Similar Holocene glaciation histories in tropical South America and Africa

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Tropical glaciers have retreated alongside warming temperatures over the past century, yet how these trends fit in a long-term geological context is largely unclear. Here we present reconstructions of Holocene glacier extents relative to today from the Quelccaya Ice Cap, Peru, and the Rwenzori Mountains, Uganda, based on measurements of in situ ^{14}C and ^{10}Be from recently exposed bedrock. Ice extent histories are similar at both sites, and suggest that ice was generally smaller than today during the first half of the Holocene and larger than today for most, if not all, of the last several millennia. The similar glaciation history in South America and Africa suggests that large-scale warming followed by cooling of the tropics during the late Holocene primarily drove ice extent, rather than regional changes in precipitation. Our results also imply that recent tropical ice retreat is anomalous in a multi-millennial context.

INTRODUCTION

Determining how temperatures evolved over the Holocene is important to provide long-term context for modern warming, test climate models, and understand how climate around the world is coupled. Yet in the tropics, Holocene temperature trends are often inconsistent between proxies (Leduc et al., 2010) and near the noise level of many records. Furthermore, unlike over Pleistocene glacial cycles, when tropical temperatures were closely linked to the high latitudes through strong feedbacks, Holocene climate forcing was dominated by regional and seasonal variations in insolation that had marked effects on tropical hydrology (Seltzer et al., 2000; Shanahan et al., 2015) but less certain imprints on temperature. Models typically predict modest tropical warming from the mid to late Holocene due to small increases in greenhouse gases and mean annual insolation, but not all agree (Liu et al., 2018).

Alpine glaciers may serve as especially sensitive monitors of temperature change in the tropics. For instance, the near-uniform lowering of glacial snowlines during the Last Glacial Maximum provides some of the most robust evidence for tropical cooling then, and widespread tropical glacier retreat today points to their sensitivity to recent warming. Unfortunately, tropical glacier behavior across the Holocene is poorly constrained, and existing records of glacier length tend to be qualitative or discontinuous

(Solomina et al., 2015). Moreover, while tropical glaciation during Pleistocene glacial periods was largely related to temperature (Hostetler and Clark, 2000), the driver of Holocene glacier fluctuations remains less clear given the smaller magnitude of temperature variations and the potential for hydroclimatic controls on tropical glaciers (Mölg et al., 2003; Thompson et al., 2005).

We apply the in situ ^{14}C-^{10}Be chronometer to bedrock (Goehring et al., 2011) at the margin of the Quelccaya Ice Cap, Peru and a recently deglaciated site in the Rwenzori Mountains of East Africa to generate a more complete and quantitative Holocene record of tropical glaciation (Fig. 1). The use of multiple cosmogenic nuclides enables an estimate of the cumulative amount of time, and broadly when, the glaciers were larger or smaller than today, informing our understanding of what drove their long-term fluctuations as well as how anomalous current glacier retreat may be in a Holocene context.

STUDY SITES

The Quelccaya Ice Cap in the Peruvian Andes (13.9 °S, 70.9 °W, 5670 m) is the largest tropical ice cap in the world, covering ~40 km^2. It is particularly sensitive to changes in temperature owing to its relatively low relief and dome shape, which enables a small change in the equilibrium line altitude to drive a potentially large change in its marginal position (Malone et al., 2015). Monitoring suggests its outlet glaciers have been retreating in recent decades due to warming (Rabatel et al., 2013). Radiocarbon dating suggests that the ice retreated to near or within its late Holocene extent by 11.6 ka (Kelly et al., 2012). Plant material exposed by recent retreat suggests that the ice cap was as small as or smaller than today from at least 7 ka until 5.2 ka when the plants grew and likely more extensive thereafter, as the material would have probably decomposed if it had been uncovered previously (Buffen et al., 2009). Moraine ages indicate that this late Holocene advance culminated at ~0.5 ka, which, when compared with local ice core records, was likely due to changes in temperature rather than net accumulation (Stroup et al., 2014). Confirming Quelccaya's full Holocene history requires additional work because these constraints are mostly indirect or discontinuous.

