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LETTERS

Glacier retreat in New Zealand during the Younger Dryas stadial

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Millennial-scale cold reversals in the high latitudes of both hemispheres interrupted the last transition from full glacial to interglacial climate conditions. The presence of the Younger Dryas stadial (~12.9 to ~11.7 kyr ago) is established throughout much of the Northern Hemisphere, but the global timing, nature and extent of the event are not well established. Evidence in mid to low latitudes of the Southern Hemisphere, in particular, has remained perplexing[1–6]. The debate has in part focused on the behaviour of mountain glaciers in New Zealand, where previous research has found equivocal evidence for the precise timing of increased or reduced ice extent[1–3]. The interhemispheric behaviour of the climate system during the Younger Dryas thus remains an open question, fundamentally limiting our ability to formulate realistic models of global climate dynamics for this time period. Here we show that New Zealand's glaciers retreated after ~13 kyr BP, at the onset of the Younger Dryas, and in general over the subsequent ~1.5-kyr period. Our evidence is based on detailed landform mapping, a high-precision ^{10}Be chronology[7] and reconstruction of former ice extents and snow lines from well-preserved cirque moraines. Our late-glacial glacier chronology matches climatic trends in Antarctica, Southern Ocean behaviour and variations in atmospheric CO_2. The evidence points to a distinct warming of the southern mid-latitude atmosphere during the Younger Dryas and a close coupling between New Zealand's cryosphere and southern high-latitude climate. These findings support the hypothesis that extensive winter sea ice and curtailed meridional ocean overturning in the North Atlantic led to a strong interhemispheric thermal gradient[8] during late-glacial times, in turn leading to increased upwelling and CO_2 release from the Southern Ocean[9], thereby triggering Southern Hemisphere warming during the northern Younger Dryas.

The transition of Earth's climate from the last ice age to the warm conditions of the Holocene epoch (the past ~11.5 kyr) is not yet fully explained. Polar ice-core records show that during this transition a period of general warming was interrupted in each hemisphere. The Antarctic cold reversal (ACR), as defined by a distinct levelling off or slight reversal of warming over Antarctica between ~14.5 and ~12.9 kyr ago, is mirrored by parallel deglacial changes in atmospheric CO_2 (ref. 10). Subsequently, Antarctic temperatures and atmospheric CO_2 concentrations increased and reached full interglacial values by ~11.5 kyr ago. In the North Atlantic region, the Younger Dryas stadial (YDS) period between ~12.9 and ~11.7 kyr ago[11,12] saw annual temperatures cool by ~15 °C in Greenland (and perhaps farther afield from there) despite steadily increasing global atmospheric CO_2 concentrations[13,14]. The YDS coincided with weakened intensity of the Asian monsoon[15], cooler sea surface temperatures in the tropical Atlantic[16] and increased precipitation in Brazil as far south as 28 °S[17].

Thus, the sea surface temperature signature of the YDS can be traced south to at least the northern tropics, and affected precipitation patterns even in the southernmost tropics[17]. Outstanding questions include determining the location of the southern boundary of the YDS climate imprint, the nature of the transition to the 'ACR-type' climate that is recorded in southern polar latitudes and the place where this transition occurred. We investigate past atmospheric conditions in the southern mid latitudes to find a missing piece of the jigsaw puzzle of late-glacial climate. New Zealand's oceanic island setting in the southwest Pacific Ocean is ideal for testing hypotheses concerning late-glacial climate change, far from the influence of Northern Hemisphere ice sheets and the North Atlantic deep-water convection. So far, studies in the New Zealand region have shown ambiguous signatures of late-glacial climate. Some records show a late-glacial reversal spanning both the ACR and the YDS time interval, and others display dominant imprints of the ACR (see, for example refs 1–4, 18–20).

We report here on a cirque basin, of about 7-km^2 extent, at the head of Irishman Stream in the Ben Ohau range on the eastern side of the Southern Alps of South Island, New Zealand (Fig. 1). This basin was purposely chosen for study because of its outstanding suitability for quantifying palaeoclimate (Supplementary Information). The moraines of the Irishman basin are exceptionally well preserved and the topographic setting allows the former glaciers to be reconstructed to a high degree of certainty. As a result, precise limits can be placed on the dimensions and snow lines associated with these glaciers. Furthermore, the basin floor gradients are such that the former glacier was particularly sensitive to small climate fluctuations. To track late-glacial glacier dynamics in detail, we produced a geomorphic map (~1:10,000 scale), which forms the foundation for a comprehensive, precise and accurate ^{10}Be chronology[7] based on a nearby production rate calibration of high precision[21]. To evaluate the amplitude of late-glacial climate changes, we reconstructed the former glacier extents and estimated their commensurate equilibrium line altitudes (ELAs).

