Holocene Glacier Fluctuations in the Peruvian Andes Indicate Northern Climate Linkages

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The role of the tropics in triggering, transmitting, and amplifying interhemispheric climate signals remains a key debate in paleoclimatology. Tropical glacier fluctuations provide important insight on regional paleoclimatic trends and forcings, but robust chronologies are scarce. Here, we report precise moraine ages from the Cordillera Vilcabamba (13°20′S) of southern Peru that indicate prominent glacial events and associated climatic shifts in the outer tropics during the early Holocene and late in the "Little Ice Age" period. Our glacier chronologies differ from the New Zealand record but are broadly correlative with well-dated glacial records in Europe, suggesting climate linkages between the tropics and the North Atlantic region.

Peru harbors the world's greatest concentration (71%) of present-day tropical glaciers (*1*) and contains extensive geomorphic features that demarcate former glacier expansion (*2*). Accurate chronologies of Peru's recent glacial history are key indicators of tropical paleoclimates and are thus critical for evaluating mechanisms of global climate variability and interhemispheric linkages (*3*). The high sensitivity of tropical mountain glaciers to relatively small-amplitude climate changes makes them particularly useful as indicators of past climatic fluctuations. In addition, understanding past Andean glacier events is imperative for predicting responses to future climate change and consequences for local water resources (*4*) and vital for identifying environmental impacts on the succession of ancient civilizations in the region (*5*).

Published chronologies of late Quaternary glacier fluctuations in the central Andes are based on a combination of radiocarbon, lichenometric, and terrestrial cosmogenic nuclide dating methods (*6*, *7*). However, robust age control of Holocene glacial deposits remains notably sparse. Here, we report high-precision cosmogenic ^{10}Be surface exposure ages of the two most prominent Holocene glacial episodes in the Cordillera Vilcabamba of southern Peru. This new glacial chronology augments nearby ice core (*8*), lacustrine (*9*, *10*), and marine (*11*) paleoclimate records.

The field site is located in the vicinity of Nevado Salcantay (6271 m above sea level; 13°20′S, 72°33′W), the highest peak in the Cordillera Vilcabamba (Fig. 1). Glacial troughs emanating from Salcantay and nearby peaks contain exceptionally well-preserved moraines with large granitic surface boulders. Geomorphic mapping was conducted in the upper Rio Blanco valley south of Salcantay, the Sisaypampa valley east of Salcantay, and the Tucarhuay valley south of adjacent Nevado Tucarhuay (5910 m above sea level). The most prominent moraine sequences in these three drainages are grouped into sharp-crested and largely unweathered "inner" moraines with subangular boulders that commonly preserve glacial polish and "outer" moraines that are more subdued and surfaced with subrounded boulders. Some geomorphic evidence exists for more extensive earlier glacial episodes, perhaps corresponding to the considerably larger late glacial positions described elsewhere in the tropical Andes (*6*), but the focus of this study is on the Holocene advances (*12*).

Samples were collected from 25 boulders atop the outer (n = 13) and inner (n = 12) moraine crests for ^{10}Be surface exposure dating (*12*); data are given in table S1 and age results are plotted in fig. S4. We interpret the arithmetic means of boulder exposure ages from each moraine to reflect the end of moraine construction and, thus, constrain the timing of glacial culminations. The identified patterns of Holocene glaciation and the major conclusions drawn from them are not affected by current uncertainties in ^{10}Be production rates scaled to our field site (*12*).

Five of six boulder exposure ages on the Rio Blanco outer moraine show high internal consistency and yield a mean of 8.6 ± 0.3 thousand years ago (ka) (n = 5), corresponding to a glacial culmination during the early Holocene (tables S1 and S2). One boulder here (PE06-1; 7.0 ± 0.2 ka) yielded a young outlying age interpreted to indicate a postglacial rockfall. Mean ages on the most distal (9.9 ± 0.7 ka; n = 4) and most proximal (8.0 ± 0.5 ka; n = 2) ridges of the Sisaypampa outer moraine succession (figs. S2 and S4) flank the age of the Rio Blanco outer moraine and bracket oscillations of a prolonged early Holocene glacial episode. The sole age (4.4 ± 0.1 ka) on the Tucarhuay outer moraine is discordant with ages in the Rio Blanco and Sisaypampa valleys and suspected to reflect postdepositional boulder rotation.

