Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand

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ABSTRACT

Advance and retreat of temperate glaciers is largely controlled by changes in temperature and precipitation, but the relative importance of these drivers is debated. Numerical modeling of a New Zealand glacier reveals that temperature is the dominant control on glacier length. We find that a glacial advance, dated to ca. 13,000 yr B.P., requires a cooling event of 3–4 °C. This mid-latitude Southern Hemisphere cooling is similar in magnitude to the Antarctic Cold Reversal in the Vostok ice core record and likely to be a response to the same climate signal.

Keywords: Younger Dryas, Little Ice Age, Southern Hemisphere, New Zealand, glaciers.

INTRODUCTION

Reconstructing climate from glaciers yields important insights into the magnitude and timing of recent climatic changes. The Franz Josef Glacier, New Zealand (NZ), is critical in this regard, as it has the longest observed record of glacier length in the Southern Hemisphere and a well-dated moraine record (Denton and Hendy, 1994; McKinzey et al., 2004). However, studies of the Waiho Loop moraine (Fig. 1), deposited by the Franz Josef Glacier ca. 13,000 yr B.P. (Denton and Hendy, 1994; 30 ^{14}C dates derived from wood fragments at Canavans Knob were calibrated with INTCAL04 [Reimer et al., 2004] resulting in a 1σ mean age range of 12,989 to 13,154 yr B.P.—here the age is quoted as ca. 13,000 yr B.P.), have given rise to competing hypotheses of how global climatic changes occur during abrupt events such as the Younger Dryas (Singer et al., 1998; Lowell et al., 1995). Furthermore, use of glaciers as climate proxies is dependent upon knowledge of the key drivers of glacier length, which in the case of the Franz Josef Glacier are controversial (Denton and Hendy, 1994; Singer et al., 1998; Lowell et al., 1995; Turney et al., 2003; Robinson et al., 2004; Rodbell, 2000).

BACKGROUND

Glaciers are influenced by local meteorological and topographic variables (Oerlemans and Fortuin, 1992) and one hypothesis is that length fluctuations of glaciers reflect mainly temperature changes, as indicated by modeling studies of 20th Century glacial retreat (Oerlemans, 1997). An alternative hypothesis is that precipitation variation is the dominant control on glacier length. This view is based on correlations between glacier length and synoptic climatology (Hooker and Fitzharris, 1999), and the interpretation of some pollen (Singer et al., 1998; McGlone, 1995) and speleothem (Robinson et al., 2004) records in NZ and South America (Rodbell, 2000). We use glacier modeling to assess whether temperature or precipitation changes have driven length fluctuations of the Franz Josef Glacier, New Zealand (Fig. 1), during key advances spanning the past 13,000 yr.

New Zealand straddles the latitudinally variable boundary between subtropical and subpolar air and water masses; hence its temperate alpine glaciers are sensitive to shifts of this climatic boundary. The Southern Alps form a 600-km-long and 2–3-km-high barrier to the prevailing westerly winds, and receive more than 10 m of precipitation per year on their windward flank (Henderson and Thompson, 1999). The combination of relief and high precipitation results in over 3000 glaciers occupying an area of 1159 km^2 and volume of 53 km^3 (Chinn, 1989). Temperate maritime glaciers, especially those that descend into low elevation coastal areas such as Franz Josef Glacier, are particularly sensitive to climatic perturbations due to their high accumulation and ablation rates (Oerlemans and Fortuin, 1992). Franz Josef Glacier covers 35 km^2, and descends 11 km from ~3000 m to its terminus at ~300 m above sea level, where the mean annual temperature is ~11 °C and the Tasman Sea is <20 km distant (Fig. 1). The lower glacier tongue experiences high rates of year-round ablation, measured at 20 m water equivalent per year, and ice velocities of up to 1 km per year (Anderson, 2004).

GLACIER RESPONSE TO TEMPERATURE AND PRECIPITATION

We used a new process-based numerical model of the Franz Josef Glacier, constrained by an extensive set of field measurements, to assess the climatic significance of four key glacial advances that have been dated in the Waiho Valley. Mass balance was calculated using a degree-day model (Braithwaite and Oleson, 1989) with parameters calculated from measurements of climate and mass balance (2000–2003). Model output has been verified by comparison with an independent set of measured mass balance measurements (2003–2005; Anderson, 2004). Glacier flow is simulated using a flow line model (Oerlemans, 1986). The accumulation area of the glacier is modeled using six flow lines (Fig. 1) and flow parameters have been tuned to present-day velocity measurements.

