High-Frequency Holocene Glacier Fluctuations in New Zealand Differ from the Northern Signature

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Understanding the timings of interhemispheric climate changes during the Holocene, along with their causes, remains a major problem of climate science. Here, we present a high-resolution ^{10}Be chronology of glacier fluctuations in New Zealand's Southern Alps over the past 7000 years, including at least five events during the last millennium. The extents of glacier advances decreased from the middle to the late Holocene, in contrast with the Northern Hemisphere pattern. Several glacier advances occurred in New Zealand during classic northern warm periods. These findings point to the importance of regional driving and/or amplifying mechanisms. We suggest that atmospheric circulation changes in the southwest Pacific were one important factor in forcing high-frequency Holocene glacier fluctuations in New Zealand.

Natural climate variability during the interglacial conditions of the Holocene (the past 11,500 years) is a fundamental baseline for evaluating the anthropogenic impact on global climate. Recent studies using marine and terrestrial samples from the North Atlantic region and the tropics (*1*, *2*) challenge the traditional view of a stable Holocene climate. Northern Hemisphere paleoclimate records suggest that temperatures cooled through the Holocene [e.g., (*3*)] and that this long-term trend was overprinted by millennial-scale variations (*4*), culminating in the Medieval Warm Period (MWP)/Little Ice Age (LIA) oscillation (*5*, *6*). Terrestrial paleoclimate data are sparse in the Southern Hemisphere, and it remains unclear whether the northern trend of progressive cooling was followed in the south [e.g., (*7*) versus (*6*)] and whether northern millennial-scale climate changes, including the MWP/LIA oscillation, were globally extensive. We explored this problem via the question: Were Holocene glacier advances in New Zealand generally coeval with those in the Northern Hemisphere? We present a high-resolution surface-exposure chronology of Holocene climate fluctuations derived from moraines deposited at the culmination of glacier advances in New Zealand's Southern Alps and evaluate the pattern of southern versus northern glacier behavior as a means of insight into Holocene climate forcing.

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Glaciers are highly sensitive to variations in temperature and precipitation (*8*) [supporting online material (SOM text)], but difficulties in obtaining reliable ages have been an impediment to placing glacier records in a global context. We focused on the large Mueller, Hooker, and Tasman valley glaciers (Fig. 1 and table S1) that drain east and south from the Main Divide of the Southern Alps. Their terminal zones are fringed by well-preserved Holocene moraine complexes (Figs. 1 and 2). Large greywacke boulders protruding from the moraines were the targets of our surface-exposure dating program (*9*).

Previous chronological studies of these moraines {including tree rings, radiocarbon bracketing ages [e.g., (*10*–*12*)], lichenometry [e.g., (*13*, *14*)], rock-weathering rinds (*15*, *16*), and Schmidt hammer investigations [e.g., (*6*, *17*)]} suggested that the most recent cool interval in New Zealand was equivalent to the termination of the northern LIA (mid-19th century). However, recent tree ring studies argued for a glacier maximum in the south that is somewhat older than the northern LIA termination (*18*, *19*).

Our geomorphologic maps (Fig. 1) document the detail and complexity of the preserved Holocene moraine sequences. We sampled a total of 74 boulders, with one duplicate (Figs. 1 and 2 and table S2), for ^{10}Be surface-exposure dating. We focused on the Mueller Glacier Holocene moraines comprising the most complete succession of preserved ridges, with complementary samples from the moraine sequences of Hooker and Tasman glaciers. We interpret the moraine exposure ages as dating the completion of moraine formation and thus the termination of a glacier event (SOM text). Individual boulder exposure ages within 2σ analytical uncertainties are plotted in fig. S1. Moraine ages are defined by arithmetic means of all boulder ages from the respective moraine within analytical standard deviation. The ages are calculated by using the recent production rates given in (*20*); given errors include a 5% production rate estimate. The variances between different published production rates do not affect any of the conclusions drawn below (table S3) (*9*).

