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Climate of the Past
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Holocene glaciation in the Rwenzori Mountains, Uganda

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Abstract

Tropical glaciers are retreating rapidly, threatening alpine ecosystems across the low latitudes. Understanding how tropical glaciers responded to past periods of warming is crucial for predicting and adapting to future climate change, yet relatively little is known about glacial fluctuations in tropical regions during the recent past (i.e., the Holocene Epoch). This is particularly true in the African tropics, where data constraining the timing and magnitude of Holocene glacial fluctuations in the region are sparse and where temperatures during the Middle Holocene were perhaps as warm as or warmer than today. Here we present new beryllium-10 surface-exposure ages that constrain Holocene glacial extents in the equatorial Rwenzori Mountains, Uganda. These results document rapid Early Holocene (~11.7-8.2 ka) glacial retreat in two separate catchments and indicate that Late Holocene (~4.2 ka-present) deposits mark the greatest expansion of Rwenzori glaciers during the last ~11 ka. Holocene glacial fluctuations elsewhere in tropical Africa and in tropical South America are broadly similar to those in the Rwenzori, with most tropical glaciers retreating rapidly during the Early Holocene and remaining near or inboard of their Late Holocene positions through much of Holocene time. The similarity of Holocene glacial fluctuations across the tropics implies that low-latitude glaciers responded to a common forcing mechanism, most likely temperature. Although the drivers of Holocene temperature changes in the tropics remain enigmatic, these data help constrain the expression of tropical temperature changes in the low latitudes.

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1 Introduction

The ongoing, coherent retreat of Earth's alpine glaciers is unique within the Holocene Epoch (~11.7 ka-present; Walker et al., 2012) and emblematic of anthropogenic warming (Solomina et al., 2015). The loss of alpine glaciers is of particular concern in the tropics, where high-elevation regions are warming at a rate twice the global average (Vuille et al., 2008). Tropical glaciers are a primary source of freshwater and are a fundamental component of regional economies, underpinning agriculture, hydropower, and tourism (Bradley et al., 2006; Chevallier et al., 2011). Accurately projecting the response of glaciers to future climate change is thus crucial for effective community response and adaptation (Stocker et al., 2013), and these projections rely on robust understanding of the sensitivity of tropical glaciers to past climate conditions.

Tropical glaciers respond to changes in both temperature and precipitation, although the relative influence of these forcings depends upon a glacier's unique climatic setting (Sagredo et al., 2014). Recent work to reconstruct past glacial fluctuations in tropical South America indicates that glaciers there were near or inboard of their Late Holocene (~4.2 ka-present; Walker et al., 2012) maxima during much of the Holocene Epoch (Jomelli et al., 2014; Solomina et al., 2015; Stansell et al., 2017). Although relatively little is known about Holocene glacial fluctuations in the African tropics (Kaser and Osmaston, 2002; Solomina et al., 2015), recently produced terrestrial paleotemperature reconstructions provide greater paleoclimatic context for understanding past changes in tropical African glacial extent (Weijers et al., 2007; Tierney et al., 2008; Woltering et al., 2011; Loomis et al., 2012, 2017). Of particular interest is the response of glaciers to climate conditions during the Middle (~8.2-4.2 ka) and Early (~11.7-8.2 ka) Holocene Epoch (Walker et al,. 2012), when temperatures in tropical Africa may have been similar to or

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higher than modern (Ivory et al., 2017 and references therein). Determining when and how glaciers in the African tropics fluctuated during past warm periods provides crucial information for assessing whether, or how long, tropical glaciers may persist under future warming scenarios.

Here we present new data from the equatorial Rwenzori Mountains of Uganda (0.3ºN, 30.0ºE; Figure 1) that constrain the extent of glaciers in two separate valleys during the Holocene. These data include twelve beryllium-10 (^{10}Be) surface-exposure ages of glacial landforms which provide evidence of past glacial extents in the Rwenzori during Holocene time. We then compare the Rwenzori glacial chronology with records of East African glaciation and paleoclimate to assess both the potential drivers of past glacial fluctuations as well as the response of these glaciers to changes in Holocene climate.