The Rwenzori Mountains in Uganda and the Democratic Republic of Congo (0.3 °N, 29.9 °E, highest elevation 5109 m) feature the most extensive system of glaciers in Africa. Rwenzori glaciers have also undergone substantial retreat over the past century and less than 1 km^2 of ice now remains. Similar to other glaciers in the humid inner tropics, the relatively wet conditions and lower elevations in the Rwenzori result in melt-dominated glaciers, and modeling suggests they are particularly sensitive to temperature (Doughty et al., in press). Holocene constraints are sparse, but ^{10}Be dating suggests that ice retreated to within 0.25 km of its early 20th century position at ~11 ka and reached a Holocene maximum a few centuries ago, before modern retreat began ~1870 C.E. (Jackson et al., 2020a; Russell et al., 2009). The lack of deposits between these earliest and latest Holocene positions suggest that ice may have been within the Little Ice Age margin throughout the Holocene, but it is unclear how small ice typically was or how it trended through time (Jackson et al., 2020b).

THE ^{14}C-^{10}BE CHRONOMETER

Concentrations of ^{14}C and ^{10}Be, and the ratio between them, in proglacial bedrock are a function of the history of ice cover and erosion at the site (Goehring et al., 2011). During intervals of reduced ice extent, these nuclides accumulate proportionally to the duration of exposure. When ice advances over the site, production effectively ceases and the nuclides decay (^{10}Be $t_{1/2}$ = 1.39 Myr; ^{14}C $t_{1/2}$= 5.7 kyr), leading to a decrease in the $^{14}C/^{10}Be$ ratio. Importantly, the cosmogenic signal is sensitive to the timing, as well as the duration, of exposure. For instance, while exposure during the first versus second half of the Holocene might yield similar ^{10}Be concentrations, the $^{14}C/^{10}Be$ ratio would be lower in the former scenario due to subsequent decay under late Holocene ice cover. Additionally, glacial erosion reduces the concentrations of both nuclides. Thus, the Holocene history of ice extent relative to today can be constrained by measuring ^{14}C and ^{10}Be concentrations in recently exposed bedrock samples collected adjacent to the current ice margin, which presumably have experienced the same exposure history but potentially different magnitudes of erosion.

METHODS

We measured ^{14}C and ^{10}Be concentrations from several bedrock samples at each site. Five samples were collected along the western edge of the Quelccaya Ice Cap, only meters (Q-2-03 to Q-4-03) to tens of meters (Q-80 and Q-81) from the 5 ka plant remains dated by Buffen et al. (2009) (Fig. 1a). All samples were within meters of the ice margin at the time of sampling (2003 and 2008). Two additional samples were collected 3 km down valley (Q-74 and Q-75) to better constrain the timing of the last deglaciation and provide a maximum-limiting age for initial Holocene exposure. In the Rwenzori Mountains, three samples were collected from a headwall high on Weismann's Peak (Fig. 1b), which was deglaciated within the past 80 years based on historical photography. All samples were from smooth bedrock surfaces with no nearby sediment cover.

Nuclide concentrations are consistent with a number of Holocene glacier histories. To evaluate which histories are most probable, we modeled 100,000 random simulations of ^{10}Be and ^{14}C concentrations that result from a wide range of exposure and erosion scenarios. Our model tracks the evolution of nuclides in a column of bedrock for each sample site, simulating nuclide accumulation during exposure, and nuclide loss via glacial erosion and decay when ice-covered. All simulations begin at 11 ka, based on evidence discussed above that ice had not retreated near the sampling sites before this time. Scenarios that yield bedrock surface nuclide concentrations within uncertainty of measured concentrations of both nuclides in all samples are considered plausible. We show results using the global nuclide production rate calibration, but a regional production rate yields similar solutions.

RESULTS

Measured ^{14}C and ^{10}Be ratios and apparent ages for the recently deglaciated Quelccaya and Rwenzori samples are strikingly similar, suggesting similar glacier histories at both sites. The highest concentration ^{10}Be samples at both locations register at least 5 kyr of exposure, while $^{14}C/^{10}Be$ ratios imply several kyr of later burial (Fig. 2). The Quelccaya samples exhibit a range of concentrations, suggesting that some have been more deeply eroded than others, while the Rwenzori samples all have similarly high nuclide concentrations, consistent with minimal erosion. The nearly linear relationship between ^{14}C and ^{10}Be concentrations implies concordant burial histories of all samples at each site. The one exception is sample Q-81 from Quelccaya, which has a substantially higher ^{10}Be concentration and lower $^{14}C/^{10}Be$ ratio, implying >20 kyr of total history; this sample is therefore contaminated by pre-Holocene inheritance and excluded. The two down valley samples at Quelccaya have ^{10}Be ages of 10.9 ± 0.2 and 11.0 ± 0.2 ka, confirming our assumption that initial exposure of the ice marginal samples did not occur until after the start of the Holocene.