The ^{10}Be chronology (Figs. 1 and 2, fig. S1, and table S3) includes some of the youngest exposure ages reported so far. The ^{10}Be measurements show low uncertainties, and the ^{10}Be boulder ages from individual moraines are remarkably consistent (*9*). All ages are compatible with position in the moraine sequence except for two boulders from the outermost margin of the right lateral Hooker moraines [–930 and –931 (Fig. 1)], which are incompatibly young. Lying at the downslope margin of an alluvial fan, it is plausible that they fell from the nearby mountainside onto the moraine subsequent to its formation. Ages of Kiwi-904 and -X60 plot outside the 95% confidence level (fig. S1). Otherwise, the data set is free of outliers. Hence, we include 70 out of 74 boulders (and 71 of the 75 ^{10}Be measurements) in the discussion (*9*).

The innermost moraine of the Mueller sequence (Figs. 1 and 2) represents a historically documented glacier position from the mid- to late 1800s (*9*, *12*). Three boulders from this ridge yielded ^{10}Be ages of 132 ± 17 years, 164 ± 22 years, and 185 ± 22 years (mean: 160 ± 30 years). The general correspondence between the ^{10}Be dating and the historic age of the moraine provides confidence in the ^{10}Be method and implies a maximum preexposure signal, the concentration of ^{10}Be atoms produced in the sampled boulder surface before boulder deposition on the moraine, of less than 100 years [difference between older bound of the oldest age, 210 years, and the historic age (SOM text)]. An outboard set of at least three moraines, the innermost of which is thought to be historic (*10*–*12*), yielded ages of 220 ± 10 years (n = 2), 270 ± 50 years (n = 10), and 400 ± 70 years (n = 9). A little outside lies a complex of ridges dominating the last-millennium moraine sequence of Mueller Glacier, 570 ± 70 years (n = 12) in age. The outermost left lateral Holocene ridge gave an age of 2000 ± 150 years (n = 2), consistent with the 2100 ± 100 year age of Kiwi-X66 from the right lateral sequence. Seven boulders from at least two distinct moraines slightly inboard yielded ages ranging from 1720 years to 1990 years, with a mean of 1840 ± 130 years. The outermost well-preserved right lateral moraine yielded a mean age of 3230 ± 220 years (n = 4), and, lastly, an isolated mound of moraine (Foliage Hill; Fig. 1) represents the outermost preserved remnant dated to 6370 ± 760 years (n = 1).

At Hooker Glacier (Fig. 1), two prominent left lateral ridges yielded ages of 1020 ± 70 years (n = 5) for the inner and 1370 ± 180 years (n = 6) for the outer ridge. One boulder from an isolated ridge inside gave an age of 810 ± 70 years (–927).

At Tasman Glacier, an inner moraine ridge yielded an age of 1040 ± 100 years (n = 1), coinciding with the 1020-year moraine of Hooker Glacier, whereas an outer ridge gave 1650 ± 110 years (n = 3). An isolated remnant of moraine projecting a few meters from the outwash plain (Little Hump) has an age of 6550 ± 370 years (n = 5). Its overlap with the oldest Mueller Glacier moraine (6370 years) suggests that both represent coeval glacier positions, distal to the late Holocene moraines.

This precise, high-frequency ^{10}Be chronology of Holocene fluctuations of the Mueller, Hooker, and Tasman glaciers compares well with a radiocarbon (^{14}C) chronology from wood within soils buried by tills in the lateral moraines (*11*). The ^{14}C ages date glacier expansion events after periods of reduced ice and distal soil formation (table S4). Together, the ^{10}Be and ^{14}C data define a minimum number of 15 pulses of glacier advance and retreat since the mid-Holocene, with the timing of the advance (^{14}C) and/or termination (^{10}Be) of events at about 6500 years ago (termination, ^{10}Be), 3650 to 3200 years [advance commencing 3650