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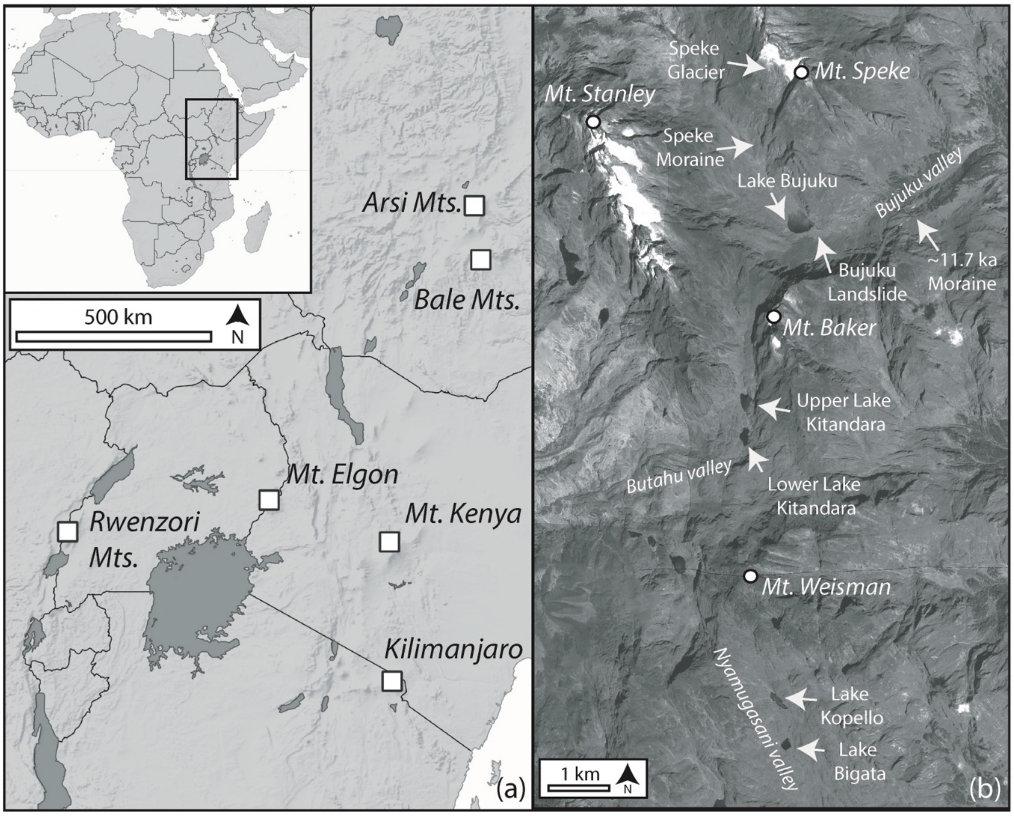

Figure 1. Tropical East Africa and the Rwenzori Mountains. (a) The Rwenzori Mountains, Kilimanjaro, and Mt. Kenya are the only three still-glacierized sites in East Africa. Mt. Elgon in Uganda and the Arsi and Bale Mountains in Ethiopia also host glacial deposits, though are no longer glacierized. (b) Worldview-1 satellite image of the central Rwenzori massif and locations mentioned in the text. Glaciers persist in the Rwenzori on Mt. Stanley, Mt. Speke, and Mt. Baker. Although no longer glacierized, the former Thomson Glacier occupied the peak of Mt. Weisman during the early 20th century.

2 Background

The Rwenzori Mountains are an uplifted horst of crystalline bedrock and are an extreme example of rift shoulder uplift (McConnell et al., 1953; Ring, 2008). Mt. Stanley, the highest point in the range, reaches an elevation of 5,109 meters above sea level (m asl) and, with Mt. Speke and Mt. Baker, is one of three still-glacierized peaks in the Rwenzori (Figure 1). The first quantitative observations of Rwenzori glaciers were made in the early 20th century (Abruzzi,

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1907). Rwenzori glaciers have retreated markedly since then, decreasing in area from ~6.5 to 0.96 km^2 between 1906 and 2003 CE and losing an estimated 50% of their areal extent between 1987 and 2003 CE (Taylor et al., 2006). Modern glaciers in the Rwenzori occur only above ~4,400 m asl and are predicted to disappear within the coming decades (Kaser and Osmaston, 2002; Taylor et al., 2006).