South Island glaciers are very responsive to climate fluctuations, particularly variations in summer temperatures. Consequently, response times for glaciers of the sizes that existed in Irishman basin are on the order of years[22,23]. The glacier in the Irishman basin recorded atmospheric changes well above sea level, between ~1,700 and ~2,300 m. Our chronology of glacier and snow-line changes is thus interpreted to represent a centennial-scale proxy record of regional

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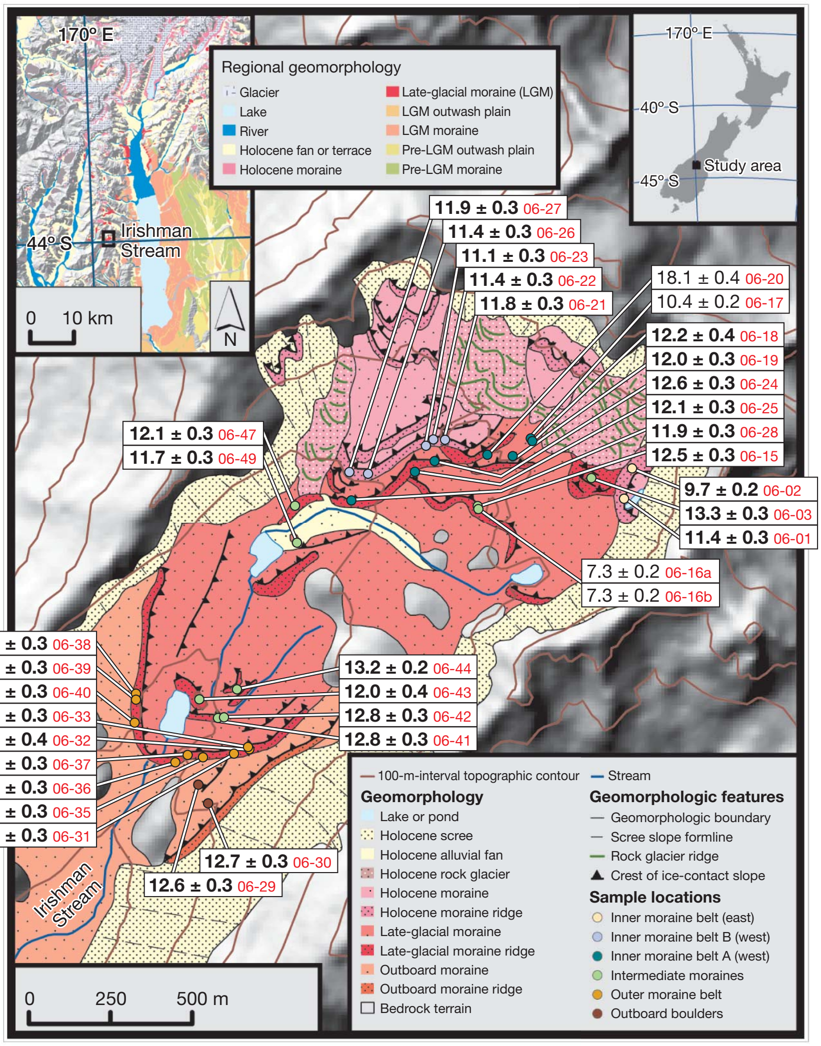

Figure 1 | Glacial geomorphology map of the moraines in the Irishman basin, showing locations of sample sites and measured ^{10}Be ages. The map (~1:10,000 scale) differentiates between discrete moraine ridges and areas of more diffuse moraine[28]. Individual ages are shown in kiloyears with their 1σ analytical errors. Outliers are in non-bold. Systematic uncertainties, such as that associated with the production rate, are minimal when comparing ages of adjacent moraines. Inset maps show location on South Island (top right) and in relation to adjacent major valley systems (top left).

atmospheric conditions, especially summer conditions, for South Island.