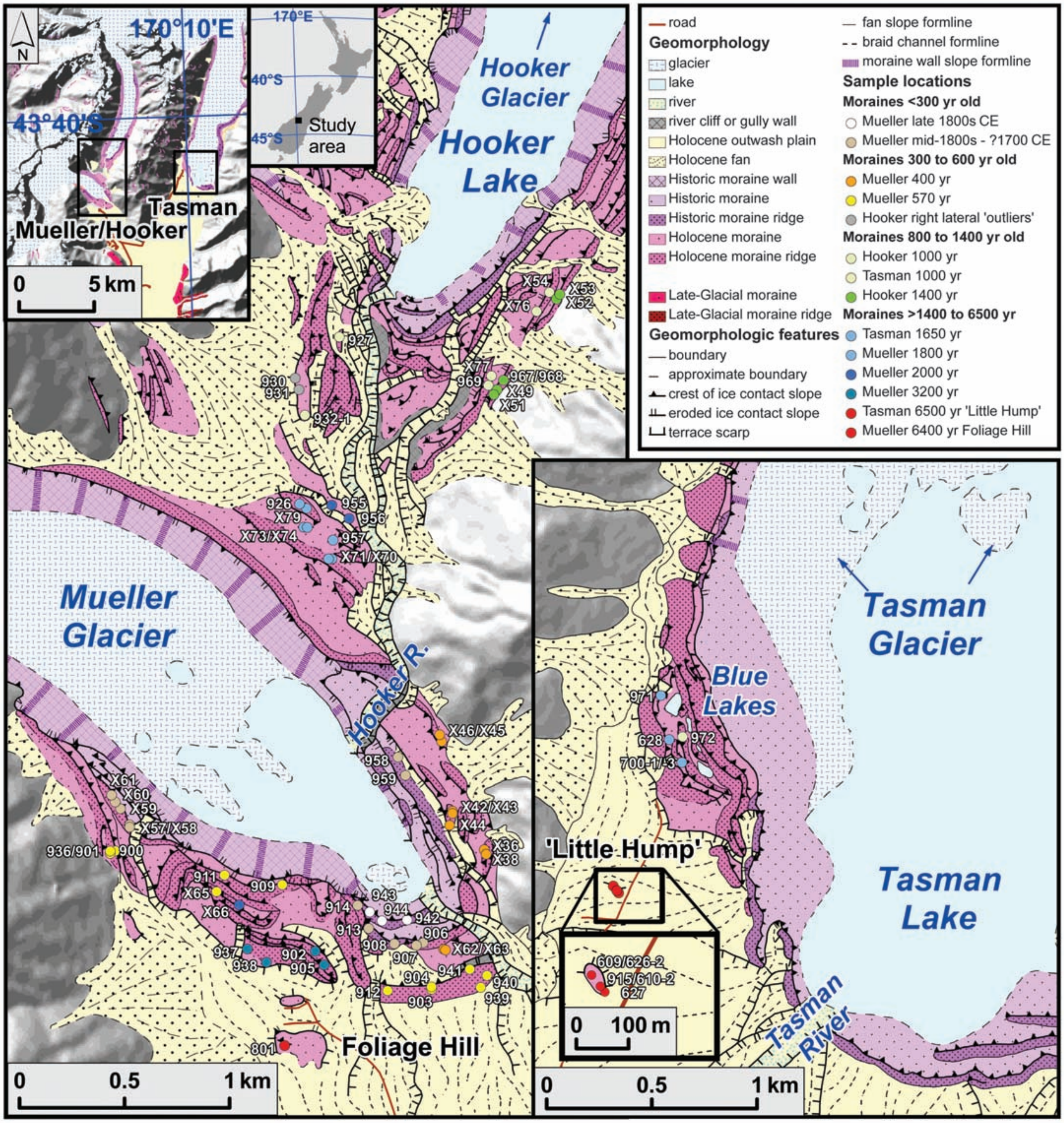

Fig. 1. Glacial geomorphology map, compiled at 1:5000 scale, of the Holocene moraine sequences of Mueller, Hooker, and Tasman glaciers, showing locations of sample sites. The map differentiates between discrete moraine ridges and areas of more diffuse moraine morphology.

years ago (^{14}C), progressive ice buildup for 400 years (^{14}C), terminating around 3200 years ago (^{10}Be)], 2300 years (^{14}C), 2000 to 1650 years (at least three events; ^{10}Be and ^{14}C), 1400 years (^{10}Be), 1000 years (^{10}Be and ^{14}C), 850 (^{14}C) to 800 years (^{10}Be, sample –927), 650 (^{14}C) to 570 years (^{10}Be), 400 years (at least two events; ^{10}Be and ^{14}C), and 270 years to ~110 years (historic and ^{10}Be).