Monte Carlo simulations suggest that only a small subset of exposure scenarios (~2%) can explain the measured nuclide concentrations at both sites; all are characterized by exposure in the early Holocene and burial in the late Holocene (Fig. 3g,h). Inferred erosion rates for the Rwenzori samples are on the order of tens of meters per Myr but reach up to one to two orders of magnitude higher for some of the Quelccaya samples, with the most deeply eroded sample likely glacially plucked given the magnitude of erosion.

DISCUSSION

The pattern of early Holocene exposure followed by mid to late Holocene burial recorded by our cosmogenic nuclide data at the Quelccaya Ice Cap and in the Rwenzori Mountains fits with other records of glacier extent from these regions. Moraine ages and clastic sediment fluxes to Andean glacial lakes suggest ice retreated from early Holocene positions by ~10 ka and grew after the mid Holocene reaching maximum extents in the late Holocene (Rodbell et al., 2008; Stansell et al., 2015, 2017), while the ~5 ka age of plant remains adjacent to our sample sites at Quelccaya implies continuous ice cover since the plants were overrun (Buffen et al., 2009). Likewise, low dust concentrations in a Kilimanjaro ice core suggest fairly continuous ice accumulation for the past ~4 kyr, and clastic sediment fluxes and radiocarbon dating of moraines suggest glacier renucleation and/or readvance on Mount Kenya in the mid Holocene (Karlén et al., 1999; Gabrielli et al., 2014).

The similar Holocene glacier histories we find in tropical South America and Africa suggest that they were driven by a common factor, most likely large-scale changes in temperature. Indeed, temperature variations at high altitudes are relatively homogeneous across the tropics due to the weak Coriolis force at low latitudes. Furthermore, proxy records suggest different precipitation histories in these regions. Precipitation increased in the southern tropical Andes during the late Holocene as the Intertropical Convergence Zone migrated southward and the South American Summer Monsoon strengthened (Kanner et al., 2013; Seltzer et al., 2000) (Fig. 3e), whereas much of east Africa became drier when the African Humid Period ended (Shanahan et al., 2015), including near the Rwenzori (Ivory and Russell, 2018) (Fig. 3f). We therefore interpret the glacier histories as records of Holocene temperature across the tropics, with conditions generally warmer than today in the early Holocene and colder than today since ~5 ka. We note that our results may not apply to glaciers elsewhere in the tropics, however, particularly those in precipitation-limited regions where ice loss is dominated by sublimation rather than melt (Rupper and Roe, 2008; Sagredo et al., 2014).

East African lake biomarker records as well as a tropics-wide sea surface temperature stack show cooling trends over the past 5 kyr, consistent with tropical glacier expansion around that time (Ivory and Russell, 2018; Marcott et al., 2013) (Fig. 3c,d). Both datasets have similar average early and late Holocene temperatures, however, which is more difficult to reconcile with the early Holocene exposure and late Holocene burial suggested by our data. We suggest that the glaciers may provide more sensitive records of temperature change than these other proxies, and contend that the early Holocene was in fact warmer than the late Holocene in these regions. Indeed, geochemical paleotemperature proxies typically carry uncertainties ≥1°C (Russell et al., 2018; Tierney et al., 2019; Tierney and Tingley, 2018), whereas modeling suggests that 0.9°C and ~2.5°C of warming would be sufficient to remove all ice from the Rwenzori and Quelccaya (Doughty et al., in press; Yarleque et al., 2018). It is also possible that Holocene temperature changes were amplified at higher elevations nearer the glaciers, as has been found for the Last Glacial Maximum (Loomis et al., 2017), but not detectable at the lower elevations of the lake and marine records.