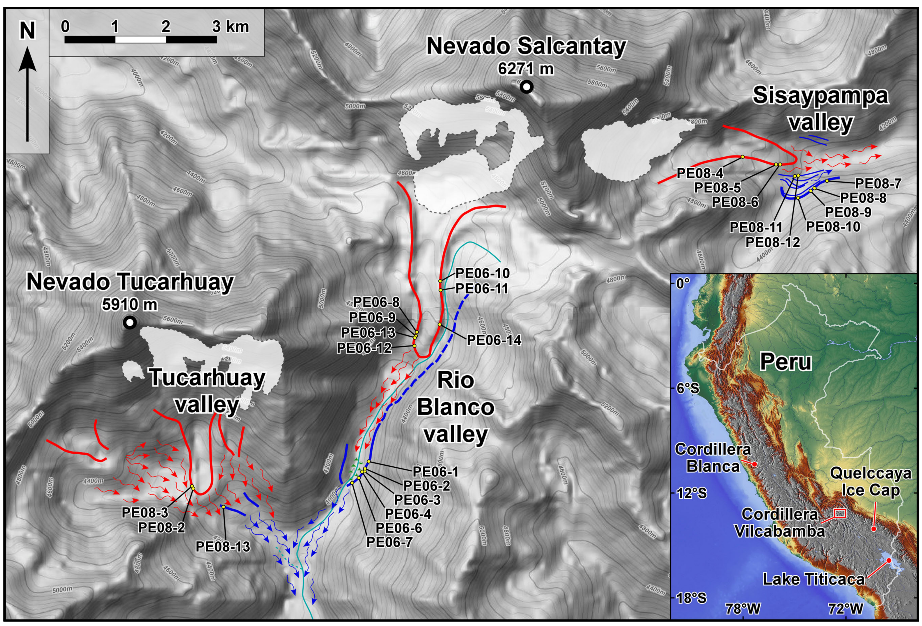

Fig. 1. Geomorphic map of field site. Solid lines show inner (red) and outer (blue) moraines, and arrows show associated outwash; dashed lines indicate inferred locations. White areas represent approximate locations of present-day glaciers in mapped drainages. Base maps from Google Maps.

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Five of seven boulder exposure ages on the Rio Blanco inner moraine yield a tightly clustered mean of 200 ± 20 years [Common Era (CE) 1810 ± 20; $n = 5$]. These results are among the youngest ^{10}Be ages reported so far and show that cosmogenic chronologies can be established to overlap historical records and, in turn, modern observations. The high internal consistency of these five ages suggests that isotope inheritance in these very young samples is negligible. However, two ages (PE06-8, 12) from this moraine are old outliers, most likely due to isotope inheritance from previous exposure. Three boulders from the Sisaypampa inner moraine yield a mean age of 240 ± 80 years (C.E. 1770 ± 80; $n = 3$). Two boulders atop the largest Tucarhuay inner moraine (fig. S3) yield a mean age of 270 ± 30 years (C.E. 1740 ± 30; $n = 2$). Mean ages of inner moraines in all three valleys overlap within 2σ uncertainties and correlate with the late Little Ice Age (LIA), as defined in the Northern Hemisphere and generally considered to extend from ~C.E. 1300 to 1860 (*13*).

