LETTERS

Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere

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In agreement with the Milankovitch orbital forcing hypothesis[1] it is often assumed that glacial–interglacial climate transitions occurred synchronously in the Northern and Southern hemispheres of the Earth. It is difficult to test this assumption, because of the paucity of long, continuous climate records from the Southern Hemisphere that have not been dated by tuning them to the presumed Northern Hemisphere signals[2]. Here we present an independently dated terrestrial pollen record from a peat bog on South Island, New Zealand, to investigate global and local factors in Southern Hemisphere climate changes during the last two glacial–interglacial cycles. Our record largely corroborates the Milankovitch model of orbital forcing but also exhibits some differences: in particular, an earlier onset and longer duration of the Last Glacial Maximum. Our results suggest that Southern Hemisphere insolation may have been responsible for these differences in timing. Our findings question the validity of applying orbital tuning to Southern Hemisphere records and suggest an alternative mechanism to the bipolar seesaw for generating interhemispheric asynchrony in climate change.

Local insolation variation in the mid-latitudes of the Southern Hemisphere is almost completely out of phase with insolation variation at the high northern latitudes, so it is plausible that global signals of climate change are modulated or even driven by local insolation effects in the south. For example, it has long been argued, but not established[3], that the Southern Hemisphere may have led the Northern Hemisphere into (and out of) glaciations[4]. This assertion implies a southern 'trigger', perhaps involving local insolation forcing, amplified in some way by the Antarctic ice sheet and its influence on global sea level, ocean circulation or atmospheric circulation in the form of the circum-Antarctic westerly winds[5].

Southern New Zealand is a prime location for examining interhemispheric linkages in climate change. It is located in the mid-latitudes of the Southern Ocean directly in the path of the southern westerly winds, and has high mountains (the Southern Alps) that support glaciers that are sensitive to short-term climate change. The deposits and landforms of these glaciers provide a complex record of late Quaternary ice advance[6], which has been linked to global climate events[7]. Associated sedimentary sequences provide opportunities for comparing terrestrial changes in southern New Zealand with marine and Antarctic records. Okarito Pakihi (43° 14′ 30″ S, 170° 13′ E, 70 metres above sea level, m.a.s.l.) is a moraine-impounded peat bog over 10 m deep (Supplementary Fig. 1) situated outside the limits of the Last Glacial Maximum (LGM) ice advance on the West Coast of South Island, New Zealand. Lowland podocarp/hardwood forest dominated by *Dacrydium cupressinum* surrounds the site, montane and subalpine low forest and shrubland occurs regionally between 400 and 1,200 m.a.s.l. and alpine grassland above 1,200 m.a.s.l. (ref. 8). The pollen record at Okarito Pakihi shows temporal shifts in these regional altitudinal vegetation zones, which today are mainly controlled by temperature[8].

Multiple cores, recovered using a 5-cm-diameter square-rod piston corer and Russian D-section corer, show consistent stratigraphy across the bog (Supplementary Fig. 1). This comprises two dark-brown organic units and two pale-blue-grey micaceous silty sand units, the lower of which is laminated (Fig. 1). Two cores (OKA1 and 913) that represent the entire sequence were sampled for pollen (Fig. 1). An age scale for the record has been established through radiometric dating and tephrochronology from the core OKA1 and replicate cores from the site (Supplementary Information). Radiocarbon (^{14}C) dating (reported here as calibrated kyr, 1 kyr = 1,000 yr) on bulk sediment, wood and pollen concentrates provide the chronology back to ~22 kyr ago (ref. 9) with the Kawakawa Tephra giving an age tie point at ~26.5 kyr ago (ref. 10). Luminescence dating of the upper micaceous silts provide ages from ~12.5 kyr (pooled average, $n = 4$) below the upper organic bed to 48–75 kyr for the lower part of the unit. A pooled weighted mean age of 127 ± 29 kyr was obtained for the basal laminated silts (Fig. 1, Supplementary Fig. 2, Supplementary Tables 2 and 3). The lower organic unit (Fig. 1) contains no detectable ^{14}C and is also less suitable for luminescence dating (Supplementary Information). These age constraints suggest that the lower organic unit is older than ~48 kyr (most of Marine Isotope Stage (MIS) 3), and was presumably deposited during the Last Interglacial (MIS 5, 125–80 kyr; ref. 11). The lowermost laminated silty sand unit is therefore likely to have been deposited during the latter stages of the penultimate glaciation (MIS 6). These assertions underpin the following correlation of the Okarito pollen record with the marine isotopic record.

