Antarctic lakes suggest millennial reorganizations of Southern Hemisphere atmospheric and oceanic circulation

Brenda L. Hall[a,1], George H. Denton[a], Andrew G. Fountain[b], Chris H. Hendy[c], and Gideon M. Henderson[d]

[a]Department of Earth Sciences and Climate Change Institute, University of Maine, Orono, ME 04469; [b]Portland State University, Portland, OR 97207; [c]Department of Chemistry, University of Waikato, Hamilton, New Zealand; and [d]Department of Earth Sciences, University of Oxford, Oxford OX1 3PR, United Kingdom

Edited by Michael L. Bender, Princeton University, Princeton, NJ, and approved October 19, 2010 (received for review May 26, 2010)

The phasing of millennial-scale oscillations in Antarctica relative to those elsewhere in the world is important for discriminating among models for abrupt climate change, particularly those involving the Southern Ocean. However, records of millennial-scale variability from Antarctica dating to the last glacial maximum are rare and rely heavily on data from widely spaced ice cores, some of which show little variability through that time. Here, we present new data from closed-basin lakes in the Dry Valleys region of East Antarctica that show high-magnitude, high-frequency oscillations in surface level during the late Pleistocene synchronous with climate fluctuations elsewhere in the Southern Hemisphere. These data suggest a coherent Southern Hemisphere pattern of climate change on millennial time scales, at least in the Pacific sector, and indicate that any hypothesis concerning the origin of these events must account for synchronous changes in both high and temperate latitudes.

Antarctica | Dry Valleys | lake-level change | radiocarbon

The origin of abrupt, millennial-scale changes is one of the most pressing problems in paleoclimate research, with important implications for climate prediction. These rapid events have been attributed to variations in ocean and/or atmospheric circulation (1), possibly modulated by external forcing (2), but the root cause remains unknown. Such changes in Antarctic ice cores appear to be out of phase with those of the Northern Hemisphere (3, 4), leading to the idea that abrupt climate changes are controlled by a seesaw in ocean thermohaline circulation (5). However, most comparisons focus on large warming events during Marine Oxygen Isotope Stage 3, with relatively little attention devoted to the last glacial maximum (LGM), which many Antarctic ice cores show as a relatively stable period (6). Moreover, poor geographic coverage in the Antarctic does not allow separation of continent-wide from regional events, which might point to the importance of internal ocean-atmosphere oscillations, such as extended El Niño-Southern Oscillation events, in causing abrupt climate changes.

To examine the timing of millennial-scale events in high southern latitudes during the LGM, we present here a well-dated lacustrine record from the Dry Valleys (77–78 °S, 160–164 °E, Fig. 1) of the Transantarctic Mountains, which allows precise comparison to areas north of Antarctica. In the Dry Valleys, more than a dozen closed-basin lakes show evidence of past surface-level changes suitable for reconstructing hydrologic variations and hence climate. Many of these lakes today show strong density stratification with hypersaline bottom waters thought to have formed during lowstands. Water levels in this hyperarid environment are controlled by the balance between surface inflow and sublimation of the perennial ice cover (see *SI Text*). Lakes with this type of hydrology (amplifier lakes) respond rapidly to slight shifts in water balance, magnify even small environmental changes, and thus are highly sensitive recorders of past climate (7).

Results

We focus on three enclosed lakes, Bonney, Vanda, and Vida (Fig. 1). We also include supplemental data from Lake Fryxell, which was connected to Lake Bonney periodically at the LGM (see *SI Text*). Surface-level data consist of small (generally <400 m^2, <5 m of relief) radiocarbon-dated relict deltas (Fig. S1 and Table S1) and shorelines perched as much as 450 m above present lake levels. We dated algal mats from these features and converted the ages to calendar years (see *Materials and Methods*). Finally, we include as supporting information (Table S2 and Fig. S2) a small number of preliminary uranium-thorium disequilibrium ages of lowstand evaporite sequences from sediment cores.