Due to selective preservation of moraine ridges, our records do not exclude the possibility of multiple Holocene glacier expansions. However, the combined geomorphic and geochronologic evidence clearly indicates the dominance of two major episodes in the Cordillera Vilcabamba, including an early Holocene glacial interval and a somewhat less extensive glaciation during the LIA. The early Holocene deposits correlate with moraines ^{10}Be-dated to 8.5 ± 0.7 ka ($n = 7$) in the southern Andes (*14*), hinting at inter-regional coherency, but documentation for other contemporaneous glacial events in the Andes is sparse (*15*). Worldwide, well-dated records of early Holocene glacial advances have been developed in only a few locations. End moraines marking the Erdalen Event, an expansion of Jostedalsbreen outlet glaciers in southern Norway, are dated with radiocarbon (*16*) and ^{10}Be ($n = 3$) (*17*) to ~10.2 to 9.7 ka. The nearby Flatebreen glacier experienced a termination at ~10.2 ka and a subsequent expansion from ~8.4 to 8.1 ka (*18*). Moraines in the Austrian Alps were recently dated with ^{10}Be to 10.8 ± 1.0 ka ($n = 3$) and 8.4 ± 0.7 ka ($n = 5$) (*19*). The ~9.9 to ~8.0 ka glacial culminations in the Cordillera Vilcabamba are broadly consistent with these European glacier chronologies and similarly correspond to the greatest Holocene extents only ~1 to 2 km downvalley from those reached during the LIA.

Moraines related to the LIA in Peru were first radiocarbon-dated more than three decades ago (*20*), but the limiting ^{14}C age control on recent glacial histories remains of low temporal resolution (*6*). Lichenometric dating [e.g., (*21*)] shows the maximum LIA glacier extent around C.E. 1630 ± 30 in the Cordillera Blanca of Peru (*7*) and from C.E. 1660 ± 20 to C.E. 1690 ± 30 in the eastern Cordilleras of Bolivia (*22*). These lichen studies also identified successions of moraines ranging from C.E. 1330 ± 30 in the Cordillera Blanca to C.E. 1910 in Bolivia. Notably, the most recent glacier expansions in the Cordillera Vilcabamba are marked by a single massive moraine ridge, unlike the multiple widely spaced crests in the Cordillera Blanca and in Bolivia. This difference implies contrasting dynamic responses of latest Holocene glaciers in various tropical Andean ranges, perhaps related to differences in glacier size, geometry, and aspect. Moreover, the most precisely dated LIA maximum in the Vilcabamba (C.E. 1810 ± 20) postdates LIA maxima in the Cordillera Blanca and in Bolivia by ~180 years and ~120 years, respectively, which may be explained in part by uncertainties in lichenometric and ^{10}Be exposure dating methods, but probably indicates real differences in the timing of glacial culminations.

Despite geologic evidence suggesting that the LIA was a global phenomenon (*13*), exact temporal relationships between worldwide glacier chronologies from this interval are poorly defined due to difficulties in establishing precise moraine ages. Glacial and climatic conditions of the LIA are most thoroughly documented in northern and western Europe by extensive historical accounts,

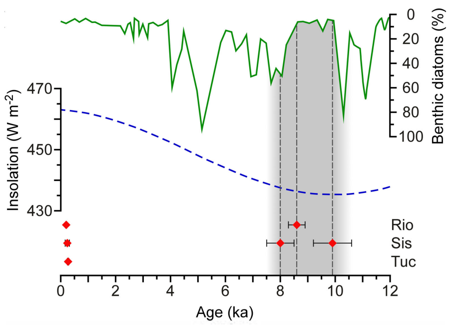

Fig. 2. Timing of Holocene events in southern Peru. Green line shows percentage of benthic diatoms in Lake Titicaca core 1PC (*9*), with lower percentage of diatoms corresponding to higher lake levels. Dashed blue line shows precessional wet-season (September to March) insolation at 13°S (*30*). Red diamonds and error bars are means and uncertainties of moraine ages in Rio Blanco (Rio), Sisaypampa (Sis), and Tucarhuay (Tuc) valleys.