Episodic fluctuations of the large valley glaciers at Mount Cook since mid-Holocene time have resulted in ice front advances to, and returning from, positions only short distances outside the mid- to late 19th century glacier termini, with a decrease in amplitude during the last millennium. The summer temperature time series based on tree-ring data from the nearby Oroko Swamp (*21*) (Fig. 3) shows similarly the coldest period during the past 1100 years around 1000 common era (C.E.), followed by abrupt climate fluctuations superimposed on a trend to slightly warmer temperatures. Collectively, these data point to a coherent record of summer temperature changes and concomitant glacier fluctuations in the Southern Alps during the late Holocene.

To evaluate the wider implications of our results, we compared the Holocene moraine record from Mount Cook over the past 4000 years with Northern Hemisphere records (Fig. 3). Three main conclusions can be drawn. First, there is a notable interhemispheric disparity in the timing of the maximum ice extent. The Mount Cook glaciers were further advanced about 6500 years ago than at any subsequent time. In contrast, most Northern Hemisphere glaciers reached their greatest Holocene extents during the LIA (1300 to 1860 C.E.).

Second, several glacier advances beyond the extent of the 19th century termini occurred in New Zealand during northern warm periods characterized by diminished or even smaller-than-today northern glaciers, such as between 7500 and 5500 years ago in the Swiss Alps (*22*) and Scandinavia (*23*), during the Bronze Age Optimum [about 1500 to 900 before the common era (B.C.E.)], during the Roman Age Optimum (200 B.C.E. to 300 C.E.), and during the MWP (800 C.E. to 1300 C.E.).

Third, the greatest coherency between the Mount Cook and Northern Hemisphere records was during the Dark Ages (300 C.E. to 700 C.E.), and broad similarities were apparent during the past 700 years (the northern LIA), with multiple glacier advances followed by a general termination commencing in the mid- to late 19th century. However, northern Holocene moraine sequences are dominated by the LIA-maximum terminal moraine less than 400 years old (typically mid-19th century in the Swiss Alps and mid-18th century in Scandinavia), whereas the most prominent moraine of the past millennium at Mueller Glacier is about 570 years old and is followed inboard by several smaller moraines. This pattern of broad consistency but differing detail of glacier behavior has continued over the past 150 years (SOM text).