Although at present glaciers occupy only the highest peaks (Figure 1), the Rwenzori host glacial deposits that attest to more extensive glaciation during and since the last ice age. Osmaston (1965; 1989) grouped moraines in the Rwenzori into distinct glacial stages based on their relative weathering, stratigraphic position, and morphology. The 'Omurubaho' stage moraines occur at elevations ~3,600-4,000 m asl and feature ~3-30 m relief above the valley floors (Osmaston, 1989). Osmaston (1989) estimated these moraines to have been deposited during the Early Holocene. Recent ^{10}Be dating of Omurubaho stage moraines in the Bujuku and Nyamugasani valleys indicates deposition during late-glacial (~15.0-11.7 ka) and Early Holocene time (Jackson et al., in review). The 'Lac Gris' stage moraines (Osmaston, 1989) are located up valley and stratigraphically inboard of the Omurubaho stage moraines. Lac Gris stage moraines are predominantly low-relief features (1-2 m above the valley floors) and are within ~100 m of observed 1906 CE ice extents (Abruzzi, 1907). Osmaston (1989) estimated Lac Gris stage moraines to be ~700-100 years old. Based on lichenometry, Bergström (1955) suggested that Lac Gris stage moraines observed near the margin of Elena Glacier on Mt. Stanley date to ~1750 CE. However, the rate at which lichens colonize rock surfaces in the Rwenzori is unconstrained (Osmaston et al., 1989) and the ultimate age of pre-observation Lac Gris moraines remains undetermined.

Livingstone (1967) obtained radiocarbon ages of lake sediments that provide minimum limits on the timing of deglaciation at several locations in the Rwenzori. In the Butahu valley, dated organic sediments within a horizon roughly one meter above presumed basal silts in Upper Lake Kitandara (4,000 m asl; Figure 1) yield a radiocarbon age of ~7.7 cal kyr BP (Livingstone, 1967). This provides a minimum-limiting age for glacial recession past this location in the valley. In the Bujuku valley, one radiocarbon age from a layer of gravel-rich peat in a sediment core from Lake Bujuku (3,920 m asl) yields an age of ~3.1 cal kyr BP (Livingstone et al, 1967). However, this core did not recover the complete sedimentary succession from the lake and, therefore, may significantly postdate the onset of post-glacial sedimentation in the lake. Rwenzori glacial fluctuations that occurred between the Early Holocene and the (near) historical period are largely unconstrained. A sediment core from Lower Lake Kitandara (~4,000 m asl) indicates changes in lake water chemistry at the turn of the 18th century consistent with greater glacier meltwater flux to the lake, although with no corresponding changes in pollen or diatom assemblages (McGlynn et al., 2010). High-resolution analyses of clastic sediment input to numerous Rwenzori alpine lakes indicate that recent historical glacial recession began about 1870 CE (Russell et al., 2009).

Evidence from elsewhere in tropical East Africa suggests that glaciers across the region were near or inboard of their maximum Late Holocene extents for much of Holocene time. Radiocarbon ages from lake sediments in the Bale Mountains and on Mt. Arsi in the Ethiopian Highlands, as well as from Mt. Elgon in Uganda, indicate that glaciers at these sites were inboard of their late-glacial extents, and perhaps had ablated completely, by the Early Holocene (Hamilton and Perrot, 1982; Tiercelin et al., 2008). In Tanzania, the persistence of Holocene ice cover on Kilimanjaro is a subject of ongoing debate. Multiple studies show that the Kilimanjaro

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Ice Cap has become less extensive over the last ~1 ka, although whether the ice cap may have ablated completely at some point during the Holocene and later re-nucleated is uncertain (Thompson et al., 2002; Kaser et al., 2010; Thompson et al., 2011; Noell et al., 2014). Recent radiocarbon dating of dust and soil horizons within the ice cap suggests a period of net ice cap ablation occurred prior to ~4 ka, followed by net accumulation during the Late Holocene that persisted until near-historical time when recent recession began (Gabrielli et al., 2014).