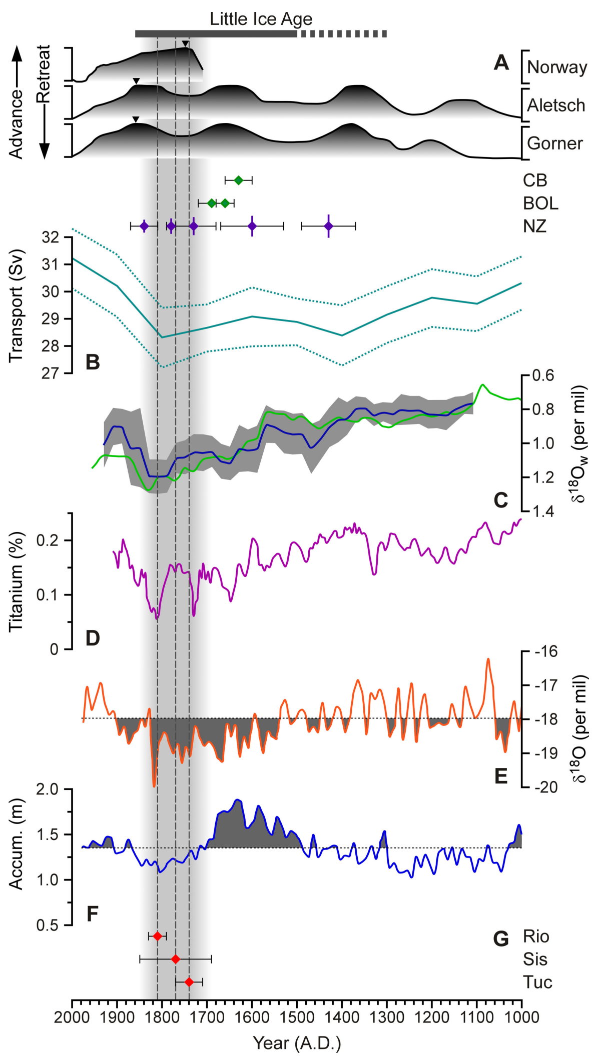

Fig. 3. Comparison of climate and proxy records spanning the last millennium. (**A**) Fluctuations of Nigardsbreen, Norway (*23*), and Great Aletsch and Gorner glaciers, Swiss Alps (*24*), with black triangles indicating maximum extension; lichenometrically dated glacial maxima in the Cordillera Blanca, Peru (CB) (*7*), and eastern Cordilleras, Bolivia (BOL) (*22*); ^{10}Be-dated glacial maxima in New Zealand (*25*), with vertical bars schematically showing decreasing amplitudes of events. (**B**) Volume transport of the Florida Current (*27*). (**C**) Surface water $\delta^{18}O_w$ in two Dry Tortugas cores, with higher values reflecting higher Florida Current surface salinity (*26*). (**D**) Titanium percentages in Cariaco Basin sediments, with lower values implying greater aridity in northern Venezuela and a more southerly mean latitude of the ITCZ (*29*). (**E** and **F**) Quelccaya Ice Cap $\delta^{18}O$ and accumulation data, with inferred colder and wetter intervals shaded in gray (*8*). (**G**) Glacial maxima from this study.

instrumental data, and proxy climate indicators. The LIA maximum occurred across Europe within the past 500 years, but records show asynchronous maxima in Scandinavia (~C.E. 1750) (*23*) and the Swiss Alps (~C.E. 1860) (*24*). The ^{10}Be-dated culminations in the Cordillera Vilcabamba show similar timing and temporal variability and support broad coherency between glacier maxima in the tropical Andes and in Europe during the late LIA. In contrast, a high-resolution ^{10}Be chronology of Holocene glacier fluctuations in the Southern Alps of New Zealand (*25*) reveals that the dominant glacial event of the last millennium occurred around C.E. 1400 and was followed by several more pulses before the final termination, highlighting a marked difference with the Peruvian record and implying a complex global pattern of glacial events during the LIA period.