The model was forced using climate data from Hokitika, 100 km to the north of the glacier. We calculated monthly mean values of temperature and precipitation based on the present-day climatic period of 1970–1999. Temperature was reduced relative to these values by up to 6 °C in 0.25 °C increments, while precipitation was varied from −80% to +400% of its present-day value in 20% increments. The glacier flow model is run to equilibrium with each combination of temperature and precipitation (n = 625).

We simulated three Little Ice Age advances and an advance that went to either the Waiho Loop or Canavans Knob during the late-glacial, defined here as the period including the Antarctic Cold Reversal and the Younger Dryas. Modeling indicates that a cooling of ~1 °C for the Little Ice Age advances, and up to 4.7 °C for the late-glacial advances, is sufficient to drive the glacier without a change in precipitation (Table 1). If precipitation was solely responsible for the advances, increases of ~37% to more than 400% are required to simulate the same ice limits. The modeled glacier advances at ~3.3 km per 1 °C cooling until it reaches a length of 16 km, after which the length response to decreasing temperature change halves (Fig. 2A). A similar behavior is evident in the response to increasing precipitation (Fig. 2B), where the ice initially advances ~6 km for a 100% increase in precipitation, but after 16 km the length response to increasing precipitation reduces by a factor of 3. The reduced response of glacier length to climate forcing beyond 16 km reflects the changing valley width as the glacier spreads laterally onto a poorly confined outwash surface.

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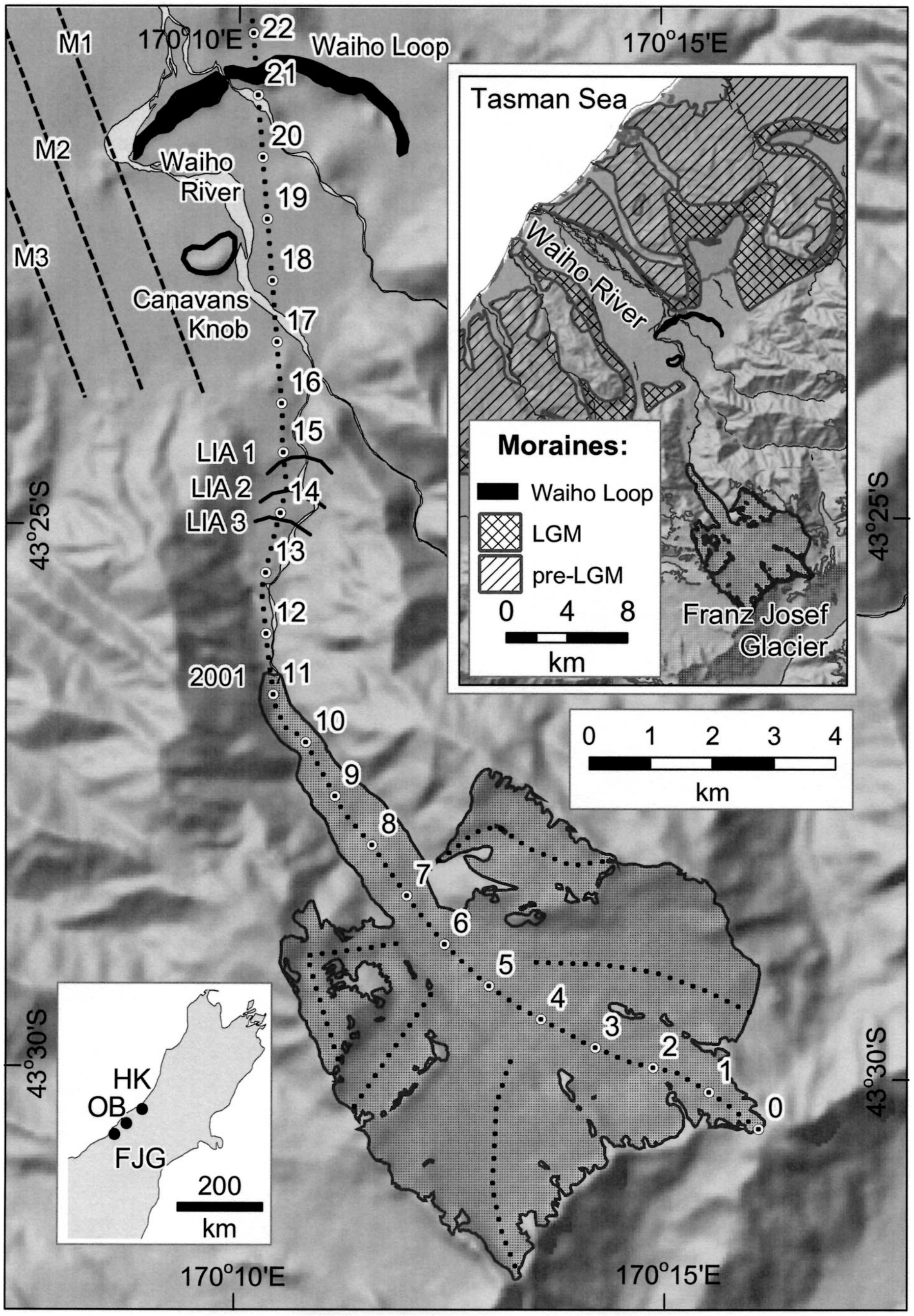