Although today the Dry Valleys are located by the coast, at the LGM they were ~1,000 km from the nearest open water, because an ice sheet extended close to the continental shelf edge in the Ross Sea (8). This Ross Sea ice sheet (RSIS) impinged on the mouth of Taylor Valley (Fig. 1), damming Glacial Lake Washburn, which encompassed Lakes Bonney and Fryxell when water level was above 118 m and 76 m above sea level, respectively (9). Large lakes also existed in valleys both to the north and south. We focus on Glacial Lakes Wright (modern Lake Vanda) and Victoria (modern Lake Vida), which were only ice dammed at their highest levels. All three glacial lakes fluctuated on millennial time scales and showed large-magnitude changes characteristic of amplifier lakes. Because variations occurred even when the lakes were not in contact with glaciers and because the same changes took place in more than one lake, we infer that water-level fluctuations reflected climate, rather than local changes due to displacement of water by glacier advance.

Dry Valleys lakes, which today are as much as 76 m deep, have a history of large changes in surface level (8, 10, 11). Limited and geographically scattered evidence indicates that lakes experienced highstands periodically during both the early LGM and Holocene. However, between ~9,000–22,000 cal yr B.P., abundant geomorphological and sedimentological evidence indicates that the lakes underwent a prolonged stage of large-scale fluctuations and reached high levels not attained since (Fig. 2 and Figs. S3–S8). Preservation of relict shorelines and deltas is excellent, suggesting that the changes in lake level were so rapid that erosion of preexisting landforms was minimal. The most complete glacial-age record comes from Lake Bonney, where eight cycles of surface-level change occurred between 22,200 and 13,400 cal yr B.P., and a few deltas record high water as early

Author contributions: B.L.H. designed research; B.L.H., G.H.D., A.G.F., C.H.H., and G.M.H. performed research; B.L.H., G.H.D., A.G.F., C.H.H., and G.M.H. analyzed data; and B.L.H., G.H.D., A.G.F., and G.M.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: BrendaH@maine.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1007250107/-/DCSupplemental.

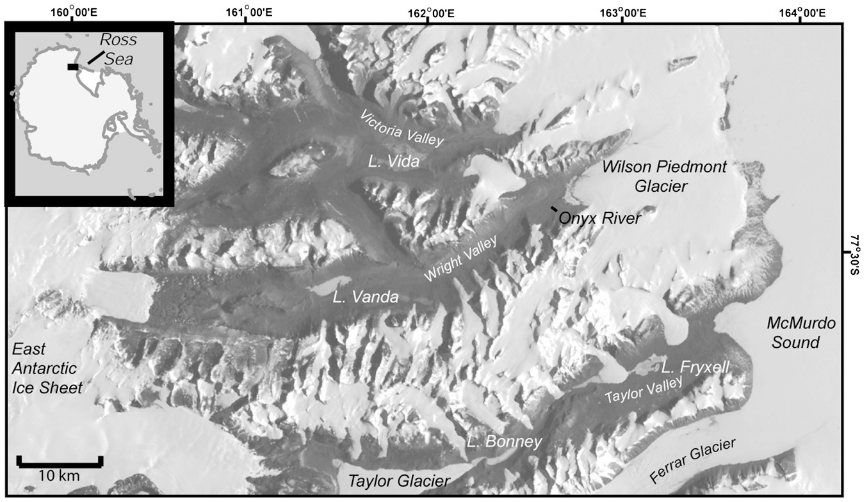

Fig. 1. Location map of the Dry Valleys, Antarctica, and the lakes used in this study.

as ~28,500 cal yr B.P. (Fig. 2 and Table S1). The Lake Vanda record spans ~30,000 years and indicates that water-level changes also occurred during the Holocene (see *SI Text*). In contrast, there is no evidence of higher-than-present Holocene levels at Lake Bonney, probably because rising lake levels due to advance of Taylor Glacier have surpassed any early or midHolocene highstands (12). The Lake Vida record is discontinuous, but shows changes similar to those in the other two valleys, between