At Mt. Kenya, chlorine-36 (^{36}Cl) surface-exposure dating of moraines and glacially molded bedrock in the Teleki Valley indicates that glaciers retreated from their Early Holocene maximum extents by ~10 ka and that the modern Lewis Glacier reached its maximum Late Holocene extent ~200 years ago (Shanahan and Zreda, 2000). In contrast to the existing evidence for limited Middle Holocene glacial expansion in the Rwenzori and on Kilimanjaro, radiocarbon ages of Mt. Kenya's Naro Moru Tarn moraine dam, located ~250 m down valley of the ~200 year old Lewis Glacier moraine, suggest a glacial advance occurred in the Teleki Valley between ~6.9 and 4.7 cal yr BP (Johansson and Holmgren, 1985; Karlen et al., 1999). Although disputed (Mahaney et al., 1989), radiocarbon ages from Thomson Tarn in the Hobley Valley also suggest a Middle Holocene glacial advance on Mt. Kenya between ~7.1 and 6.2 cal yr BP (Perrot, 1982). In addition, clastic sediment fluxes to high alpine lakes on Mt. Kenya indicate more dynamic, erosive glacial activity after ~5 cal yr BP (Karlen et al., 1999), although the extent of corresponding glacial margins throughout this period is not known.

This study aims to establish the timing of Holocene glacial fluctuations in the Rwenzori Mountains and compare directly the Holocene Rwenzori glacial chronology with records of glaciation and paleoclimate elsewhere in tropical East Africa. Prior work mapping and dating Last Glacial Maximum (LGM) and late-glacial Rwenzori glacial deposits lends crucial temporal

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and spatial context for the Holocene chronology (Kelly et al., 2014; Jackson et al., 2019; Jackson et al., in review) and allows a more robust comparison of the Rwenzori glacial record with records of past regional climate conditions.

3 Study Sites

We focused our study within the Bujuku and Nyamugasani valleys, two independent catchments in the Rwenzori that contain Holocene-age glacial deposits amenable for ^{10}Be dating and for which there is pre-existing numerical age control on pre- or Early Holocene glacial deposits (Jackson et al., 2019; Jackson et al., in review).

3.1 Bujuku valley

The modern Speke Glacier occupies the south-facing peak of Mt. Speke (4,890 m asl) near the head of the Bujuku valley (Figure 1, 2). Although today the glacial terminus occurs at ~4,600 m asl, in 1958 CE the glacier extended down slope to ~4,350 m asl (Whittow et al., 1963). Lac Gris stage deposits occur on Mt. Speke between ~4,000 and 4,500 m asl (Osmaston, 1989), including a Lac Gris stage moraine ~300 m downslope from the 1958 CE glacial extent (Osmaston, 1989)(Figure 2). Observations by Abruzzi (1907) indicate that ice had abandoned this Lac Gris stage moraine prior to 1906 CE, though the precise timing of retreat is not known (Whittow, 1963).

Omurubaho stage moraines occur ~2.5 km down the Bujuku valley from the Lac Gris stage moraines, and the innermost (i.e., farthest up valley) of these dates to ~11.7 ka (Jackson et al., in review). There are no moraines in the valley between the ~11.7 ka moraine and the Lac Gris stage deposits on Mt. Speke. Approximately 1.5 km up valley from the ~11.7 ka moraine,

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the outlet of Lake Bujuku is dammed by a landslide that originated on the north-facing slope of Mt. Baker (Figure 1). This landslide is dated to ~11 ka and shows no evidence of having been impeded or reworked by ice either during or subsequent to deposition (Cavagnaro, 2017). Therefore, it is likely that the landslide was emplaced after ice retreated up valley and the age (~11 ka) is a minimum-limiting age for deglaciation of the valley floor at this location (Jackson et al., in review).