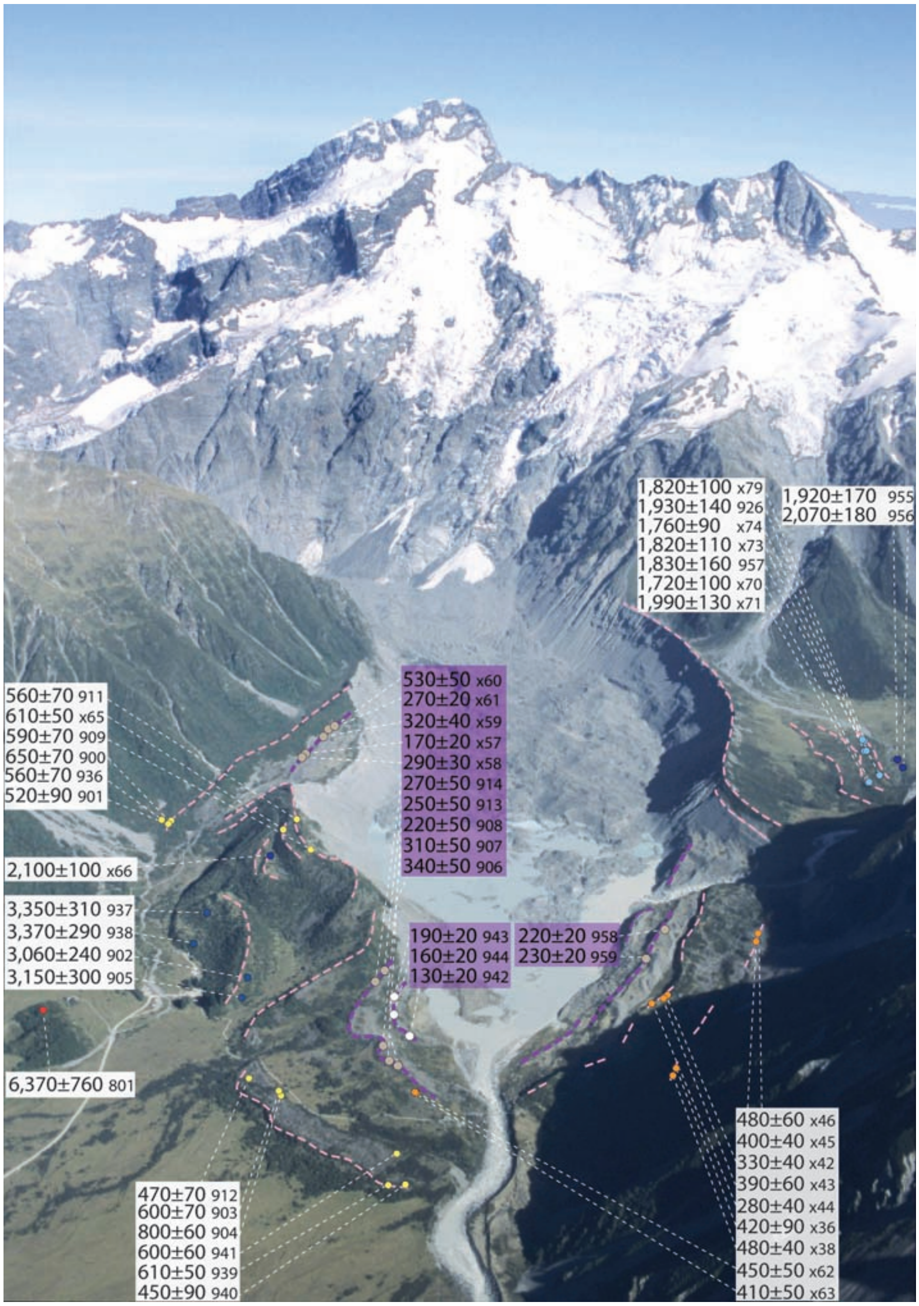

Fig. 2. Oblique view of the Holocene moraines of Mueller Glacier together with the ^{10}Be chronology. The ^{10}Be ages are given in years together with analytical uncertainties (2σ) and sample number (fig. S1 and tables S2 and S3). The innermost moraine ridge (dark purple) was deposited during the mid- to late 19th century (*12*).

Decreasing extent of New Zealand Holocene glaciers conflicts with nearby mean-annual sea surface temperature proxies [e.g., (*24*)] that show progressive cooling. However, melt-layer records in West Antarctic ice (*25*) that indicate increasing Holocene summer maximum temperatures are more commensurate with New Zealand glacier behavior.

Our results are in accord neither with the hypothesis of interhemispheric synchrony of mid- to late Holocene climate change nor with a rhythmic asynchrony, downplaying the importance of global driving mechanisms. This includes solar irradiation changes translating quasi-linearly into near-surface climate. However, recent studies show that climate models driven by solar changes can induce regionally distinct temperature changes (*26*), and indeed the Mount Cook moraine chronology shows some similarities to the solar record [e.g., (*26*)]. Alternatively, variations in the strength of deep-water production between the north and the south have been proposed (*27*) to explain interhemispheric incoherencies in Holocene climate. But this mechanism predicts strictly antiphased glacier behavior in north and south and it is not