Several paleolimnological indices of tropical Andean paleoclimate show the early Holocene to be relatively warm and arid, with drought peaking earlier near the equator and progressively later in the southern tropics (*10*). Sediment core proxy data from Lake Titicaca, whose hydrologic balance is diagnostic of precipitation patterns across a wide swath of tropical South America (*9*), indicate a lake level rise to overflow conditions between 10 to 8.5 ka, followed by a sharp drop and ensuing period of desiccation. These lake level trends agree closely with the timing of early Holocene Vilcabamba glacial culminations (Fig. 2). High lake stands and expanded glaciers were probably maintained by some combination of lower temperatures and higher precipitation, but the relative importance of temperature versus precipitation controls is unclear. Overflowing lake levels at Lake Titicaca likely reflect enhanced moisture delivery via prevailing easterly flow across the Amazon Basin (*9*), and we similarly hypothesize that Vilcabamba glaciers were sustained by an overall increase in snowfall, humidity, and/or cloudiness at high elevations during the early Holocene. The underlying cause of this hydrologic variability has been attributed to past fluctuations in tropical Atlantic sea surface temperatures (SST) and their impact on precipitation patterns in Amazonia, with high levels of Lake Titicaca promoted by anomalously low Atlantic SSTs and vice versa (*9*). We speculate that Atlantic forcings may also have played a prominent role in early Holocene Vilcabamba glacier fluctuations.

For the past millennium, it is instructive to compare the Vilcabamba glacial record to regional climate indices from the Quelccaya Ice Cap 250 km southeast of our study area (*8*). Low δ^{18}O and high electrical conductivity from ~C.E. 1500 to 1900 in Quelccaya ice cores are interpreted to reflect lower temperatures and increased wind velocities corresponding to the LIA, whereas ice accumulation data show a wet phase from C.E. 1500 to 1720 followed by dry conditions from C.E. 1720 to 1860 (Fig. 3). The ages of the Vilcabamba inner moraines fall within the latter dry period, possibly signifying that glacier buildup during the wet phase was followed by a delayed onset of retreat in response to gradual moisture starvation under sustained cold conditions. A complementary perspective comes from proxy data in marine sediment cores off Peru at ~12°S and ~14°S (*11*), which show an abrupt shift toward the modern regime of nutrient-rich, oxygen-depleted waters around C.E. 1820 and a coeval transition from wetter to drier conditions on the western slopes of the Andes. The apparent coincidence of these shifts in the marine-based proxies with the latest LIA culmination in our Vilcabamba glacial record suggests that oceanic and terrestrial systems at these latitudes were influenced by a common climate forcing toward the end of the LIA.

Plausible climate drivers must be in accord with the occurrence of early Holocene glacial events and only slightly less extensive LIA glacial culminations during relative maxima and minima in precessional wet-season insolation, respectively (Fig. 2). For the latest Holocene, we postulate that migration of the Atlantic Intertropical Convergence Zone (ITCZ) may explain concurrent glaciations in tropical South America and northern high latitudes. Proxy data from the Florida Straits (*26*, *27*) indicate a reduction in Gulf Stream strength during the LIA, possibly leading to decreased northward oceanic heat transport and cooling of the North Atlantic (Fig. 3). This cooling may have altered cross-equatorial SST gradients and caused southward migration of the ITCZ (*28*). Mineralogic data from the Cariaco Basin (*29*) provide evidence for a southerly excursion of the ITCZ during the LIA, lending credence to this scenario. We envision cold conditions in the north promoting European glacier expansions while a south-shifted ITCZ simultaneously brought increased glacier-nourishing snowfall to the Peruvian Andes. Subsequent northward migration of the ITCZ in step with North Atlantic warming at the close of the LIA would diminish high-elevation snowfall in the southern tropics and trigger glacier retreat in both regions. This hypothesis is consistent with the Quelccaya ice core record (*8*), which suggests that a reduction in regional snow accumulation preceded the retreat of Vilcabamba glaciers toward the end of the LIA (*27*) (Fig. 3).