3.2 Nyamugasani valley

Mt. Weisman (4,620 m asl) marks the head of the Nyamugasani valley (Figure 1, 2). Although no longer glacierized, the former Thomson Glacier occupied a cirque on the south-facing slope of the peak until the mid-20th century (Osmaston and Pasteur, 1972). Omurubaho-stage moraines occur in the Nyamugasani valley between ~3,800 and 4,000 m asl. The innermost (i.e., farthest up valley) Omurubaho moraine is dated to ~11.2 ka and dams Lake Bigata (~4,000 m asl)(Jackson et al., in review). There are no moraines between Lake Bigata and the peak of Mt. Weisman, although glacially transported boulders are ubiquitous on the valley floor. Approximately 0.5 km up valley from the ~11.2 ka moraine, four boulders on a bedrock rise at the outlet of Lake Kopello (~4,020 m asl) yield ages between ~12.1 and 10.5 ka, indicating continued recession of ice in the valley after ~11 ka (Jackson et al., in review).

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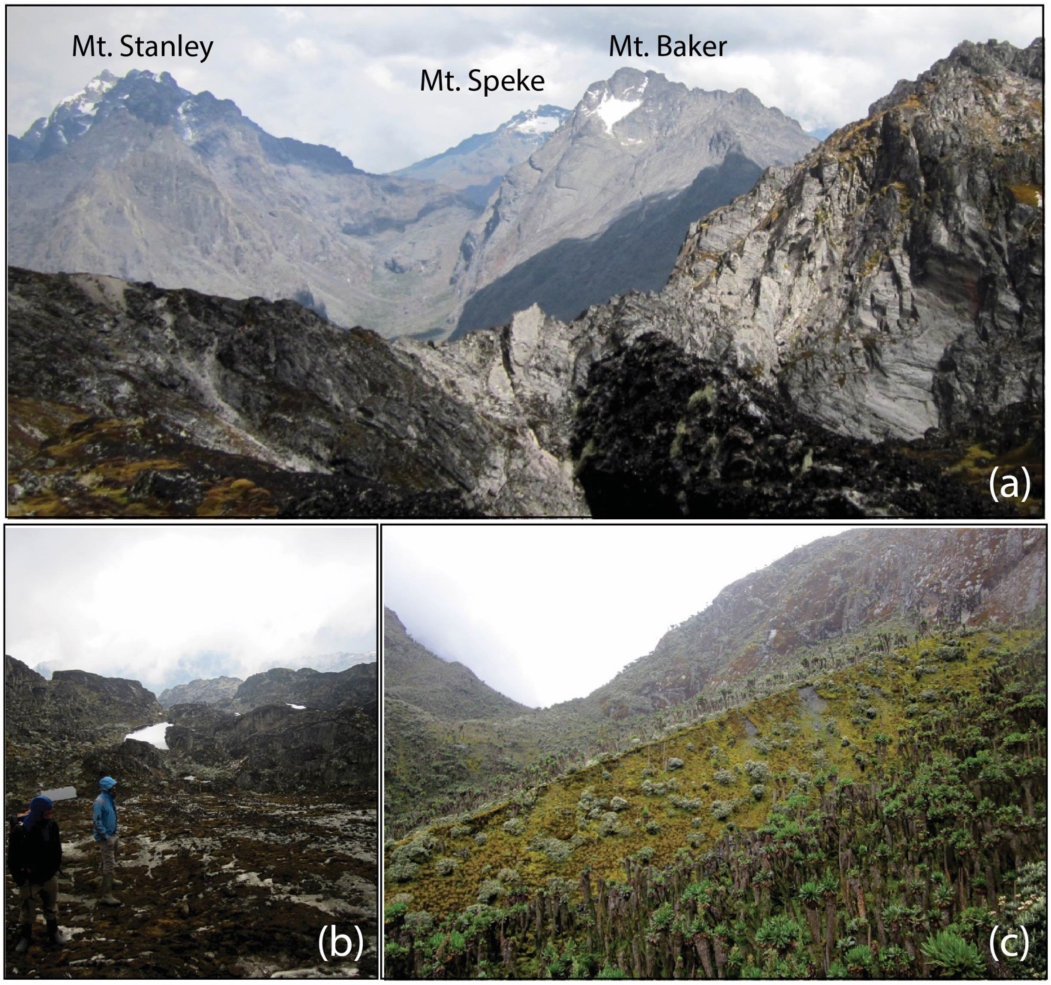