Figure 1. Franz Josef Glacier (FJG), South Island, New Zealand. Waiho Loop advance dated at 13,000 yr B.P. from wood collected at Canavans Knob (Denton and Hendy, 1994); Little ce Age (LIA) advances date from younger than A.D. 1600–1800 (McKinzey et al., 2004). Ice-thickness change calculated along the six flow lines (dotted lines) with kilometers marked on main flowline. Present-day climate data recorded in Hokitika (HK); LIA summer temperatures have been reconstructed from Oroko Bog (OB: Cook et al., 2002). Moraines from the Last Glacial Maximum (LGM) and earlier shown in top right inset. Western glacier margin position is uncertain beyond 15.4 km where the valley becomes unconfined. Sensitivity of the results to this uncertainty is investigated by running the model at each of the three margin definitions M1–M3.

CLIMATIC SIGNIFICANCE OF GLACIAL ADVANCES

The model calculates that either a cooling (0.8–1.2 °C), or an increase in precipitation (+37% to +57%) can account for the glacier advances to the three Little Ice Age positions (Fig. 3a). As the New Zealand instrumental climate record does not extend before the 1860s, the model results are compared to a summer temperature reconstruction from A.D. 900 using tree rings from nearby Oroko Bog (Cook et al., 2002). Three cool periods are identified in the reconstruction: before A.D. 1600, where 40 yr mean summer temperatures were 1.4 °C cooler than the present day; at ca. A.D. 1600 (1.1 °C cooler); and before A.D. 1800 (0.8 °C cooler). Assuming no change in seasonality, there is a close correspondence between the cooling required for the Little Ice Age advances and the Oroko Bog record (Table 1), indicating that precipitation cannot have increased significantly during this period.

The late-glacial advance to the well-known Waiho Loop moraine requires either a substantial cooling of 4.1–4.7 °C, a 330%–450% precipitation increase, or some combination thereof (Fig. 3B). For the glacier to advance to Canavans Knob, the dating site where late-glacial age wood was found (Denton and Hendy, 1994), either a cooling of 3.1 °C or an increase in precipitation of 210% (Fig. 3B) is required. The temperature and precipitation changes required to cause these late-glacial advances are larger than deduced from local pollen records. Pollen records from sensitive bog sites in New Zealand indicate a cooling either coincident with the Antarctic Cold Reversal or straddling the Antarctic Cold Reversal and Yonger Dryas (Turney et al., 2003; Newnham and Lowe, 2000; Vandergoes et al., 2005) (Fig. 4). The Kaipo Bog pollen record from northeastern New Zealand implies a maximum tree-line depression of ~100–200 m, suggesting that the late-glacial cooling was probably no more than 2 °C (Newnham and Lowe, 2003; Newnham personal commun.). This cooling is less severe than the estimated 4–5 °C cooling during the Last Glacial Maximum (LGM) (Newnham et al., 1989). Some speleothem records also point toward a large cooling that started 1000 yr later than the start of the Antarctic Cold Reversal but continued into the Younger Dryas (Williams et al., 2005), although the magnitude of the cooling has not been quantified. An alternative view, based mainly on low-elevation pollen records, is that little or no late-glacial cooling occurred and that glacier fluctuations in New Zealand were caused by precipitation increases (Singer et al., 1998; Turney et al., 2003; Robinson et al., 2004). We find that it is not possible to advance the model glacier to its late-glacial position in the absence of cooling without imposing unrealistic precipitation values.

