a commonly applied lapse rate of 6 °C/km, to a 0 °C isotherm at ~1500 m above sea level (asl). This matches the full-glacial average snowline for the Ohau catchment of ~1500 m asl independently calculated by Putnam et al. (2013b). Linkage between SSTs and glacier extent is consistent with the dominant ocean temperature signature of modern mid-latitude air masses passing over the Southern Alps (McKinnon et al., 2013). An ocean-glacier linkage also accords with the finding that energy from turbulent heat flux heavily influences present-day glacier mass balance in the Southern Alps (Anderson and Mackintosh, 2012). A SST influence on southern mid-latitude ice fields is further suggested by the similarity between fluctuations of glaciers in Chile (Denton et al., 1999a) and changes in nearby surface ocean temperatures (Kaiser et al., 2005).

There are broad similarities between the CO₂ record and both the glacier and SST record (Fig. 3), but the SST record exhibits sharper variations than the CO₂ record. Between ca. 23 ka and 18 ka, notable signatures in SST fluctuations and glacier maxima are not evident in the CO₂ record. Thus in the New Zealand region, glacier maxima have had a closer association with SST than with atmospheric CO₂.

Overall, we infer that there was a close association between Southern Ocean SSTs and atmospheric temperatures over the Southern Alps and southern Andes, and hence on the respective mountain ice fields, during the last glaciation back at least to 42 ka. Possible controls on ocean surface temperatures and atmospheric temperatures, and therefore glacier fluctuations, in the Southern Hemisphere mid-latitudes include the far-field effect of orbital forcing from high northern (Barrows et al., 2007; Vandergoes et al., 2005) or southern (Huybers and Denton, 2008) latitudes, of a bipolar seesaw in ocean circulation (Broecker, 1998), and of latitudinal shifts of the Subtropical Front (Barker et al., 2009; De Deckker et al., 2012) likely associated with similar shifts of the Southern Hemisphere westerly wind belt (Anderson et al., 2009). The radiative forcing from the associated changes in atmospheric trace gases, including carbon dioxide, undoubtedly affected SSTs and glacier extent at southern mid-latitudes, but its importance is yet to be quantified.

ACKNOWLEDGMENTS

We are grateful to T.J. and G. Wills of Irishman Creek Station, J. Murray of The Wolds Station, and Guide Hill Station for permitting access to the moraines, and T. Ritchie and K. Ritchie of Lake Ruataniwha Holiday Park for providing excel-

lent accommodation. We appreciate assistance from S. Travis in sample collection and D. Sprecher in laboratory techniques. We thank W.S. Broecker for insightful discussions about glacial cycles. We thank S. Birkel and B. Hall for insightful discussions and help with early drafts of this manuscript. Reviews by B. Laabs, D. Sugden, and three anonymous reviewers helped us to improve the paper, and we are grateful to editor E. Thomas for additional comments and guidance. Funding was provided by the Gary C. Comer Science and Education Foundation and the U.S. National Science Foundation (EAR-0745781; EAR-1102782). D. Barrell was supported by funding from the New Zealand Government through the GNS Science "Global Change through Time" research program. This is Lamont-Doherty Earth Observatory contribution #7879.