Well-defined moraine ridges are preserved in the outer and inner parts of the Irishman basin. Most striking is a prominent, very well-preserved, arcuate moraine that was a focus of our study (Fig. 1). We refer to this moraine as 'the outer moraine belt'. On its down-valley (outboard) side lies very subdued morainal and ice-smoothed bedrock topography, with few distinct moraine features (Supplementary Information). The inner parts of the basin, within ~0.75 km of the headwall, contain a set of two prominent ridges, referred to here as 'inner moraine belt A' and 'inner moraine belt B'. Between the outer moraine belt and inner moraine belts A and B, there are a few discontinuous 'intermediate' moraine ridges. Up-valley of inner moraine belt B, within 100 to 200 m of the headwall, are several small moraine ridges partly overlain by subsequent scree and rock-glacier (that is, mass-creep) deposits.

We sampled large boulders protruding from the moraine deposits in the Irishman basin. Analytical results and ages are presented in Fig. 1 and in Supplementary Tables 1 and 2. Individual ^{10}Be data are shown with 1σ analytical uncertainties, and the arithmetic mean ages of moraines are presented with an error that includes propagation of the analytical uncertainty and the uncertainty in the local production rate (Supplementary Fig. 4). The data set is of high internal consistency and only three out of 37 ages are considered outliers (IS-06-16, IS-06-17 and IS-06-20; Fig. 1). All nine ^{10}Be ages from the outer moraine belt are normally distributed and have a high internal consistency ($\chi^2 = 1.3$). They range from 13.7 ± 0.3 to 12.6 ± 0.3 kyr, with a mean of 13.0 ± 0.5 kyr. Four samples from the outermost of the intermediate ridges yielded a statistically indistinguishable mean age of 12.7 ± 0.6 kyr. Farther inboard, three ^{10}Be ages from inner intermediate ridges yield a mean age of 12.1 ± 0.5 kyr. On inner moraine belt A (Fig. 1), five boulders yield a mean age of 12.2 ± 0.4 kyr, which is statistically indistinguishable from that determined from the inner intermediate ridges. On inner moraine belt B, five boulders range in age from 11.9 ± 0.3 to 11.1 ± 0.3 kyr, with a mean age of 11.5 ± 0.4 kyr ($\chi^2 = 1.4$). Collectively, the moraine ages in the Irishman basin are sufficiently precise to bracket an overall period of reduction in glacier size over ~1.5 kyr, from ~13.0 to ~11.5 kyr ago.

The ^{10}Be chronology indicates that most of the moraine sequence in the Irishman basin was formed during late-glacial time. The prominent ~13-kyr moraine represents a distinct glacier terminal position, probably in equilibrium with the climate prevailing at the time. Between ∼13 and ∼12 kyr ago, the record attests to a large change in glacier dimensions and overall recession, with no prominent moraines deposited during this time. By ∼12 kyr ago, the glacier was much less than half of its 13-kyr ice extent (Figs 1 and 2). By ∼500 yr later, the glacier had built another moraine less than 100 m farther inboard (Fig. 1). This moraine indicates the glacier position at the Pleistocene/Holocene boundary, the end of the YDS. The ∼12- and ∼11.5-kyr inner moraine belts A and B represent the most important pauses in general retreat up the basin after ∼13 kyr ago, and were built by a glacier of much smaller dimensions. We cannot determine whether recession and re-advance preceded the formation of inner moraine belts A and B, or whether these moraines simply represent stillstands during recession.

We reconstructed the geometries of the former glacier when the margin was at the outer moraine belt and inner moraine belt A terminal positions. From these reconstructions, we estimated the formative ELAs and associated climate changes (Supplementary Information). Between ∼13 and ∼12 kyr ago, the ELA rose by 75 ± 40 m. Assuming an adiabatic lapse rate of 0.6–1° per 100 m, this ELA change translates into a warming of between ∼0.25 and ∼1 °C (neglecting precipitation change). The ELA at ∼11.5 kyr ago was slightly higher than at ∼12 kyr ago, but the difference was probably of the order of metres, judging by the <100-m separation between inner moraine belts A and B.