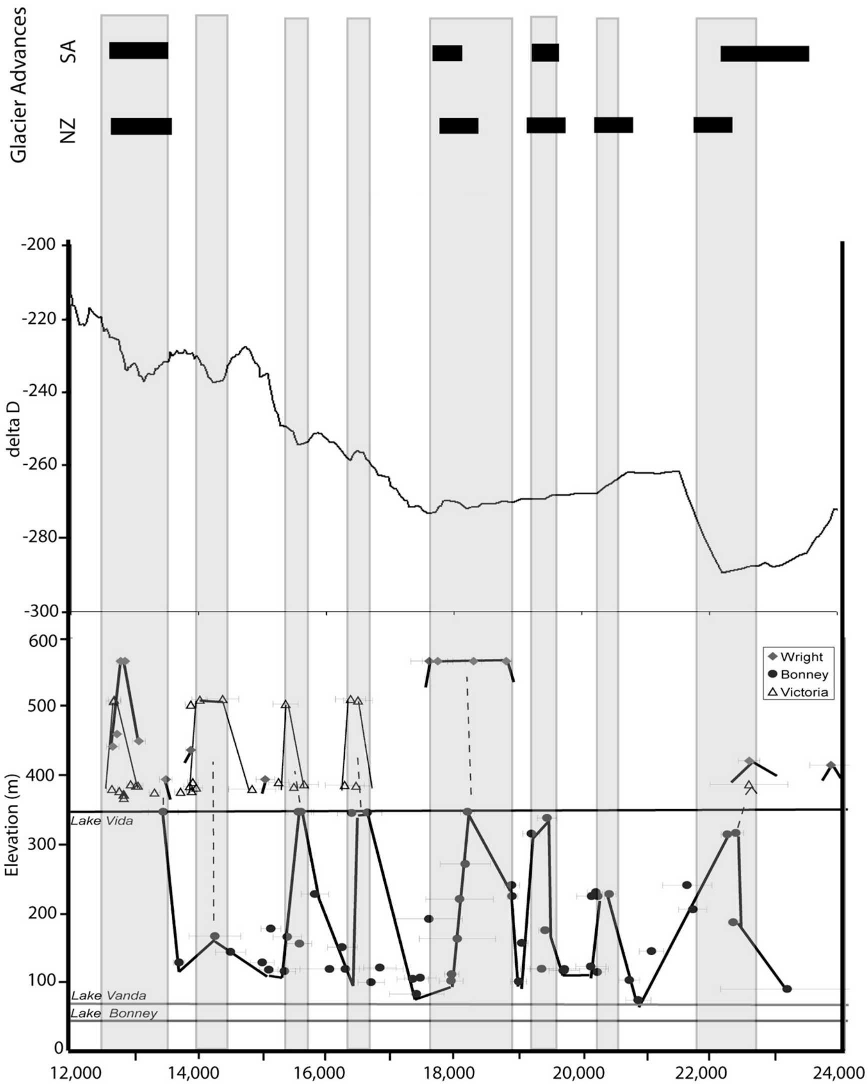

Fig. 2. Surface-level data from Lakes Bonney, Vanda, and Vida, as well as records from New Zealand and South American glaciers and the Siple Dome ice core. The base of the figure shows the lake data. Each symbol represents an individual radiocarbon-dated delta or shoreline that records the former lake surface. Horizontal lines mark present-day lake levels. We separated peaks based on the fact that their ages do not overlap, within errors. Most highstands are defined by several points, but a few are indicated by only single deltas. Although treating these latter peaks with caution, we consider them to be real events, because their magnitude and pacing are similar to those which are defined better, and because we find similar-aged highstands in other valleys. Note that this figure only shows the period between 12,000 and 24,000 cal years B.P. For the entire lake records, see Figs. S3–S6. The center shows the Siple Dome δD data [courtesy of A. Schilla and (4)], smoothed with a five-point running mean. The top displays the approximate timing of glacial advances in South America (40) and New Zealand (40, 49–52), as indicated by dated moraines.

~10,000 and 16,500 cal yr B.P., as well as fragmentary evidence of higher-than-present levels in the Holocene. Records from all lakes indicate highstands during the late LGM, Termination, and late-glacial period were of greater magnitude than those in the Holocene.

The lake-level records reveal a characteristic millennial-scale periodicity. The most complete record, from Lake Bonney, shows a recurrence interval of ~1,000 years for highstands between 22,000 and 13,400 cal yr B.P. The occasional longer interval, ~2,000 years, may result from lack of evidence for every event. Nearby Lake Fryxell exhibits similar fluctuations (Fig. S4), as well as events not shown at Lake Bonney that occurred when water level was below the sill that separates the two basins.