Figure 2. Glacial features in the central Rwenzori Mountains. (a) A view toward the north from the peak of Mt. Weisman. Mt. Stanley, Mt. Speke, and Mt. Baker are the three still-glacierized peaks in the Rwenzori. Above 4,000 m asl, the Rwenzori are dominated by bare bedrock with some lichen and moss cover. (b) A view down valley, toward the south, from the unoccupied cirque on Mt. Weisman that once held the former Thomson Glacier. (c) The right-lateral Speke moraine beneath Speke Glacier features a sharp crest and steep ice-proximal slope. View is toward the east.

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4 Methods

We conducted three field seasons in the Rwenzori between 2012 and 2016. While in the field we classified glacial-geomorphic features based on their morphology, stratigraphic position, and degree of weathering and mapped these features onto WorldView-1 0.5-m resolution satellite imagery. We collected samples for ^{10}Be dating from boulders on moraines, boulders on bedrock, and from bedrock surfaces using a hammer and chisel and the drill-and-blast method of Kelly (2003). We took care to sample boulders that showed no indication of post-depositional movement and, where possible, surfaces with no dip in order to minimize topographic shielding correction uncertainties. We recorded sample locations with a handheld GPS (± 3 m vertical, ± 1 m horizontal), determined topographic shielding using a clinometer, and measured sample surface dip and dip direction, if applicable, with a handheld compass (Table 1).

Table 1: Rwenzori Sample Information

Map ID	Sample ID	Landform	Latitude (DD)	Longitude (DD)	Elev. (m)	Atm.	Thickness (cm)	Density (g/cm3)	Shielding	Erosion (mm/yr)	10-Be (atoms/g)	± 10-Be (atoms/g)
Bujuku Valley												
1	RZ-12-21	Speke moraine	0.38750	29.88821	4095	std	1.5	2.65	0.909	0	9.29E+03	7.84E+02
2	RZ-12-22	Speke moraine	0.38768	29.88816	4046	std	1.2	2.65	0.909	0	6.96E+03	4.80E+02
3	RZ-12-24	Speke moraine	0.38768	29.88816	4046	std	1.3	2.65	0.909	0	1.02E+04	5.07E+02
4	RZ-12-25	Speke moraine	0.38768	29.88816	4046	std	1.5	2.65	0.909	0	1.17E+04	3.87E+02
Nyamugasani Valley												
Map ID	*Sample ID*	*Landform*	*Latitude (DD)*	*Longitude (DD)*	*Elev. (m)*	*Atm.*	*Thickness (cm)*	*Density (g/cm3)*	*Shielding*	*Erosion (mm/yr)*	*10-Be (atoms/g)*	*± 10-Be (atoms/g)*
5	RZ-15-10	Perched boulder	0.32265	29.89128	4397	std	4.0	2.65	0.976	0	3.78E+05	3.56E+03
6	RZ-15-11	Perched boulder	0.32263	29.89132	4400	std	2.0	2.65	0.976	0	3.60E+05	2.50E+03
7	RZ-15-09	Perched boulder	0.32385	29.89034	4431	std	3.0	2.65	0.983	0	3.51E+05	3.79E+03
8	RZ-15-07	Perched boulder	0.32589	29.88928	4488	std	1.9	2.65	0.989	0	1.51E+05	1.50E+03
9	RZ-15-08	Perched boulder	0.32601	29.88953	4498	std	2.0	2.65	0.99	0	2.19E+05	4.14E+03
10	RZ-15-01	Cirque Bedrock	0.32793	29.88877	4509	std	1.9	2.65	0.969	0	1.66E+05	1.81E+03
11	RZ-15-02	Cirque Bedrock	0.32786	29.88887	4526	std	1.4	2.65	0.97	0	1.69E+05	1.84E+03
12	RZ-15-03	Cirque Bedrock	0.32781	29.88871	4536	std	2.8	2.65	0.97	0	1.89E+05	1.68E+03

Table 1. Geographic data and sample characteristic information for Rwenzori samples.