It is unclear what drove the early Holocene warmth and mid to late Holocene tropical cooling that we infer was responsible for increasing ice cover at both sites during the past ~5 kyr. While there were large variations in seasonal insolation over the Holocene, mean annual insolation – which tropical glaciers may be more sensitive to since they ablate all year long – increased slightly in the tropics (Fig. 3a). Greenhouse gas forcing also rose modestly during the mid to late Holocene (Fig. 3b), suggesting that it too was not the main driver. Notably, Quelccaya and the Rwenzori are located at 0˚ and 14 ˚S latitude, but the trends in their ice extents parallel those of many Northern Hemisphere glaciers, which were typically smaller during the early Holocene and expanded during the late Holocene in response to declining boreal summer insolation (Solomina et al., 2015). This similarity might suggest that tropical glaciers responded to feedbacks related to boreal summer temperature.

Our paired ^{10}Be-^{14}C measurements on recently exposed proglacial bedrock in South America and Africa provide the first time-integrated constraints on tropical glacier extents relative to today spanning the Holocene. This bedrock approach complements the moraine and lake sediment record of Holocene glaciation, and together these archives offer the potential of developing continuous records of ice extent. Our data suggest that modern tropical glacier retreat has reversed a late Holocene trend toward expanded ice cover, and current glacier extents are probably anomalous in the context of the last several millennia. Moreover, our results imply that these glaciers responded sensitively to temperature over the Holocene, pointing to their continued retreat with additional warming in the future.

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SUPPLEMENTAL INFORMATION

Supplemental information (Figures DR1-DR5, Tables DR1-DR4, and model codes) is available online at the GSA Data Repository.

FIGURE CAPTIONS

Figure 1. Locations of bedrock samples (light grey circles) from (**a**) Quelccaya Ice Cap, Peru, and (**b**) Rwenzori Mountains, Uganda. Green triangles show recently emerged ~5 ka plant remains (Buffen et al., 2009).

Figure 2. ^{14}C and ^{10}Be concentrations with 1σ measurement uncertainties in recently exposed bedrock from the Quelccaya Ice Cap (red) and Rwenzori Mountains (blue). Concentrations normalized by surface production rate, such that ^{10}Be concentrations are equivalent to surface exposure durations in years. Solid black line represents the evolution of surface concentrations under continuous exposure. Dashed lines are hypothetical burial isochrons and neglect erosion.

Figure 3. Inferred glacier histories compared to paleoclimate records. (**a**) Mean annual insolation at the equator. (**b**) Radiative forcing from CO_2+CH_4+N_2O (Marcott et al., 2013). (**c**) Tropical sea surface temperature stack (Marcott et al., 2013). (**d**) Equatorial East Africa average temperature change from organic geochemical reconstructions (Ivory and Russell, 2018). (**e**) South American $\delta^{18}O$ records from Huagapo Cave (light purple), Diamante Cave (medium purple), El Condor Cave (blue-purple), and Lake Junin (dark purple) (Cheng et al., 2013; Kanner et al., 2013; Seltzer et al., 2000). (**f**) African leaf wax δD from the Gulf of Aden (light blue), Lake Challa (medium blue), and Lake Tanganyika (dark blue) (Tierney and deMenocal, 2013). (**g, h**) Modeled exposure histories for (**g**) Quelccaya and (**h**) Rwenzori samples showing the proportion of Monte Carlo simulations with exposure during each time step.