Discussion

Surface-level variations of closed-basin lakes in the Dry Valleys result from imbalance between meltwater flow and sublimation/evaporation from the lake. In this hyperarid polar environment, meltwater is derived from snow-free ("blue-ice"), glacier ablation zones. Snow reflects ~90% of incoming solar energy and, in the current environment, contributes little to runoff, because it largely sublimates (13–15). Moreover, snow also depresses surface melt (16). In contrast, under snow-free conditions, several mechanisms amplify melting. First, sediment on or near the surface (i.e., Fig. S9 and see *SI Text*) reduces albedo and promotes heat gain by the ice from solar radiation, thus greatly enhancing melt. Second, subsurface melting occurs during windy, sunny days by a solid-state greenhouse effect (17, 18), even with air temperatures below freezing. In addition, turbulent heat transfer in the Dry Valleys is relatively large and keeps ice surfaces cool (18, 19). Thus, a drop in wind speed reduces latent and sensible heat losses such that ablation shifts from sublimation-dominated to melt-dominated (increases in downslope winds also can warm the valleys to melting temperatures, but such winds are infrequent in summer when melting takes place). All of these amplifying processes likely were critical for producing the excess meltwater needed to raise lakes to such high levels.

Large changes in melting thus relate to fluctuations in absorbed radiation determined primarily by snow cover and by turbulent exchange of heat with the atmosphere determined by wind. Based on data linking lake-level drop to snowy conditions (13, 16, 20), Hall et al. (10) proposed that reduction or elimination of precipitation would increase blue-ice ablation zones and boost meltwater production through the amplifying mechanisms described above. An alternative hypothesis for increased meltwater is that air temperatures were warmer (21). These hypotheses are not mutually exclusive. However, because mean summer air temperatures today in the region are below freezing (16, 21, 22) and were colder at the LGM and during the Termination (23) when lakes were large, we suggest that the overarching condition for high lakes is not warm temperatures but an arid environment which allows for the formation of blue-ice zones on adjacent glaciers. This model is borne out by the fact that lakes have been at both high and low elevations during the LGM, Termination, and Holocene, times which have had significantly different temperature histories. Our preferred interpretation, therefore, is that high lakes are linked to aridity.

Thus, somewhat counterintuitively, water levels in lakes in the Dry Valleys are not controlled directly by precipitation in their catchments nor by temperature changes, but by the melting of blue ice that actually is suppressed by snowfall. Two facets of the lake-level records require explanation: (*i*) lakes attained their highest levels overall at times between ~9,000–22,000 cal yr B.P. and dropped in the Holocene, and (*ii*) there is a superimposed millennial-scale pattern during both glacial and interglacial times.

We suggest that the general glacial/interglacial pattern of lake-level change was the result of three factors. First, and perhaps most important, is that the expanded RSIS and coastal piedmont glaciers provided a greatly enlarged meltwater catchment for the Dry Valleys relative to that which exists at present. This ice provided the reservoir necessary to supply large volumes of meltwater, as well as the dam which allowed some lakes to attain very high levels. In addition, this ice likely would have been debris-rich (see *SI Text*), which would have enhanced melting during snow-free periods. The timing of the highest lakes corresponds well with the existence of the RSIS in the western Ross Sea (8, 24–26).

In addition to providing the necessary meltwater for the high lakes, the RSIS also would have minimized advection of moist marine air masses to the Dry Valleys, as suggested by decrease in accumulation to near zero at nearby Taylor Dome (27). Because of the ice sheet, the snow-bearing cloud banks and moist marine air brought into the valleys today on the prevailing easterly winds were absent, and the eastern parts of the valleys would have warmed. Indeed, because of the easterlies, the valleys today become warmer both inland (westward) at 0.09 °C km^{-1} (21) and also up the valley walls away from the floor at 0.24 °C km^{-1} (28). As a consequence of the decrease in both precipitation and Ross Sea air masses at the LGM, the Dry Valleys became drier with lower albedo, locally warmer temperatures, and greatly expanded blue-ice ablation zones. These factors allowed the meltwater amplifier mechanisms described above to take effect. Together, these factors allowed lakes to reach high levels not attained since retreat of the ice sheet at ~8,000 years B.P. (10).