A more thorough exploration of global-scale Holocene climate drivers will require testing with coupled ocean-atmosphere model simulations, but the advancement of these models depends on regional calibration with reliable paleoclimate data. Tropical glacier chronologies hold tremendous potential for this approach, and our results demonstrate that the new generation of ^{10}Be data has attained the precision necessary for reconstructing high-resolution records throughout the Holocene and up to the present day.

References and Notes

1. G. Kaser, H. Osmaston, *Tropical Glaciers* (Cambridge Univ. Press, Cambridge, 2002).
2. C. M. Clapperton, *Quat. Sci. Rev.* **2**, 83 (1983).
3. M. Cane, A. C. Clement, in *Mechanisms of Global Climate Change at Millennial Time Scales,* P. U. Clark, R. S. Webb, L. D. Keigwin, Eds. (American Geophysical Union, Washington, DC, 1999), pp. 373–383.
4. M. Vuille *et al.*, *Earth Sci. Rev.* **89**, 79 (2008).
5. T. D. Dillehay, A. L. Kolata, *Proc. Natl. Acad. Sci. U.S.A.* **101**, 4325 (2004).
6. J. A. Smith, B. G. Mark, D. T. Rodbell, *J. Quaternary Sci.* **23**, 609 (2008).
7. V. Jomelli, D. Grancher, D. Brunstein, O. Solomina, *Geomorphology* **93**, 201 (2008).
8. L. G. Thompson, E. Mosley-Thompson, W. Dansgaard, P. M. Grootes, *Science* **234**, 361 (1986).
9. P. A. Baker *et al.*, *Science* **291**, 640 (2001).
10. M. B. Abbott *et al.*, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **194**, 123 (2003).
11. R. M. Gutiérrez *et al.*, *Biogeosciences* **6**, 835 (2009).
12. Materials and methods are available as supporting material on *Science* Online.
13. J. M. Grove, *Little Ice Ages: Ancient and Modern, Vols. 1 and 2* (Routledge, New York, 2004).
14. D. C. Douglass *et al.*, *Geology* **33**, 237 (2005).
15. D. L. Farber, G. S. Hancock, R. C. Finkel, D. T. Rodbell, *J. Quaternary Sci.* **20**, 759 (2005).
16. S. O. Dahl, A. Nesje, Ø. Lie, K. Fjordheim, J. A. Matthews, *Holocene* **12**, 17 (2002).
17. J. A. Matthews, R. A. Shakesby, C. Schnabel, S. Freeman, *Holocene* **18**, 1155 (2008).
18. A. Nesje, J. A. Matthews, S. O. Dahl, M. S. Berrisford, C. Andersson, *Holocene* **11**, 267 (2001).
19. H. Kerschner, S. Ivy-Ochs, *Global Planet. Change* **60**, 58 (2008).
20. J. H. Mercer, M. O. Palacios, *Geology* **5**, 600 (1977).
21. D. T. Rodbell, *Holocene* **2**, 19 (1992).
22. A. Rabatel, B. Francou, V. Jomelli, P. Naveau, D. Grancher, *Quat. Res.* **70**, 198 (2008).
23. A. Nesje, S. O. Dahl, *Holocene* **13**, 171 (2003).
24. H. Holzhauser, M. Magny, H. J. Zumbühl, *Holocene* **15**, 789 (2005).
25. J. M. Schaefer *et al.*, *Science* **324**, 622 (2009).
26. D. C. Lund, W. B. Curry, *Paleoceanography* **21**, 10.1029/2005PA001218 (2006).
27. D. C. Lund, J. Lynch-Steiglitz, W. B. Curry, *Nature* **444**, 601 (2006).
28. J. C. H. Chiang, W. Cheng, C. M. Bitz, *Geophys. Res. Lett.* **35**, L07704 (2008).
29. G. H. Haug, K. A. Hughen, D. M. Sigman, L. C. Peterson, U. Röhl, *Science* **293**, 1304 (2001).
30. A. Berger, *Quat. Sci. Rev.* **11**, 571 (1992).

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Supporting Online Material

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Materials and Methods
Figs. S1 to S4
Tables S1 and S2
References

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