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Abstract
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RESEARCH ARTICLE

TROPICAL GLACIERS

Recent tropical Andean glacier retreat is unprecedented in the Holocene

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Tropical glaciers have retreated over recent decades, but whether the magnitude of this retreat exceeds the bounds of Holocene fluctuations is unclear. We measured cosmogenic beryllium-10 and carbon-14 concentrations in recently exposed bedrock at the margin of four glaciers spanning the tropical Andes to reconstruct their past extents relative to today. Nuclide concentrations are near zero in almost all samples, suggesting that these locations were never exposed during the Holocene. Our data imply that many glaciers in the tropics are probably now smaller than they have been in at least 11,700 years, making the tropics the first large region where this milestone has been documented.

Glaciers are sentinels of climate change, and their global retreat has accelerated over recent decades (*1*, *2*). Placing this retreat in the context of glacier fluctuations over the Holocene interglacial [the last 11.7 thousand years (kyr)] provides a critical lens for assessing the implications of different magnitudes of global warming (*3*, *4*), the possible onset of a new "Anthropocene" epoch (*5*), and the latest Intergovernmental Panel on Climate Change report's finding that global temperature is very likely (90 to 100% probability) warmer now than during any multicentury interval of the past 100,000 years (*6*). Global surveys suggest that, except for some sites in the Southern Hemisphere and tropics, glaciers generally retreated to their minimum extents during the early and/or mid-Holocene. At least in most places around the Northern Hemisphere, glaciers are still currently larger than their Holocene minima (*7*). However, the comparison between present and early-to-late Holocene glacier extents is complicated by long response times—which imply further retreat even in the absence of additional global warming (*8*)—and by the paucity of continuous Holocene-glacier length constraints in many areas (*7*). The tropics may be among the first places that a signal of anthropogenic glacier change exceeds Holocene bounds, for three reasons: (i) Natural temperature variability is smallest in this region (*9*, *10*); (ii) models and data suggest elevated modern warming at high tropical altitudes where tropical glaciers exist (*11*, *12*); and (iii) glacier response times are typically shorter in the tropics than elsewhere (*13*). The Andes in South America are of particular interest because they are home to >99% of tropical glaciers.

Previous work at the Quelccaya Ice Cap in Peru, the world's largest tropical ice body (40 km^2), suggests that recent tropical glacier retreat is unusual, but not yet unprecedented, in the Holocene. Radiocarbon dating of in situ plant remains sequentially exposed by recent retreat indicates that the ice cap was smaller than its 2000 CE extent before 4.6 thousand years ago (ka) and its 2020 CE extent before 7.0 ka, when the mid-Holocene climate was warm and dry (Fig. 1A) (*14*). However, the large size of the Quelccaya Ice Cap may make it a poor bellwether for the state of the tropical cryosphere; many much smaller tropical glaciers

flux and glacier size. In addition, paraglacial sedimentation after ice retreat may maintain elevated clastic fluxes for some time, causing current glacier lengths interpreted from clastic fluxes to appear larger than they actually are (*16*). More tropical-glacier length reconstructions are needed to obtain a comprehensive view on past and present glacier responses to climate change.

Paired measurements of the cosmogenic nuclides ^{10}Be and ^{14}C in recently exposed bedrock along a glacial margin can help constrain for how long during the Holocene a glacier was larger and smaller than it is today (*17*). During periods of proglacial bedrock exposure when a glacier recedes, cosmic radiation produces ^{10}Be and ^{14}C in quartz near the bedrock surface. Production attenuates rapidly in the first few meters of the subsurface, where it is primarily controlled by spallation reactions, and then more gradually for tens of meters below this, where deeper-penetrating muons dominate (*18*). Production by muons comprises a larger fraction of total production for ^{14}C than for ^{10}Be, leading to measurable ^{14}C accumulation at considerable depth under rock or ice that is not necessarily indicative of subaerial exposure (fig. S6). During periods of bedrock burial, when a glacier expands, production is suppressed and ^{14}C concentrations decrease because of decay (half-life = 5.7 kyr), whereas ^{10}Be (half-life = 1.4 million years) remains nearly unchanged. In addition, subglacial erosion reduces the surface concentration of both nuclides by exhuming weakly dosed subsurface material. Measuring multiple bedrock samples along a glacier margin helps disentangle the effects of glacial erosion and exposure because all the samples likely experienced the same exposure history but different amounts of erosion. In sum, paired ^{14}C-^{10}Be measurements can record past intervals when glaciers were smaller and did not produce moraines or down-valley lake deposits, which have typically been the focus of Holocene glacier reconstructions. Vickers *et al.* (*19*) previously applied this paired-nuclide approach to proglacial bedrock at the Quelccaya Ice Cap and inferred a Holocene–ice extent history that is consistent with the radiocarbon-based plant chronology discussed above (Fig. 1A).

To determine if recent tropical warming has

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