The millennial-scale oscillations superimposed on the glacial/interglacial lake-level pattern likely also resulted from variations in meltwater input, rather than sublimation/evaporation from the lakes. Because meltwater production operates over large catchments, it is much more effective than sublimation/evaporation in changing lake size. In addition, meltwater formation in this environment is highly variable due to its sensitivity to surface energy conditions. In contrast, sublimation varies comparatively little. Large-scale changes in meltwater input could come about by: (*i*) altering ice extent and thus catchment area (which we suggest is a factor in controlling the glacial-interglacial pattern of lake-level change), (*ii*) varying wind speed, and/or (*iii*) changing the amount of snow covering potential ablation zones. We prefer the latter mechanism for the millennial-scale oscillations, as there is no evidence at present of significant changes in the configuration of the RSIS or local alpine glaciers on such short time scales. Increasing wind velocity would enhance sublimation and contribute to lake-level drop but, given that wind speed has been relatively constant over the observational period, we suggest that its effect is secondary to that of precipitation changes. We therefore propose that times of low snowfall (aridity) correspond to high water levels and somewhat higher snowfall causes shut-off of meltwater production and lake dessication. The highest of these millennial-scale increases in water level should occur when strong aridity and the presence of the RSIS and expanded coastal piedmont glaciers combine to produce extensive blue-ice ablation zones. Arid periods also could produce smaller highstands, such as those documented for the Holocene or early in the LGM, in the absence of the RSIS.

These alternating drier and slightly snowier periods in the Dry Valleys may have been a function of millennial-scale reorganizations of the Southern Ocean and atmosphere. We suggest, as have others before us (i.e., 29–31), a strong coupling between Antarctica and the southern temperate regions, and that during the LGM the polar cell and probably sea ice expanded (32, 33) and westerly winds and oceanic fronts moved north (31, 34, 35). This scenario would have made it more difficult for snow-bearing storms to penetrate the distance to the Dry Valleys. We further propose that the same process also happened on millennial time scales, leading to the aridity that resulted in high lake levels. Conversely, we suggest that dessication events occurred when periodic southward shifts in the westerlies and contraction of the polar cell pushed humid air masses close to Antarctica, bringing snow to the Dry Valleys. We note that this proposed model applies to the millennial-scale fluctuations superimposed on the larger glacial-interglacial lake-level record. During the Termination, upwelling proxies derived from biogenic silica preserved in sediment cores taken from the Drake Passage suggest that the westerlies shifted south (36)—conditions that might be expected to produce low lake levels by our model and, indeed, during the Termination and especially in the Holocene lakes have been low for more than half the time. However, during the overall southward trend, we propose that millennial-scale variations occurred and, at times, the latitudinal position of the westerlies may have shifted north, as suggested by evidence from South America (i.e., 37–39). We emphasize here again that by their very nature the Dry Valleys lakes amplify the effect of even small climate changes so the magnitude of lake-level variation is greatly out of proportion with the forcing. This behavior makes quantitative interpretations of the degree of climate change impossible. However, these lakes are highly sensitive recorders of the number of events, regardless of the magnitude of forcing.

Comparison of the Dry Valleys lake record with paleoclimate data from north of the Antarctic Convergence shows similar millennial-scale climate events elsewhere in the Southern Hemisphere. High lake levels, which we infer correspond to northward shifts in the storm tracks during cool periods, are synchronous with glacier advances in both New Zealand and South America (Fig. 2) (40), suggesting a common climate forcing. In addition, although resolution differences make it difficult to compare records directly, Southern Ocean temperature (31, 41) and sea-ice (32) records also show millennial-scale variability. Such correspondence between Antarctica and midlatitudes of the Southern Hemisphere has been proposed for the initiation and termination of the LGM (30), but has only recently been suggested for millennial time scales (31). Vandergoes et al. (30) and Kaiser et al. (31) both further suggested that the climatic link between Antarctica and the temperate midlatitudes was through variations in sea-ice extent, the Antarctic Circumpolar Current, and the westerlies, a hypothesis supported by upwelling data (36) and modelling (34). Although we cannot test this scenario directly, our proposal that high lake levels are linked to northward shifts in the pressure and storm systems around Antarctica, is consistent with this concept. If correct, the implication is that the same pattern and mechanisms of climate change operating on orbital time scales also may occur during shorter events. Moreover, our conclusions suggest that fundamental reorganizations of Southern Hemisphere-wide ocean, atmosphere, and cryosphere systems occur on millennial time scales.