The presence of aquatic taxa, in particular *Isoetes*, within silty sediments, indicates that the basin persisted as a lake from MIS 6 until the end of MIS 2. Pollen of alpine grassland and subalpine shrub communities in the lower laminated inorganic silts indicates cold moist conditions and substantial lowering of the treeline during MIS 6. The combination of inorganic laminated basal sediments in a moraine-bounded basin and cold-climate pollen assemblages indicates close proximity of a glacier at this time. Two prominent grass peaks reflect periods of pronounced cooling and suggest that at least two ice advances occurred during MIS 6. High levels of beech pollen could be due to long-distance transport across an open landscape but may also indicate that during MIS 6 beech forest extended beyond its contemporary geographic range in south Westland.

The dominance of pollen from podocarp/hardwood forest, small trees and shrubs in the overlying organic silt unit indicates major

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forest expansion during MIS 5. Peaks in the podocarp/hardwood taxa indicate three periods of forest expansion, separated by two intervals when montane–subalpine shrubland became more prominent (Fig. 1). Although there is no direct age control for this interval in the record, this pattern is consistent with the fivefold subdivision of MIS 5 with periods of podocarp/hardwood forest expansion, presumably corresponding to substages 5e, 5c and 5a.

Subalpine taxa dominate the upper silt unit, dated to MIS 4–2, with grassland taxa becoming more abundant upwards. We identify six events of expanded grassland communities during this interval, indicating substantial lowering of the treeline, which agrees well with the glacial geomorphic record of the Last (Otira) Glaciation from north Westland[12] and with interpretations of ice advance derived from independent loess and speleothem records from western New Zealand[6,13]. Luminescence dating (Fig. 1, and Supplementary Information) suggests that the lowermost major grass peak probably represents the MIS 4 (Loopline) ice advance[12]. The Kawakawa Tephra (~26.5 kyr) is straddled by the two most prominent grass-pollen peaks, which occur during late MIS 3 and MIS 2 and probably represent the Larrikins (a1 and a2) ice advances[12].

Expansion of montane–subalpine shrubland occurred at around 17.3 kyr ago—at the same time as Westland glaciers underwent massive retreat from their glacial maximum limits[14]. Similar marked climate amelioration is indicated in northern New Zealand at this time in a variety of climate proxies[15]. At Okarito, this amelioration eventually culminated in the development of lowland podocarp/hardwood forest at around 11 kyr ago. A possible minor reversal in this forest development phase between ~14.4 and 11 kyr ago, encompassing both the Antarctic Cold Reversal and Younger Dryas chron, does not appear to have been as significant in other West Coast sites[16] but is evident elsewhere in New Zealand[17,18].

The independently dated pollen record from Okarito Pakihi is very similar to oxygen-isotope, carbonate and pollen records from DSDP (Deep Sea Drilling Project) Site 594 (Fig. 2), showing that deposition of terrigenous silts off the east coast of the South Island coincided with glacial advance and treeline lowering to the west of the Southern Alps. This is unequivocal evidence for a closely coupled ocean–atmosphere–terrestrial system in the Southwest Pacific during the last two glacial–interglacial cycles, as has been demonstrated for the Southeast Pacific at similar latitudes for the past 50 kyr (ref. 19). Figure 2 also compares our record with an oxygen isotope record from the Indian Ocean, MD 90-0963, thought to be driven principally by orbital forcing at high Northern Hemisphere latitudes, and with the temperature record derived from the Vostok ice core. The climate trends at Okarito are broadly consistent with the northern driver model (Fig. 2).