The Irishman basin results represent a sampling of late-glacial atmospheric conditions over New Zealand. This precisely dated record of late-glacial moraines, where former snow lines are also precisely quantified as proxies for atmospheric conditions, is unique. We look to other record types for comparison and confirmation of the regional significance of the findings. Vegetation and chironomid data from the intermontane valleys and basins of the Southern Alps show that climatic amelioration, with some variability, occurred between ∼13 and ∼11.5 kyr ago[1,18–20]. At Kaipo bog on northeastern North Island, very well-dated vegetation changes[1,19] (Fig. 2) indicate a return to cooler conditions shortly before, and warming near the onset of and generally throughout, the YDS interval. Offshore to the east of North Island, the MD97-2121 core is linked directly to the Kaipo bog record by rhyolitic tephras common to both sites. These allow direct alignment of these palaeoclimate records independently of individual dating uncertainties[1]. At MD97-2121, isotopic and chemical properties of both benthic and planktonic fossils are used to infer a major pause in deglacial warming, beginning well before 13 kyr ago[24]. During the YDS interval, the late-glacial reversal ended with marked changes in bottom-water properties and general surface warmth, with variability, through to the Holocene[24].

Thus, high-resolution records from the southwest Pacific region and elsewhere, including Antarctica[1,6,25], show a consistent Southern Hemisphere late-glacial climatic signature of overall decreased ice extent or progressive warming, with fluctuations, between ∼13 and ∼11.5 kyr ago. Atmospheric CO_2 change and Southern Ocean dynamics exhibit a similar pattern (Fig. 2). Specifically, atmospheric CO_2 concentrations increased markedly, with some minor fluctuations between ∼13 and ∼11.5 kyr ago, linked closely with Southern Ocean upwelling intensity, during the YDS[9].

This study highlights an emerging capability to use precise and accurate ^{10}Be dating of well-mapped moraines to distinguish, with submillennial-scale resolution, between northern and southern climatic signatures[7]. The ∼13-kyr outer moraine belt formed late in the ACR, as defined in Antarctica (Fig. 2). Throughout YDS time, the Irishman glacier became unequivocally smaller in comparison with its ∼13-kyr size, and by ∼12 kyr ago the ice had lost more than half its area and was almost at its 11.5-kyr limit. During this period of retreating glacier ice, rising snow lines and, thus, warmer temperatures, the