REFERENCES CITED

- Anderson, B., and Mackintosh, A., 2012, Controls on mass balance sensitivity of maritime glaciers in the Southern Alps, New Zealand: The role of debris cover: *Journal of Geophysical Research*, v. 117, F01003, doi:10.1029/2011JF002064.
- Anderson, R.F., Ali, S., Bradtmiller, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., and Burckle, L.H., 2009, Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO₂: *Science*, v. 323, p. 1443–1448, doi:10.1126/science.1167441.
- Balco, G., Stone, J.O., Lifton, N.A., and Dunai, T.J., 2008, A complete and easily accessible means of calculating surface exposure ages or erosion rates from ¹⁰Be and ²⁶Al measurements: *Quaternary Geochronology*, v. 3, p. 174–195, doi:10.1016/j.quageo.2007.12.001.
- Barker, S., Diz, P., Vautravers, M.J., Pike, J., Knorr, G., Hall, I.R., and Broecker, W.S., 2009, Interhemispheric Atlantic seesaw response during the last deglaciation: *Nature*, v. 457, p. 1097–1102, doi:10.1038/nature07770.
- Barrell, D.J.A., and Read, S.A.L., 2014, The deglaciation of Lake Pukaki, South Island, New Zealand: A review: *New Zealand Journal of Geology and Geophysics*, v. 57, p. 86–101, doi:10.1080/00288306.2013.847469.
- Barrell, D.J.A., Andersen, B.G., and Denton, G.H., 2011, Glacial geomorphology of the central South Island, New Zealand: *GNS Science Monograph* 27, 81 p. and map (5 sheets).
- Barrows, T.T., Juggins, S., De Deckker, P., Calvo, E., and Pelejero, C., 2007, Long-term sea surface temperature and climate change in the Australian–New Zealand region: *Paleoceanography*, v. 22, PA2215, doi:10.1029/2006PA001328.
- Broecker, W.S., 1978, The cause of glacial to interglacial climatic change, *in* Gautier, D., et al., *Evolution of Planetary Atmospheres and Climatology of the Earth*: Toulouse, France, Centre National d'Etudes Spatiales, p. 165–190.
- Broecker, W.S., 1998, Paleocirculation during the last deglaciation: A bipolar seesaw?: *Paleoceanography*, v. 13, p. 119–121, doi:10.1029/97PA03707.
- Carter, L., and Mitchell, J.S., 1987, Late Quaternary sediment pathways through the deep ocean, east of New Zealand: *Paleoceanography*, v. 2, p. 409–422, doi:10.1029/PA002i004p00409.
- De Deckker, P., Moros, M., Perner, K., and Jansen, E., 2012, Influence of the tropics and southern westerlies on glacial interhemispheric asymmetry: *Nature Geoscience*, v. 5, p. 266–269, doi:10.1038/ngeo1431.
- Denton, G.H., Heusser, C.J., Lowell, T.V., Moreno, P.I., Andersen, B.G., Heusser, L.E., Schlüchter, C., and Marchant, D.R., 1999a, Interhemispheric linkage of paleoclimate during the last glaciation: *Geografiska Annaler*, v. 81, p. 107–153, doi:10.1111/j.0435-3676.1999.00055.x.
- Denton, G.H., Lowell, T.V., Heusser, C.J., Schlüchter, C., Andersen, B.G., Heusser, L.E., Moreno, P.I., and Marchant, D.R., 1999b, Geomorphology, stratigraphy, and radiocarbon chronology of Llanquihue drift in the area of the southern Lake District, Seno Reloncaví, and Isla Grande de Chiloé, Chile: *Geografiska Annaler*, v. 81, p. 167–229, doi:10.1111/j.0435-3676.1999.00057.x.
- Golledge, N.R., Mackintosh, A.N., Anderson, B.M., Buckley, K.M., Doughty, A.M., Barrell, D.J.A., Denton, G.H., Vandergoes, M.J., Andersen, B.G., and Schaefer, J.M., 2012, Last Glacial Maximum climate in New Zealand inferred from a modelled Southern Alps icefield: *Quaternary Science Reviews*, v. 46, p. 30–45, doi:10.1016/j.quascirev.2012.05.004.
- Huybers, P., and Denton, G., 2008, Antarctic temperature at orbital timescales controlled by local summer duration: *Nature Geoscience*, v. 1, p. 787–792, doi:10.1038/ngeo311.
- Kaiser, J., Lamy, F., and Hebbeln, D., 2005, A 70-kyr sea surface temperature record off southern Chile (Ocean Drilling Program Site 1233): *Paleoceanography*, v. 20, PA4009, doi:10.1029/2005PA001146.