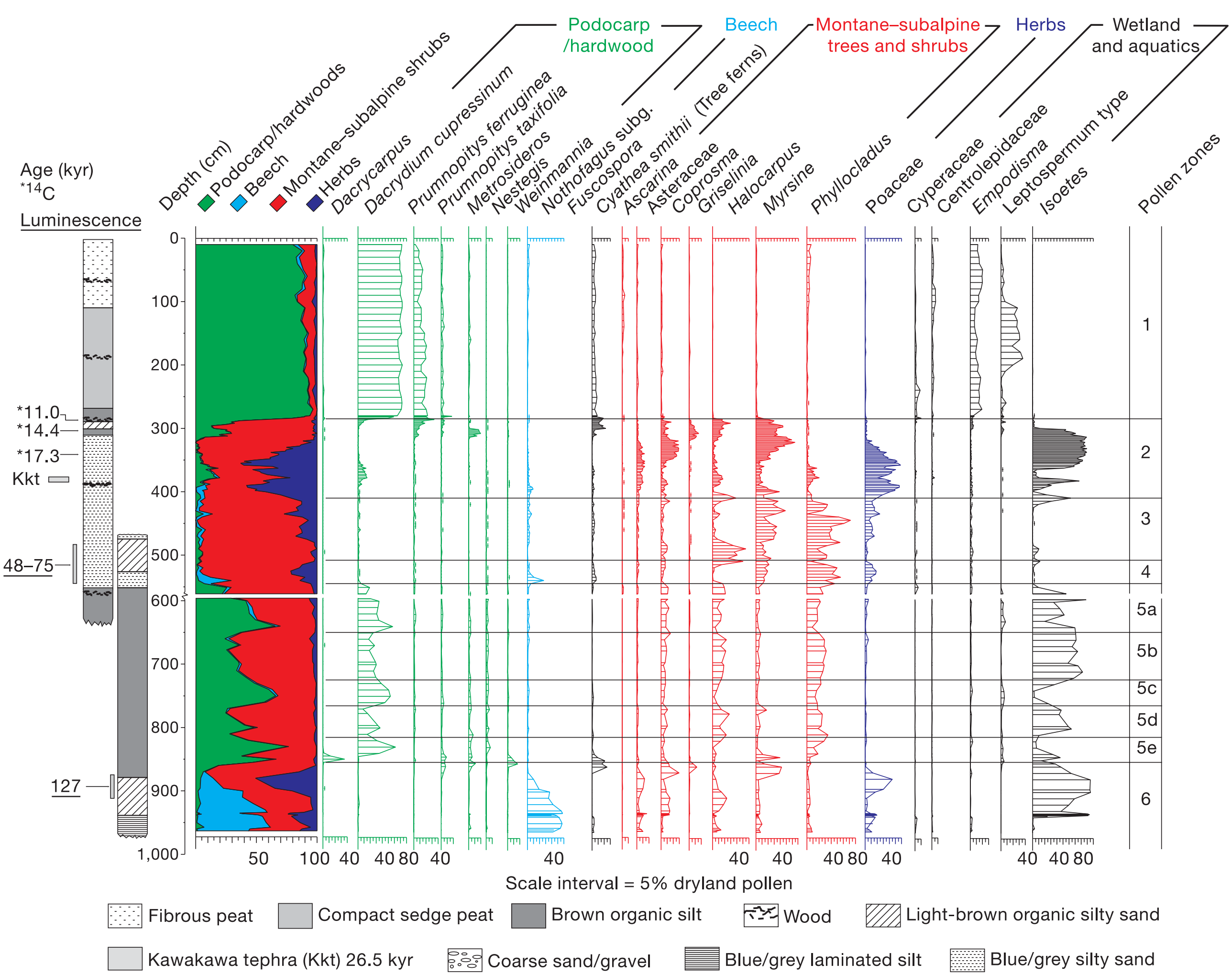

Figure 1 | Condensed pollen diagram from Okarito Pakihi. Luminescence ages (underlined) and radiocarbon ages (asterisked) represent the most reliable ages for the stratigraphy (Supplementary Information). Radiocarbon ages represent a pooled weighted mean of the age results indicated by Ψ in Supplementary Table 1 at 2σ level in calibrated kyr. Luminescence ages are correlated from replicate cores (see Supplementary Information). A pooled weighted mean age of 127 ± 29 kyr is derived from IRSL (infrared-stimulated luminescence) ages from core 0112b (Supplementary Table 2). Core sediment stratigraphy is explained by the key at base of figure.

There is however at least one significant difference. The onset of maximum cooling during the last glaciation (MIS 4–2) occurs well before the MIS 2 boundary (25–24 kyr ago) as defined in the marine isotopic record[11] and hence well before the summer insolation minimum in high northern latitudes. Although not precisely dated at Okarito, the first of the prominent MIS 3/2 grass-pollen peaks begins significantly below the 26.5-kyr ago Kawakawa Tephra, perhaps by as much as 2–4 kyr, at about 28.5–30.5 kyr ago (Fig. 1). An early LGM onset is also evident in speleothem, pollen and glacial geomorphic records from southern New Zealand and Chile[20,21,22], and in sea surface temperature reconstructions[19,23] and isotopic, pollen and carbonate records from offshore marine locations (Fig. 2). In particular, we note the strong correspondence between the grass-pollen curve at Okarito and Taiquemó in southern Chile. The Chilean record shows that an equivalent early LGM onset occurred at about 30 kyr ago (Fig. 2), and hence this pattern may be characteristic of the mid-southern latitudes. It is also notable that the Vostok temperature record begins a marked decline towards glacial maximum values before 30 kyr (Fig. 2). Although our chronology is at present too imprecise for robust comparison at the millennial scale, an apparent strong correspondence through the Okarito pollen record with the temperature record from Vostok points to consistent teleconnections between the southern mid-latitudes and Antarctica.