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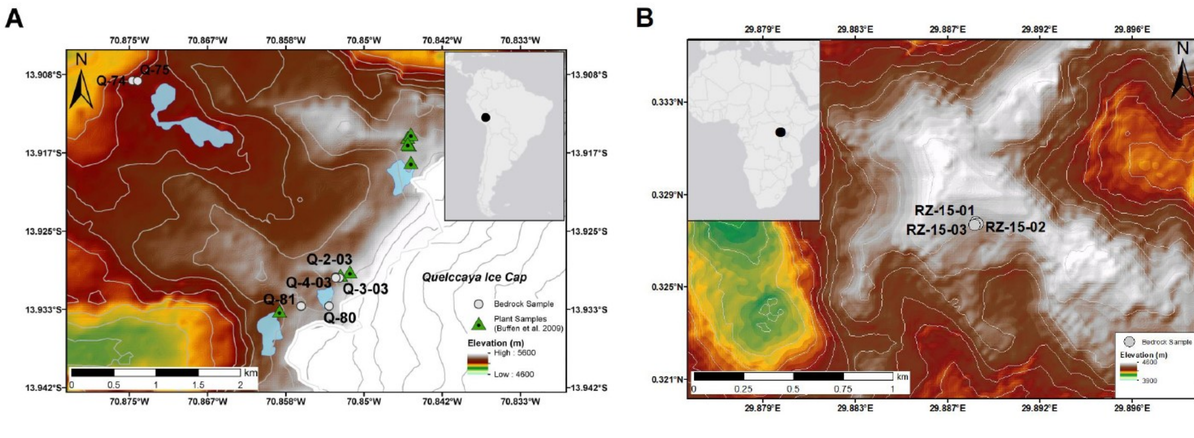
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13.933°S
13.942°S
N
Q-74
Q-75
Q-2-03
Q-4-03
Q-3-03
Q-81
Q-80
Quelccaya Ice Cap
Bedrock Sample
Plant Samples (Buffen et al. 2009)
Elevation (m)
High : 5600
Low : 4600
0 0.5 1 1.5 2 km
B
29.879°E
29.883°E
29.887°E
29.892°E
29.896°E
0.333°N
0.329°N
0.325°N
0.321°N
N
RZ-15-01
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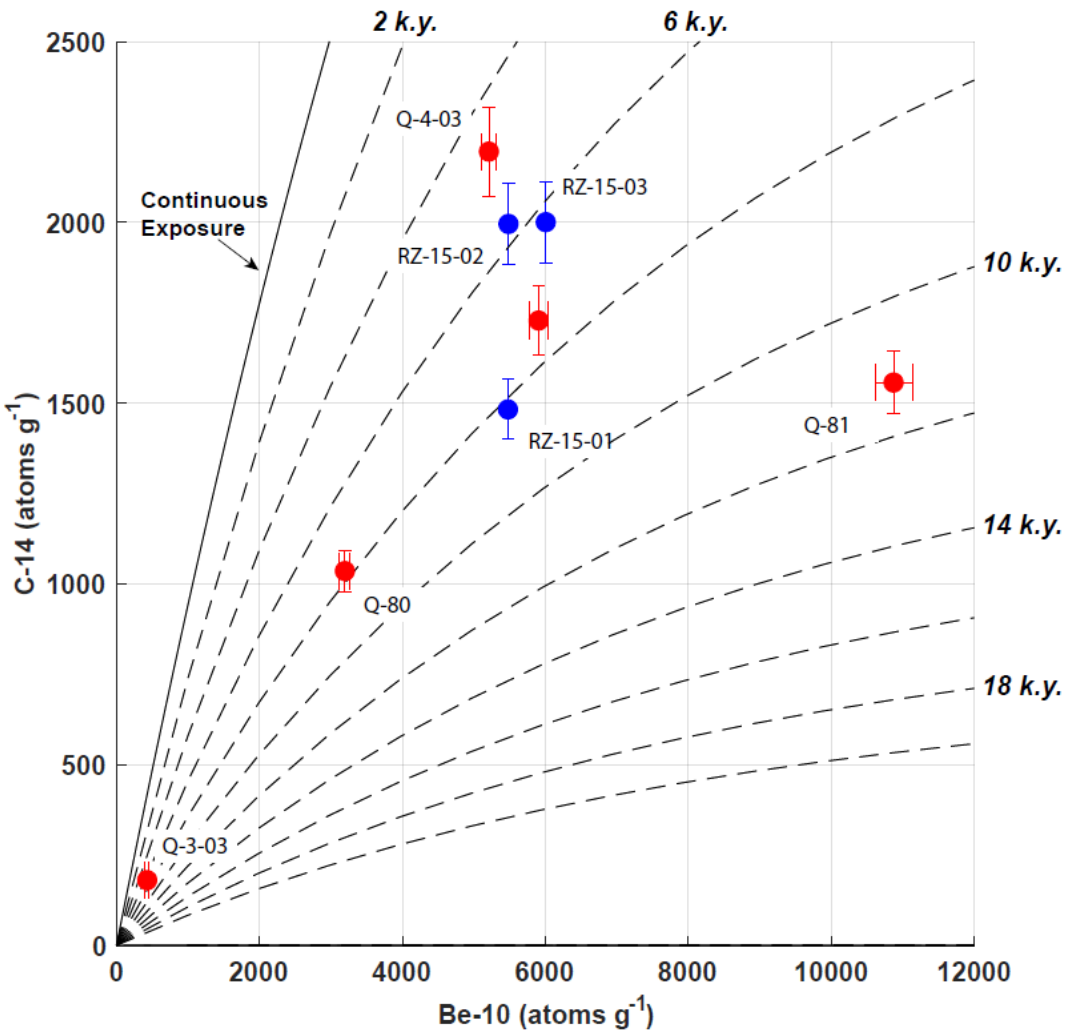
RZ-15-02
Bedrock Sample
Elevation (m)
0 0.25 0.5 0.75 1 km