- Kelley, S.E., Kaplan, M.R., Schaefer, J.M., Andersen, B.G., Barrell, D.J.A., Putnam, A.E., Denton, G.H., Schwartz, R., Finkel, R.C., and Doughty, A.M., 2014, High-precision ¹⁰Be chronology of moraines in the Southern Alps indicates synchronous cooling in Antarctica and New Zealand 42,000 years ago: *Earth and Planetary Science Letters*, v. 405, p. 194–206, doi:10.1016/j.epsl.2014.07.031.
- Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., and Levrard, B., 2004, A long-term numerical solution for the insolation quantities of the Earth: *Astronomy and Astrophysics*, v. 428, p. 261–285, doi:10.1051/0004-6361:20041335.
- McKinnon, K.A., Stine, A., and Huybers, P., 2013, The spatial structure of the annual cycle in surface temperature: Amplitude, phase, and Lagrangian history: *Journal of Climate*, v. 26, p. 7852–7862, doi:10.1175/JCLI-D-13-00021.1.
- Mercer, J.H., 1984, Simultaneous climatic change in both hemispheres and similar bipolar interglacial warming: Evidence and implications, *in* Hansen, J.E., and Takahashi, T., eds., *Climate Processes and Climate Sensitivity: American Geophysical Union Geophysical Monograph* 29, p. 307–313, doi:10.1029/GM029p0307.
- Milankovitch, M., 1941, *Kanon der Erdbestrahlung und Seine Anwendung auf das Eiszeitenproblem*: Belgrade, Royal Serbian Academy Special Publication 133, 633 p.
- Nelson, C.S., Cooke, P.J., Hendy, C.H., and Cuthbertson, A.M., 1993, Oceanographic and climatic changes over the past 160,000 years at Deep Sea Drilling Project Site 594 off southwestern New Zealand, southwest Pacific Ocean: *Paleoceanography*, v. 8, p. 435–458, doi:10.1029/93PA01162.
- Pahnke, K., Zahn, R., Elderfield, H., and Schulz, M., 2003, 340,000-year centennial-scale marine record of Southern Hemisphere climatic oscillation: *Science*, v. 301, p. 948–952, doi:10.1126/science.1084451.
- Putnam, A.E., Schaefer, J.M., Barrell, D.J.A., Vandergoes, M., Denton, G.H., Kaplan, M.R., Schwartz, R., Finkel, R.C., Goehring, B.M., and Kelley, S.E., 2010, In situ cosmogenic ¹⁰Be production-rate calibration from the Southern Alps, New Zealand: *Quaternary Geochronology*, v. 5, p. 392–409, doi:10.1016/j.quageo.2009.12.001.
- Putnam, A.E., et al., 2013a, Warming and glacier recession in the Rakaia valley, Southern Alps of New Zealand, during Heinrich Stadial 1: *Earth and Planetary Science Letters*, v. 382, p. 98–110, doi:10.1016/j.epsl.2013.09.005.
- Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Birkel, S.D., Andersen, B.G., Kaplan, M.R., Schwartz, R., Finkel, R.C., Goehring, B.M., and Doughty, A.M., 2013b, The Last Glacial Maximum at 44°S documented by a ¹⁰Be moraine chronology at Lake Ohau, Southern Alps of New Zealand: *Quaternary Science Reviews*, v. 62, p. 114–141, doi:10.1016/j.quascirev.2012.10.034.
- Roe, G., 2006, In defense of Milankovitch: *Geophysical Research Letters*, v. 33, L24703, doi:10.1029/2006GL027817.
- Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Ivy-Ochs, S., Kubik, P.W., Andersen, B.G., Phillips, F.M., Lowell, T.V., and Schlüchter, C., 2006, Near-synchronous interhemispheric termination of the Last Glacial Maximum in mid-latitudes: *Science*, v. 312, p. 1510–1513, doi:10.1126/science.1122872.
- Schaefer, J.M., et al., 2009, High-frequency Holocene glacier fluctuations in New Zealand differ from the northern signature: *Science*, v. 324, p. 622–625, doi:10.1126/science.1169312.
- Vandergoes, M.J., Newnham, R.M., Preusser, F., Hendy, C.H., Lowell, T.V., Fitzsimons, S.J., Hogg, A.G., Kasper, H.U., and Schlüchter, C., 2005, Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere: *Nature*, v. 436, p. 242–245, doi:10.1038/nature03826.

Manuscript received 25 November 2014

Revised manuscript received 5 February 2015

Manuscript accepted 11 February 2015

Printed in USA