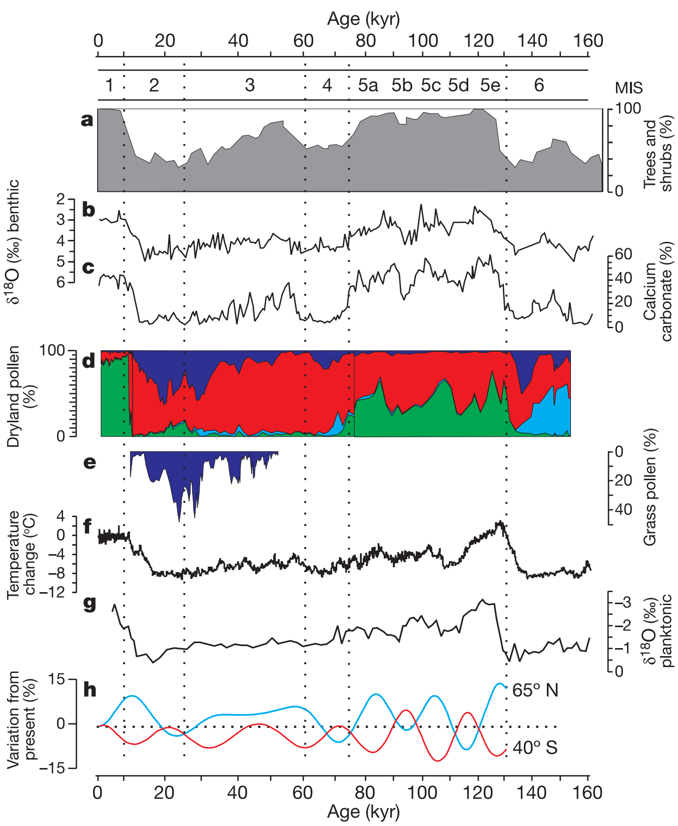

Figure 2 | Comparison of Okarito pollen and other records of climate change with summer insolation variation curves for the past 160,000 yr. a–c, DSDP 594 pollen, benthic $\delta^{18}O$ and calcium carbonate records[25,26]; **d**, Okarito Pakihi pollen stratigraphy (see Fig. 1 for shading key; **e**, Taiquemó (HE94-2B) grass pollen curve for the past 50 kyr (ref. 21); **f**, Vostok temperature reconstruction[27]; **g**, MD 90-0963 planktonic $\delta^{18}O$ record[28]; **h**, Plot of summer insolation for 40° S and 65° N (ref. 29; data is archived at the World Data Center for Paleoclimatology, Boulder, Colorado, USA. http://www.ncdc.noaa.gov/paleo/forcing.html). The climate trends at Okarito show broad similarities with records that invoke a northern driver including maximum glaciation before 130 kyr and from 25–10 kyr with less pronounced cooling from 60–75 kyr; a fivefold subdivision between 75 and 130 kyr; subdued warming from 26–60 kyr relative to the Holocene and much of the period between 75–130 kyr; and broadly synchronous warming at around 12–11 kyr. An early onset of LGM cooling at approximately 28.5–30.5 kyr, however, precedes the northern insolation minimum at about 24 kyr but occurs soon after the southern insolation minimum at 32 kyr.

The evidence for early onset of maximum glaciation provides renewed support for a Southern Hemisphere 'lead' into the LGM and some indication of its cause. Strong cooling in the south commences during, or soon after, the phase when perihelion occurs during the Austral winter (30–35 kyr ago), which means that the local insolation budget was at its lowest level for the entire precessional cycle (Fig. 2). At the same time, insolation in the Northern Hemisphere was still in a positive phase, giving a local radiation budget higher than that at present. The northern 'driver' is therefore an unlikely trigger for the onset of maximum glaciation in the south and cannot have been directly responsible for a Southern Hemisphere lead. We propose instead that the early onset of the LGM in the Southern Hemisphere was driven by the minimum in regional insolation reached at 35–30 kyr ago and propagated across the Southern Ocean by geophysical phenomena related to the Antarctic ice sheets, in particular, meridional displacement of sea ice, the circumpolar