Figure 1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14 k.y.
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Continuous
Exposure
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RZ-15-02
RZ-15-01
Q-81
Q-80
Q-3-03
C-14 (atoms g^{-1})
Be-10 (atoms g^{-1})
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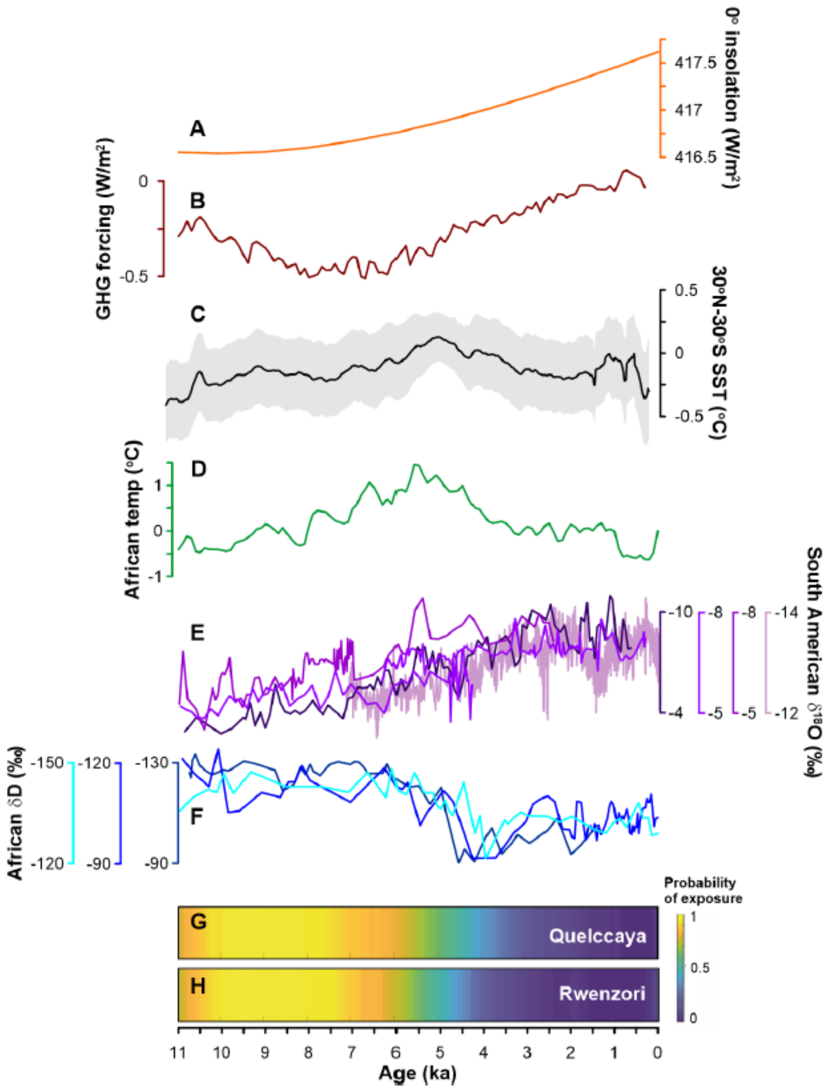
Figure 2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-0.5
30°N-30°S SST (°C)
0.5
0
-0.5
African temp (°C)
1
0
-1
South American δ18O (‰)
-10
-4
-8
-5
-8
-5
-14
-12
African δD (‰)
-150
-120
-120
-90
-130
-90
Probability of exposure
1
0.5
0
Quelccaya
Rwenzori
11
10
9
8
7
6
5
4
3
2
1
0
Age (ka)

Figure 3