In summary, we have documented large-scale changes in water level in the Dry Valleys of Antarctica. During the LGM and Termination I, the presence of the RSIS and expanded coastal piedmont glaciers greatly increased the catchment area of the present-day lakes and afforded large ice reservoirs available for melting when the climate was favorable. This expanded ice allowed for higher stands of lakes between 9,000–22,000 cal yr B.P than during the Holocene. Superimposed on the long-term record, there has been a millennial-scale periodicity in water-level changes irrespective of general climate state (LGM, Termination, and Holocene). Approximately every ~1,000–2,000 years, lake levels rose, which we attribute to expansion of blue-ice ablation zones caused by increased aridity. Although we cannot exclude other hypotheses at present, we speculate that these alternating periods of arid and snowy conditions relate to variations in the polar cell, sea ice, and the position of the westerly wind belt, which make it more difficult for precipitation to reach the Dry Valleys. The good correlation of events in the Antarctic lake record with glacier fluctuations in southern temperate latitudes is consistent with this hypothesis and suggests fundamental shifts in the Southern Hemisphere climate system on millennial time scales.

Materials and Methods

We collected algal samples from hand-dug and natural exposures in small (generally <100×100 m in area, <5 m of relief) deltas and shorelines using trowels and sterile plastic bags. We determined elevations using both a theodolite (error ~0.1 m) and barometric altimeters calibrated to points of known elevation (error estimated at <10 m). We present here the elevation of the delta apex or topset/foreset contact (where visible), rather than sample elevation, because the former is a more accurate measure of lake level.

We obtained radiocarbon ages for the algal samples (Table S1) (8, 10, 12, 42–44). Approximately one third of the dates are conventional ages, run by M. Stuiver at the University of Washington in the 1970s and 1980s; the large errors on some of these samples reflect the difficulty in finding sufficient algae for this method. Dates from the National Science Foundation-University of Arizona Accelerator Mass Spectrometry facility have tighter error ranges. We present all dates as calendar years, obtained by using a combination of the IntCal04 dataset (45) and the Fairbanks0107 calibration curve [for samples >20,000 ^{14}C yr B.P.(46)]. We restricted radiocarbon dating to algae that grew in shallow waters where the reservoir effect is thought to be absent or negligible (47, 48).

We reconstructed lake-level changes by fitting a curve through the data points, each of which represents an individual delta or shoreline. The fit of the curve to the data is imperfect and, in places, the proposed age of the highstand overlaps with the age of lake-level features at much lower elevations. To a large degree, this overlap reflects the fact that we include some dates obtained more than 30 yr ago that have large errors. Nevertheless, we use these data in the curve reconstruction, because they still show the general trend of lake-level change, even if the precision is poor. In addition, there also is some overlap between dates of proposed highstands and lowstands, because lake-level changes were rapid and the resolution of radiocarbon dating, particularly once the ages are converted to calendar years, is insufficient to resolve changes that occur within a few hundred years.

ACKNOWLEDGMENTS. T. Cruickshank, K. Faloon, E. Hofstee, B. Overturf, A. Roy, R. Verow, and T. Whittaker assisted in the field. We thank D. Bromwich and N. Bertler for helpful discussions and two anonymous reviewers and our editor for insightful comments. This work was supported by the Office of Polar Programs of the National Science Foundation and the New Zealand Antarctic Research Programme.