current system and related westerly winds. The subsequent progressive downturn in northern insolation, however, culminating in the Northern Hemisphere glacial maximum at about 25–24 kyr ago, appears to have superseded local insolation (now in a positive phase) as the driving factor in maintaining cold conditions and glaciation in both hemispheres for the remainder of the LGM. The subsequent maximum in southern insolation around 20 kyr ago may then have promoted the early deglacial warming long recognized in Southern Hemisphere records (for example, ref. 4).

If local insolation was responsible for a Southern Hemisphere lead into the LGM, then similar departures from the orbital forcing model may occur at other times of Southern Hemisphere insolation minima. Chronological control in older parts of the Okarito record does not currently permit a full examination of this postulated mechanism at earlier times. We nevertheless note that the Okarito pollen record and DSDP 594 do not show a strong thermal maximum for the Last Interglacial (MIS 5e) and speculate that this unexpected result may also be linked to strongly reduced local insolation at that time (Fig. 2). Other southern mid-latitude records, however, do not show a similar muted MIS 5e signal[23,24].

Recent efforts to explain interhemispheric patterns of Quaternary climate have concentrated on abrupt change at or below the millennial scale with particular attention given to comparison between Greenland and Antarctic ice core records. Much of this work suggests that changes in formation of North Atlantic Deep Water have triggered an asynchronous seesaw response in at least the high latitudes of the Southern Hemisphere. Testing this model against natural archives, however, is predicated on the assumption that millennial-scale patterns are superimposed on interhemispheric synchrony at the Milankovitch scale. Our record of mid-latitude climate in the Southern Hemisphere, while generally conforming to the Milankovitch model, suggests that regional insolation variation may play a greater role in climate change than has previously been attributed and additionally may provide a plausible alternative to the bipolar seesaw to explain differences in interhemispheric climate records.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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