SOUTHERN HEMISPHERE LATE-GLACIAL CLIMATE

The temperature-precipitation reconstruction for the late-glacial Waiho Loop advance of the Franz Josef Glacier developed here approaches the climatic conditions thought to occur during the LGM (Newnham et al., 1989), implying that either (1) the late-glacial climate of New Zealand was significantly colder than previously estimated or (2) that the Waiho Loop moraine is an LGM feature.

TABLE 1. CLIMATIC FORCING FOR GLACIAL ADVANCES

Advance	Glacier length (km)	Mean annual temperature forcing (°C)	Mean annual precipitation forcing (%)	Oroko Bog mean summer temperature change (°C)*
Waiho Loop (c. 13,000 yr B.P.)†	20–21.2	−4.10 to −4.70	+330 to +450	–
Canavans Knob (c. 13,000 yr B.P.)†	18.6	−3.10	+210	–
LIA 1 (<AD 1600)	14.8	−1.15	+57	−1.4
LIA 2 (c. AD 1600)	14.4	−1.00	+47	−1.1
LIA 3 (c. AD 1800)	13.8	−0.80	+37	−0.8

*The Oroko Bog summer temperature record (900 to 1957 AD) is based on tree ring analysis (Cook et al., 2002).

†The late-glacial advance was dated at Canavans Knob, but may have extended to the Waiho Loop.

The former is more likely, because the Waiho Loop records a smaller advance than other LGM moraines (Fig. 1), and the late-glacial age for the Waiho Loop is based on a robust ^{14}C chronology (Denton and Hendy, 1994). Although the wood fragments do not date the moraine directly, the dating site at Canavans Knob (Fig. 1) occurs on the lee side of a roche moutonnée indicating that thick ice advanced beyond this position during the late glacial (Denton and Hendy, 1994). Even in the event that the glacier did not extend far beyond Canavans Knob, significant late-glacial cooling of 3.1 °C is required to advance the glacier to the dating site. If cooling was coupled with a sustained precipitation increase of 39%, to the present-day interannual variability maximum, a 2.2 °C cooling is still necessary (Fig. 3).

We contend that cooling is the major driver of glacier advances, but we do not preclude a subsidiary role for precipitation changes in causing the fluctuations of the Franz Josef Glacier during the past 13,000 yr. The late-glacial cooling identified here was not confined to the Franz Josef Glacier; advances recorded more widely in the central Southern Alps (Basher and McSaveney, 1989; Ivy-Ochs et al., 1999; Denton, personal commun.) indicate that widespread cooling occurred. Temperature reductions in New Zealand may be explained by prolonged periods of southwesterly atmospheric circulation, as occurs today during El Niño events, when strong anticyclonic conditions persist to the south of Australia throughout the summer (Hooker and Fitzharris, 1999). Similarly, millennial-scale global cooling events may be characterized by enhanced El Niño conditions (Stott et al., 2002). The cooling coincides with the Antarctic Cold Reversal, when Antarctica cooled by 4 °C for ~1000 yr, but occurs slightly before the onset of the Younger Dryas in Greenland (Fig. 4) (Blunier et al., 1998). The Bi-Polar See Saw hypothesis suggests that Northern Hemisphere cooling occurs in response to changes in thermohaline circulation in the North Atlantic (Broecker et al., 1989; Stocker, 2002) while Antarctic ice-core records register warming, and vice versa. The hypothesis explains the phase difference between Antarctic–New Zealand and Greenland climate, and is supported by our finding of a late-glacial cooling in the Southern Alps.