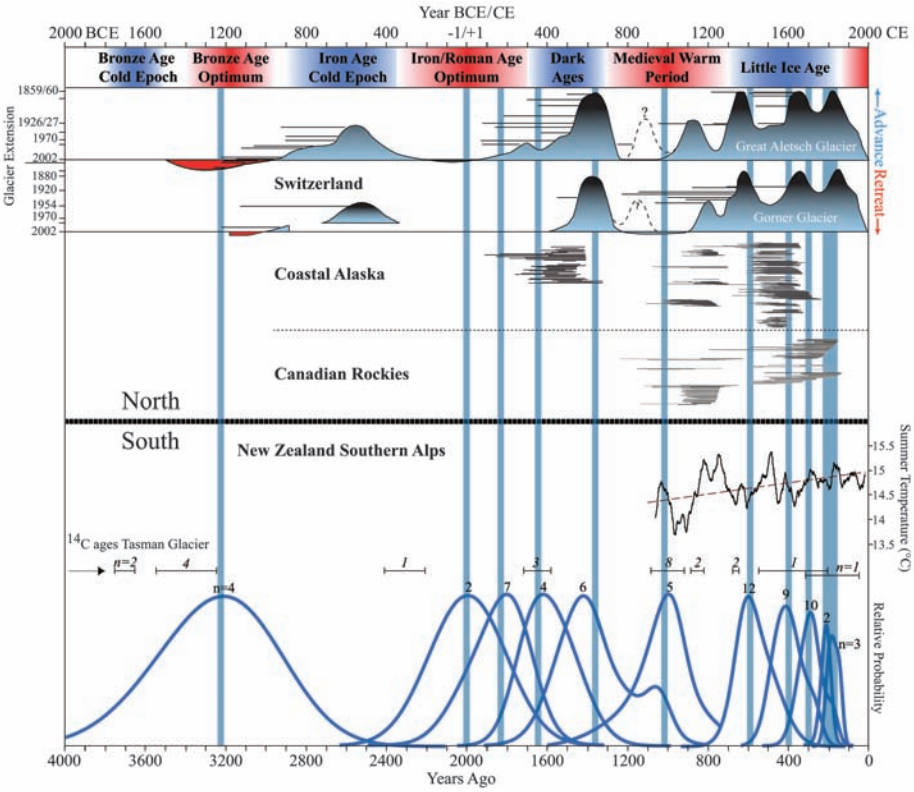

Fig. 3. The timing of Holocene glacier fluctuations near Mount Cook in New Zealand's Southern Alps (**bottom**), together with published ^{14}C ages on soils buried by Mount Cook glacier expansion events (*11*) over the past 4000 years, and a tree ring reconstruction of austral summer temperature in New Zealand over the past 1100 years (*21*), compared with glacier fluctuations in the Northern Hemisphere (**top**). The probability plots at the bottom are summary curves of all individual ^{10}Be boulder ages from each moraine dated in New Zealand. The blue bars show the arithmetic means of the moraine age (fig. S1 and table S3). The ^{10}Be ages are from Mueller Glacier moraines, except for the 1650-year moraine (Tasman Glacier) and 1370- and 1020-year moraines (Hooker Glacier). Note that we have identified a moraine corresponding to each ^{14}C soil age except for the 2300-year soil. The top graph shows fluctuations of two index glaciers in the Swiss Alps, the Great Aletsch Glacier and the Gorner Glacier, reconstructed from historical accounts and tree ring and radiocarbon data from fossil wood by (*30*). The middle graph shows the glacier advances in coastal Alaska (*31*) and the Canadian Rockies (*32*). These northern records feature high-precision glacier chronologies derived primarily from dendrochronology. Each bar shows the length of a tree ring record. The right end of each bar represents a glacier kill date.

obvious how such large-scale ocean variations may account for contemporary regional contrasts, as exhibited by the general advance of glaciers in New Zealand and southernmost South America in unison with the retreat of glaciers on the Antarctic Peninsula and northern Patagonia (*28*). Alternatively, we suggest that regional ocean-atmosphere oscillations may account for the observed glacier fluctuation pattern. Analogous to the correlation between the Atlantic Multidecadal Oscillation and glaciers in the Swiss Alps (*27*), the Interdecadal Pacific Oscillation (IPO) (SOM text) has been an important influence on glacier behavior in New Zealand over the past few decades (*29*): The IPO switched to a negative mode about 1940 C.E., bringing warmer and drier conditions to New Zealand's Southern Alps before reverting to a positive, colder, and wetter mode in 1978 C.E. These changes are well reflected in New Zealand's glacier length fluctuations. Whether or not this mechanism is generally applicable to the Holocene period, our study shows that mid- to late Holocene glacier fluctuations were neither in phase nor strictly antiphased between the hemispheres, and therefore it is likely that regional driving or amplifying mechanisms have been an important influence on climate. The ability to obtain high-precision ages for Holocene moraines, including historic times, opens the way for defining much-improved chronologies of glacier fluctuations at key sites in north and south and may help finally to solve the puzzle of what drove Holocene climate variations.

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Supporting Online Material

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Materials and Methods
SOM Text
Figs. S1 to S4
Tables S1 to S4
References

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