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We isolated beryllium from each sample and associated process blanks at the Dartmouth College Cosmogenic Nuclide Laboratory using a modified version of the methods described in Schaefer et al. (2009). All $^{10}Be/^{9}Be$ ratios were measured at the Lawrence Livermore Center for Accelerator Mass Spectrometry and normalized to the 07KNSTD3110 standard (Nishiizumi et al., 2007)(Table 2). ^{10}Be ages presented in Figures 3-5 and in Table 3 are as calculated using version 3 of the online calculator described by Balco et al. (2008 and subsequently updated) with a high-altitude, low-latitude production rate (Kelly et al., 2015) and time-invariant scaling framework ("St" scaling; Lal, 1991; Stone, 2000). We present ^{10}Be ages calculated using an alternative, time-variant scaling framework ("LSDn" scaling; Lifton et al., 2016) in Table 3. Our choice of scaling framework does not alter our overall interpretations. Where ^{10}Be concentrations are of bedrock rather than glacially deposited sediments, we report the nuclide concentration rather than the exposure-age equivalent (Figure 4, Table 1), as bedrock nuclide concentrations may reflect multiple periods of exposure rather than a single exposure duration.

Table 2: Rwenzori Sample Chemistry

Map ID	Sample ID	Landform	Cathode ID	Quartz (g)	Carrier wt. (mg)	Carrier Conc. (ppm)	Sample (10-Be/9-Be)	± Sample (10-Be/9-Be)	Process Blank Cathode ID	Blank (10-Be/9-Be)	± Blank (10-Be/9-Be)
Bujuku Valley											
1	RZ-12-21	Speke moraine	BE43754	16.1727	0.2013	0.973	1.14775E-14	9.69152E-16	BE43758	1.63761E-15	3.53685E-16
2	RZ-12-22	Speke moraine	BE43755	32.3243	0.2006	0.973	1.72402E-14	1.19007E-15	BE43758	1.63761E-15	3.53685E-16
3	RZ-12-24	Speke moraine	BE43756	23.8116	0.2013	0.973	1.85318E-14	9.2237E-16	BE43758	1.63761E-15	3.53685E-16
4	RZ-12-25	Speke moraine	BE43757	40.0454	0.2010	0.973	3.59382E-14	1.18435E-15	BE43758	1.63761E-15	3.53685E-16
Nyamugasani Valley											
5	RZ-15-10	Perched boulder	BE39810	100.945	0.0907	1.338	4.70348E-12	4.43266E-14	BE39812	3.81273E-15	6.15885E-16
6	RZ-15-11	Perched boulder	BE39811	102.028	0.091	1.338	4.51587E-12	3.13429E-14	BE39812	3.81273E-15	6.15885E-16
7	RZ-15-09	Perched boulder	BE39809	100.573	0.0916	1.338	4.30701E-12	4.65808E-14	BE39812	3.81273E-15	6.15885E-16
8	RZ-15-07	Perched boulder	BE39808	101.292	0.0881	1.338	1.94507E-12	1.93123E-14	BE39812	3.81273E-15	6.15885E-16
9	RZ-15-08	Perched boulder	BE40319	12.014	0.1650	1.340	1.78244E-13	3.36358E-15	BE40308	7.21905E-16	1.41075E-16
10	RZ-15-01	Cirque Bedrock	BE39531	100.57	0.0961	1.337	1.94043E-12	2.11829E-14	BE39534	6.99989E-15	5.814E-16
11	RZ-15-02	Cirque Bedrock	BE39532	100.79	0.0967	1.337	1.97014E-12	2.14812E-14	BE39534	6.99989E-15	5.814E-16
12	RZ-15-03	Cirque Bedrock	BE39533	101.33	0.0930	1.337	2.30326E-12	2.04419E-14	BE39534	6.99989E-15	5.814E-16

Table 2. Processing data and sample chemistry for all Bujuku and Nyamugasani valley samples.