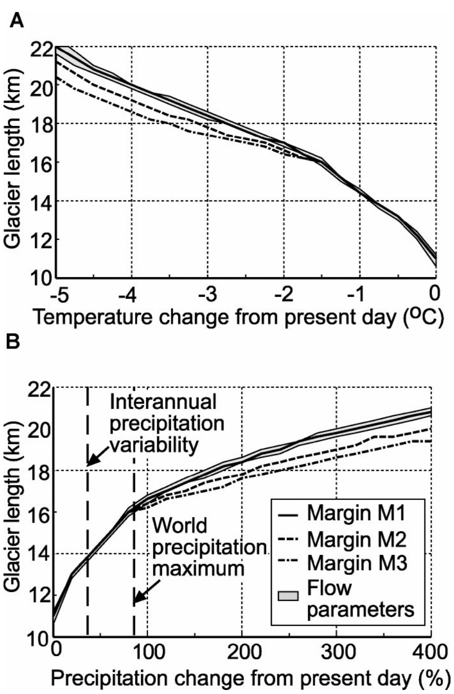

Figure 2. Sensitivity of glacier length to changes in: (A) temperature, and (B) precipitation. Maximum measured variability of Hokitika rainfall is +39%; annual world precipitation maximum is +85% (Henderson and Thompson, 1999). Definition of western margin (M1–M3, Fig. 1) influences the temperature and precipitation response. M1 represents the 13,000 yr B.P. advance; it forms a direct line between valley wall and Waiho Loop (Fig. 1). This choice could result in slight underestimation of temperature and precipitation changes. Deformation and sliding flow parameters, which control rate of ice flow, tuned to match measured ice velocity (Anderson, 2004). Glacier length variations due to a halving and doubling of these parameters range 200 m.

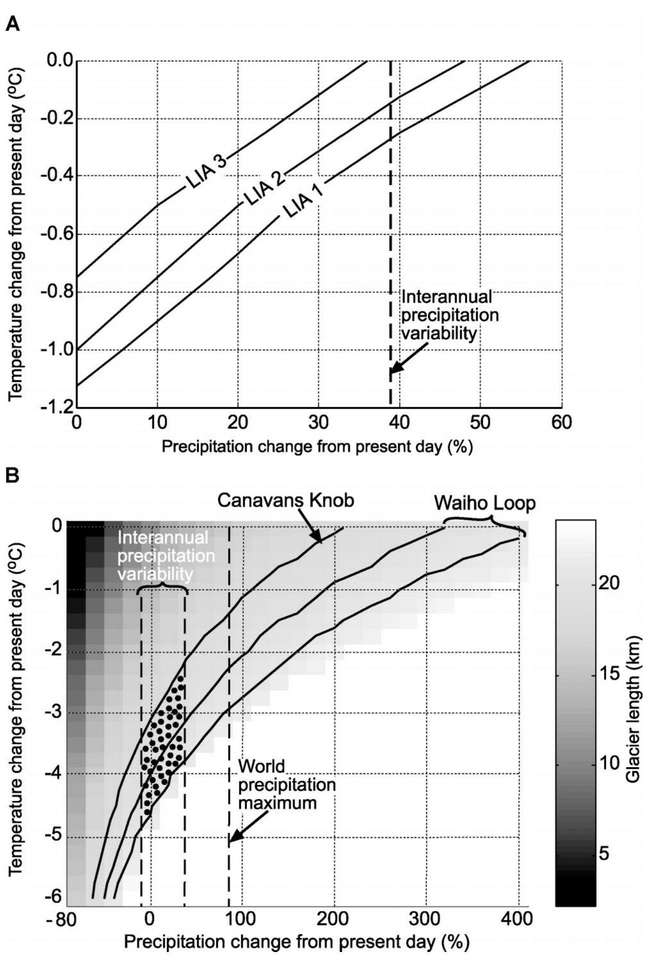

Figure 3. Sensitivity of glacier length to combined changes in precipitation and temperature for: (A) Little Ice Age (LIA) and (B) late-glacial advances. Waiho Loop extends from 20 km to 21.2 km along flow line (Fig. 1), represented by area between two lines. Shading corresponds to glacier length; scale bar on right. Dotted area: range of likely combinations of temperature and precipitation required for a late-glacial advance, within present-day range of interannual precipitation variability at Hokitika. Precipitation increase larger than present-day world maximum is considered unlikely.