1. Broecker W, Denton G (1989) The role of ocean-atmosphere reorganizations in glacial cycles. *Geochimica et Cosmochim Ac* 53:2465–2501.
2. Bond G, et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294:2130–2136.
3. Blunier T, Brook E (2001) Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. *Science* 291:109–112.
4. Brook E, et al. (2005) Timing of millennial-scale climate change at Siple Dome,West Antarctica, during the last glacial cycle. *Quaternary Sci Rev* 24:1333–1343.
5. Broecker W (1998) Paleocean circulation during the last deglaciation: a bipolar seesaw? *Paleoceanography* 13:119–121.
6. Jouzel J, et al. (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science* 317:793–797.
7. Street-Perrott FA, Harrison SP (1985) *Paleoclimate analysis and modelling*, ed AD Hecht (John Wiley and Sons, New York), pp 291–340.
8. Stuiver M, Denton G, Hughes T, Fastook J (1981) *The last great ice sheets*, eds G Denton and T Hughes (Wiley Interscience, New York), pp 319–436.
9. Hall B, Denton G, Hendy C (2000) Evidence from Taylor Valley for a grounded ice sheet in the Ross Sea, Antarctica. *Geografiska Ann* 82A:275–304.
10. Hall B, Denton G, Overturf B (2001) Glacial Lake Wright, a high-level Antarctic lake during the LGM and early Holocene. *Antarctic Sci* 13:53–60.
11. Péwé T (1960) Multiple glaciations in the McMurdo Sound region, Antarctica—a progress report. *J Geol* 68:498–514.
12. Denton G, Bockheim J, Wilson S, Stuiver M (1989) Late Wisconsin and early Holocene glacial history, inner Ross Embayment, Antarctica. *Quaternary Res* 31:151–182.
13. Chinn T (1993) Physical hydrology of the Dry Valleys lakes. *Antarctic Res S* 59:1–51.
14. Gooseff MN, et al. (2003) Snow-patch influence on soil biogeochemical processes and invertebrate distribution in the McMurdo Dry Valleys, Antarctica. *Arct Antarct Alp Res* 35:92–100.
15. Fountain AG, Nylen T, Monaghan A, Basagic H, Bromwich D (2009) Snow in the McMurdo Dry Valleys. *Int J Climatol* doi: 10.1002/joc.1933.
16. Fountain AG, et al. (1999) Physical controls on the Taylor Valley ecosystem, Antarctica. *Bioscience* 49:961–971.