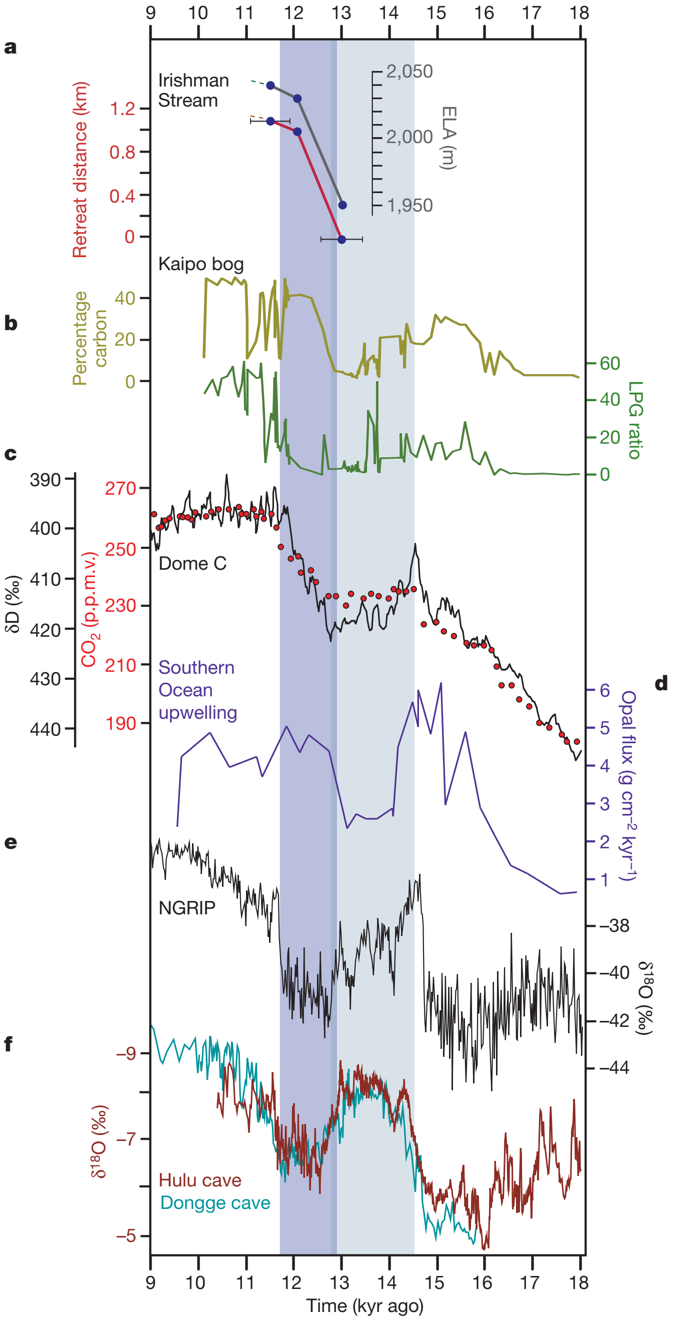

Figure 2 | Glacier changes in Irishman basin, New Zealand, in comparison with other climate proxy records. **a**, For the Irishman basin, glacier terminus retreat distance and ELA changes are shown for ∼13.0 kyr, ∼12 kyr and ∼11.5 kyr BP, calculated on the basis of ^{10}Be dating of the moraines (Supplementary Information). Retreat distance is used to show the response of the glacier. We emphasize the pattern of change during the ∼1.5-kyr interval for these two parameters. Age uncertainties for the ∼13- and ∼11.5-kyr moraines include the systematic uncertainties for production rate used, for comparison with other records. **b**, Carbon abundance (percentage carbon) and ratio of lowland podocarp to grass pollen (LPG) from Kaipo bog, North Island[19]. These proxies indicate the end of the late-glacial reversal and warming early on and through the YDS interval. The age model is based on midpoints of calibrated age ranges[19]. **c**, δD (deuterium) and CO_2 from European Project for Ice Coring in Antarctica (EPICA) Dome C[29,30]. The late-glacial ACR interrupted the prominent glacial-to-interglacial CO_2 increase. **d**, Opal flux from sediment core TN057-13PC[9]. Spanning the onset of the YDS, between ∼13 and ∼12 kyr ago, records **a**–**d** show warming in the Southern Hemisphere that matches closely the rise of CO_2 concentrations and variations in oceanic upwelling as recorded in the flux of opal. **e**, **f**, δ^{18}O $((^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} - 1 \times 1{,}000$, where the standard is standard mean ocean water) from the North Greenland Ice Core Project[11] (NGRIP; **e**) and from the Hulu and Dongge caves, China[15] (**f**). Dark- and light-blue shaded regions represent the YDS and ACR cold periods, respectively[10,11,30].

only well-defined moraines are well inboard of the ~13-kyr moraine. Inner moraine belts A and B may represent brief fluctuations of climate, conceivably manifestations of variations seen in other Southern Hemisphere records (Fig. 2b, c), during the late YDS time interval, as defined in the Greenland ice core[11].

The results presented here support the hypothesis of a steep interhemispheric thermal gradient during the YDS[8]. Whereas North Atlantic mean annual temperatures dropped drastically, by at least 15 °C (refs 13, 14), atmospheric temperatures in the southern mid latitudes increased during this period (Fig. 2). A classic explanation for these observations is the bipolar seesaw mechanism[26,27], which proposes curtailment of North Atlantic overturning, leading to heat being retained in the Southern Hemisphere, increased formation of southern deep water and a warming of the Southern Ocean and the southern atmosphere. A recently proposed, complementary mechanism involves North Atlantic cold conditions paired with southward movement of northern sea ice cover leading to more extreme seasonality[14]. This would shift the intertropical convergence zone and westerly wind patterns[8,27] southwards, which has been shown to increase Southern Ocean upwelling and outgassing of CO_2 abruptly[9]. In this picture, during late-glacial times southern mid latitudes warm owing to CO_2 forcing and New Zealand glaciers should have exhibited marked retreat between ~13 and ~11.5 kyr ago, with the possibility of pauses mirroring minor fluctuations in the CO_2 increase (Fig. 2). It remains an open question as to how much of the warming was due to rising CO_2 concentrations and how much was due to hemispheric heat redistribution by means of the bipolar seesaw mechanism. Nonetheless, the striking match between our late-glacial observations and the atmospheric CO_2 concentration indicates a link among the behaviours of the Southern Ocean, the southern atmosphere, atmospheric CO_2 and New Zealand's temperatures as indicated in the activity of its cryosphere. To conclude, CO_2 increase and atmospheric warming seem to have been key influences on glacier behaviour in the southern mid latitudes during the transition from the last ice age to the present interglacial.

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

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