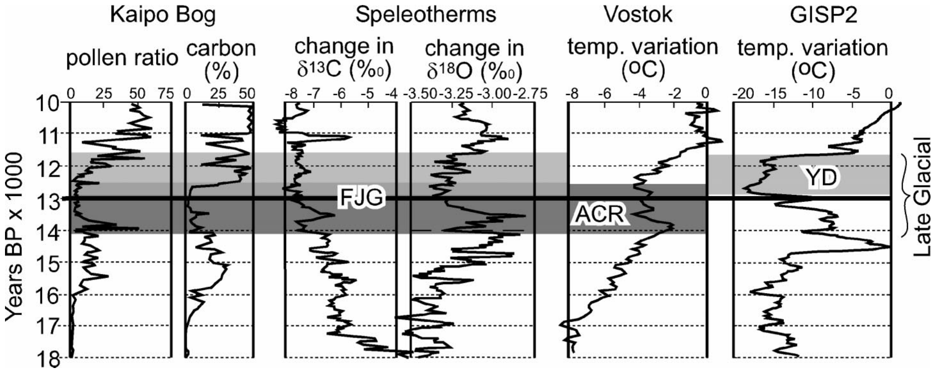

Figure 4. Franz Josef Glacier (FJG) model indicates a cooling of 3–4 °C ca. 13,000 yr B.P. (solid line) at boundary between Antarctic Cold Reversal (ACR, dark gray) and the Younger Dryas (YD, light gray), recorded in Vostok (Petit et al., 1999) and Greenland Ice Sheet Project 2 (GISP2; Alley, 2000) ice cores, Antarctica and Greenland, respectively. New Zealand speleothems (Williams et al., 2005) and Kaipo Bog pollen record (showing ratio of lowland podocarp to grass pollen; Newnham and Lowe, 2000) show cooling coincident with advance of Franz Josef Glacier, starting during Antarctic Cold Reversal and continuing into the Younger Dryas. Advance is dated ~1000 yr after start of Antarctic Cold Reversal, compatible with time required for construction of 100-m-high Waiho Loop moraine.

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REFERENCES CITED

Alley, R.B., 2000, The Younger Dryas cold interval as viewed from central Greenland: Quaternary Science Reviews, v. 19, p. 213–226.

Anderson, B.M., 2004, The response of *Ka Roimata O Hine Hukatere* Franz Josef Glacier to climate change [Ph.D. Thesis]: Christchurch, University of Canterbury, 106 p.

Basher, L.R., and McSaveney, M.J., 1989, An early Aranuian glacial advance at Cropp River, central Westland, New Zealand: Journal of the Royal Society of New Zealand, v. 19, no. 3, p. 263–268.

Blunier, T., Chappellaz, J., Schwander, J., Dällenbach, A., Stauffer, B., Stocker, T., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., and Johnsen, S.J., 1998, Asynchrony of Antarctica and Greenland climate during the last glacial: Nature, v. 394, p. 739–743.

Braithwaite, R.J., and Oleson, O.B., 1989, Calculation of glacier ablation from air temperature, West Greenland, *in* Oerlemans, J., ed., Glacier fluctuations and climate change: Amsterdam, Kluwer Academic Press, p. 219–233.

Broecker, W.S., Kennett, J.P., Flower, B.P., Teller, J.T., Trumbore, S., Bonani, G., and Wolfli, W., 1989, Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode: Nature, v. 341, p. 318–321.

Chinn, T.J.H., 1989, Glaciers of New Zealand: U.S. Geological Survey Professional Paper 1386-H2, 48 p.

Cook, E.R., Palmer, J.G., and D'Arrigo, R.D., 2002, Evidence for a 'Medieval Warm Period' in a 1,100 year tree-ring reconstruction of past austral summer temperatures in New Zealand: Geophysical Research Letters, v. 29, p. 1–4.

Denton, G.H., and Hendy, C.H., 1994, Younger Dryas Age advance of Franz Josef Glacier in the Southern Alps of New Zealand: Science, v. 264, p. 1434–1437.

Henderson, R.D., and Thompson, S.M., 1999, Extreme rainfalls in the Southern Alps of New Zealand: Journal of Hydrology, v. 38, no. 2, p. 309–330.