17. Brandt RE, Warren SG (1993) Solar-heating rates and temperature profiles in Antarctic snow and ice. *J Glaciol* 39:99–110.
18. Hoffman M, Fountain AG, Liston GE (2008) Surface energy balance and melt thresholds over 11 years at Taylor Glacier, East Antarctica. *J Geophys Res* 113 doi: 10.1029/2008JF001029.
19. Lewis K, Fountain AG, Dana G (1998) Surface energy balance and meltwater production for a Dry Valley glacier, Taylor Valley, Antarctica. *Ann Glaciol* 27:603–609.
20. Chinn T (1980) Glacier balances in the Dry Valleys area, Victoria Land, Antarctica. *Proceedings of the Riederalp Workshop IAHS-AISH Publication* 126:237–247.
21. Doran P, et al. (2002) Valley floor climate observations from the McMurdo Dry Valleys, Antarctica, 1986–2000. *J Geophys Res* 107 doi: 10.1029/2001JD002045.
22. Nylen T, Fountain AG, Doran P (2004) Climatology of katabatic winds in the McMurdo Dry Valleys, Southern Victoria Land, Antarctica. *J Geophys Res* 109 doi: 10.1029/2003JD003937.
23. Steig E, et al. (2000) Wisconsinan and Holocene climate history from an ice core at Taylor Dome. *Geografiska Ann* 82A:213–235.
24. Domack E, Jacobson E, Shipp S, Anderson J (1999) Late Pleistocene-Holocene retreat of the West Antarctic Ice Sheet in the Ross Sea: Part 2—sedimentologic and stratigraphic signature. *Geol Soc Am Bull* 111:1517–1536.
25. Conway H, Hall B, Denton G, Gades A, Waddington E (1999) Past and future grounding-line retreat of the West Antarctic Ice Sheet. *Science* 286:280–283.
26. Hall B, Denton G, Baroni C (2004) Holocene relative sea-level history of the Southern Victoria Land Coast, Antarctica. *Global Planetary Change* 42:241–263.
27. Morse D, Waddington E, Steig E (1998) Ice-age storm trajectories inferred from radar stratigraphy at Taylor Dome, Antarctica. *Geophys Res Lett* 25:3383–3386.
28. Ebnet AF, Fountain AG, Nylen T, McKnight DM, Jaros C (2005) A temperature-index model of stream flow at below-freezing temperatures in Taylor Valley, Antarctica. *Ann Glaciol* 40:76–82.
29. Lambert F, et al. (2008) Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature* 452:616–619.
30. Vandergoes M, et al. (2005) Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere. *Nature* 436:242–245.
31. Kaiser J, Lamy F, Hebbeln D (2005) A 70-kyr sea surface temperature record off southern Chile (Ocean Drilling Program Site 1233). *Paleoceanography* 20 doi: 10.1029/2005PA001146.
32. Gersonde R, et al. (2003) Last glacial sea-surface temperatures and sea-ice extent in the Southern Ocean (Atlantic-Indian sector): a multiproxy approach. *Paleoceanography* 18 doi: 10.1029/2002PA000809.
33. Shemesh A, et al. (2002) Sequence of events during the last deglaciation in Southern Ocean sediments and Antarctic ice cores. *Paleoceanography* 17 doi: 10.1029/2000PA000599.
34. Toggweiler JR, Russell JL, Carson SR (2006) Mid-latitude westerlies, atmospheric CO_2, and climate change during the ice ages. *Paleoceanography* 21 doi: 10.1029/2005PA001154.
35. Moreno P, Lowell T, Jacobson G, Jr, Denton G (1999) Abrupt vegetation and climate changes during the Last Glacial Maximum and last termination in the Chilean Lake District: a case study from Canal de la Puntilla (41 °S). *Geografiska Ann* 81A:285–311.
36. Anderson RF, et al. (2009) Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2. *Science* 323:1443–1448.
37. Moreno P, François JP, Villa-Martínez RP, Moy CM (2009) Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5,000 years in SW Patagonia. *Quaternary Sci Rev* 28:25–38.
38. Mohtadi M, Romero O, Kaiser J, Hebbeln D (2007) Cooling of the southern high latitudes during the Medieval Period and its effect on ENSO. *Quaternary Sci Rev* 26:1055–1066.
39. Villa-Martínez RP, Moreno P (2007) Pollen evidence for variations in the southern margin of the westerly winds in SW Patagonia over the last 12,600 years. *Quaternary Res* 68:400–409.
40. Denton G, et al. (1999) Interhemispheric linkage of paleoclimate during the last glaciation. *Geografiska Ann* 81A:107–153.
41. Barrows T, Juggins S, De Dekker P, Calvo E, Pelejero C (2007) Long-term sea-surface temperature and climate change in the Australian-New Zealand region. *Paleoceanography* 22 doi: 10.1029/2006PA001328.
42. Hall B, Denton G (2000) Radiocarbon chronology of Ross Sea drift, eastern Taylor Valley, Antarctica: evidence for a grounded ice sheet in the Ross Sea at the last glacial maximum. *Geografiska Ann* 82A:305–336.
43. Hall B, Henderson G (2001) Use of uranium-thorium dating to determine past ^{14}C reservoir effects in lakes—examples from Antarctica. *Earth Planet Sc Lett* 193:565–577.
44. Hall B, Denton G, Overturf B, Hendy C (2002) Glacial Lake Victoria, a high-level Antarctic lake inferred from lacustrine deposits in Victoria Valley. *J Quaternary Sci* 17:697–706.
45. Reimer PJ, et al. (2004) IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr B.P. *Radiocarbon* 46:1029–1058.
46. Fairbanks R, et al. (2005) Marine radiocarbon calibration curve spanning 0 to 50,000 years B.P., based on paired $^{230}Th/^{234}U/^{238}U$ and ^{14}C dates on pristine corals. *Quaternary Sci Rev* 24:1781–1796.
47. Doran P, et al. (1999) Dating quaternary lacustrine sediments in the McMurdo Dry Valleys, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology* 147:223–239.
48. Hendy C, Hall B (2006) The radiocarbon reservoir effect in proglacial lakes: examples from Antarctica. *Earth Planet Sc Lett* 241:413–421.
49. Denton G, Hendy C (1994) Younger Dryas age advance of Franz Josef Glacier in the Southern Alps of New Zealand. *Science* 264:1434–1437.
50. Schaefer J, et al. (2006) Near-synchronous interhemispheric termination of the last glacial maximum in mid-latitudes. *Science* 312:1510–1513.
51. Putnam A, et al. (2010) Glacier advance in the southern middle latitudes during the Antarctic Cold Reversal. *Nat Geosci* 3:700–704.
52. Kaplan M, et al. (2010) Glacier retreat in New Zealand during the Younger Dryas stadial. *Nature* 467:194–197.

GEOLOGY