Hooker, B.L., and Fitzharris, B.B., 1999, The correlation between climatic parameters and the retreat and advance of Franz Josef Glacier, New Zealand: Global and Planetary Change, v. 22, p. 39–48.

Ivy-Ochs, S., Schlüchter, C., Kubik, P.W., and Denton, G.H., 1999, Moraine exposure dates imply synchronous Younger Dryas glacier advance in the European Alps and in the Southern Alps of New Zealand: Geografiska Annaler, v. 81A, p. 313–323.

Lowell, T.V., Heusser, C.J., Anderson, B.G., Moreno, P.I., Hauser, A., Huesser, L.E., Schluchter, C., Marchant, D.R., and Denton, G.H., 1995, Interhemisperic correlation of late Pleistocene glacial events: Science, v. 269, p. 1541–1549.

McGlone, M.S., 1995, Late glacial landscape and vegetation change and the Younger Dryas climatic oscillation in New Zealand: Quaternary Science Reviews, v. 14, no. 9, p. 867–881.

McKinzey, K.M., Lawson, W., Kelly, D., and Hubbard, A., 2004, A revised Little Ice Age chronology of the Franz Josef Glacier, Westland, New Zealand: Journal of the Royal Society of New Zealand, v. 34, p. 381–394.

Newnham, R.M., and Lowe, D.J., 2000, A fine-resolution pollen record of late-glacial climate reversal from New Zealand: Geology, v. 28, p. 759–762.

Newnham, R.M., and Lowe, D.J., 2003, Pattern and timing of lateglacial climate change in New Zealand: Geophysical Research Abstracts, v. 5, abs. 05337.

Newnham, R.M., Lowe, D.J., and Green, J.D., 1989, Palynology, vegetation and climate of the Waikato lowlands, North Island, New Zealand since c. 18,000 years ago: Journal of the Royal Society of New Zealand, v. 19, p. 127–150.

Oerlemans, J., 1986, An attempt to simulate historic front variations of Nigardsbreen, Norway: Theoretical and Applied Climatology, v. 37, p. 126–135.

Oerlemans, J., 1997, Climate sensitivity of Franz Josef Glacier, New Zealand, as revealed by numerical modelling: Arctic and Alpine Research, v. 29, p. 233–239.

Oerlemans, J., and Fortuin, J.P.F., 1992, Sensitivity of glaciers and small ice caps to greenhouse warming: Science, v. 258, p. 115–117.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I, Bender, M., Chappellaz, J., Davis, M., Delayque, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, v. 399, p. 429–436.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., and Weyhenmeyer, C.E., 2004, INTCAL04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP: Radiocarbon, v. 46, p. 1029–1058.

Robinson, L.F., Henderson, G.M., Hall, L., and Matthews, I., 2004, Climatic control of riverine and seawater uranium-isotope ratios: Science, v. 305, p. 851–854.

Rodbell, D.T., 2000, The Younger Dryas: Cold, cold everywhere?: Science, v. 290, p. 285–286.

Singer, C., Shulmeister, J., and McLea, B., 1998, Evidence against a significant Younger Dryas cooling event in New Zealand: Science, v. 281, p. 812–814.

Stocker, T.F., 2002, North-south connections: Science, v. 297, p. 1814–1815.

Stott, L., Poulsen, C., Lund, S., and Thunell, R., 2002, Super ENSO and global climate oscillations at millennial time scales: Science, v. 297, p. 222–226.

Turney, C.S.M., McGlone, M.S., and Wilmshurst, J.M., 2003, Asynchronous climate change between New Zealand and the North Atlantic during the last deglaciation: Geology, v. 31, no. 3, p. 223–226.

Vandergoes, M.J., Newnham, R.M., Preusser, F., Hendy, C.H., Lowell, T.V., Fitzsimons, S.J., Hogg, A.G., Kasper, H.U., Schluchter, C., 2005, Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere: Nature, v. 436, p. 242–245.

Williams, P.W., King, D.N.T., Zhao, J.-X., and Collerson, K.D., 2005, Late Pleistocene to Holocene speleothem ^{18}O and ^{13}C chronologies from South Island, New Zealand: Did a global Younger Dryas really exist?: Earth and Planetary Science Letters, v. 230, no. 3–4, p. 301–317.

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Notes