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We do not correct ^{10}Be ages for the potential impacts of snow cover or vegetation. Snow does not persist for considerable lengths of time at the sample elevations due to warm daytime temperatures and intense solar radiation. Vegetation in the Rwenzori Mountains above ~4,000 m asl is sparse (Osmaston and Pasteur, 1972; Foster et al., 2001) and all samples were collected above this elevation. Some samples featured a patchy cover of lichen or moss (≤ 2 cm thick) and we avoided this where possible, although we note that a persistent cover of moss of 2 cm thickness would alter the resultant exposure ages by < 2% (Dunai, 2010; Plug et al., 2007). We also did not correct ^{10}Be ages for the potential influence of erosion, as samples did not show evidence that could be used to estimate quantitatively surface erosion rates. Previous applications of ^{10}Be dating in the Rwenzori suggest that raised quartz veins and rock surfaces on single moraine crests yield statistically similar ages (Jackson et al., 2019).

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Table 3: Rwenzori Surface-Exposure Ages

Map ID	Sample ID	Landform	Age (St)	± (int; St)	± (ext; St)	Age (LSDn)	± (int; LSDn)	± (ext; LSDn)
Bujuku Valley								
1	RZ-12-21	Speke moraine	360	30	40	370	30	40
2	RZ-12-22	Speke moraine	270	20	20	280	20	30
3	RZ-12-24	Speke moraine	400	20	30	410	20	30
4	RZ-12-25	Speke moraine	460	20	30	480	20	30
Nyamugasani Valley								
Map ID	*Sample ID*	*Landform*	*Age (St)*	*± (int; St)*	*± (ext; St)*	*Age (LSDn)*	*± (int; LSDn)*	*± (ext; LSDn)*
5	RZ-15-10	Perched boulder	12130	120	690	11510	110	680
6	RZ-15-11	Perched boulder	11360	80	650	11010	80	640
7	RZ-15-09	Perched boulder	10920	120	630	10700	120	630
8	RZ-15-07	Perched boulder	4520	50	260	4980	50	290
9	RZ-15-08	Perched boulder	6520	120	390	6590	130	400
10	RZ-15-01	Cirque Bedrock	5010	60	290	5400	60	320
11	RZ-15-02	Cirque Bedrock	5040	60	290	5430	60	320
12	RZ-15-03	Cirque Bedrock	5680	50	320	5930	50	350

Table 3. Cosmogenic ^{10}Be surface-exposure ages for samples from the Bujuku and Nyamugasani valleys. We report ages as calculated using both time-invariant ("St"; Lal, 1991; Stone, 2000) and time-variant ("LSDn"; Lifton et al., 2016) scaling with internal ("int") and external ("ext") error.

5 Results

5.1 Bujuku valley

We term the prominent Lac Gris stage moraine on the south-facing slope of Mt. Speke the 'Speke moraine' (Figures 2-3). The Speke moraine marks the first glacial deposit up valley of the Omurubaho-stage moraine dated to ~11.7 ka (Jackson et al., in review) and is ~300 m elevation downslope from the 1958 CE glacier extent (Whittow, 1963). The Speke moraine is also ~1.5 km up valley of the ~11.0 ka landslide that dams Lake Bujuku (Cavagnaro, 2017). The right- and left-lateral ridges of the Speke moraine are well preserved and have steep ice-contact slopes with more fan-like, low-angle ice-distal slopes. Four samples from the right-lateral ridge yield ^{10}Be ages between ~0.46 and 0.27 ka (RZ-12-21, 22, 24, 25; ~4,050 m asl)(Table 1).

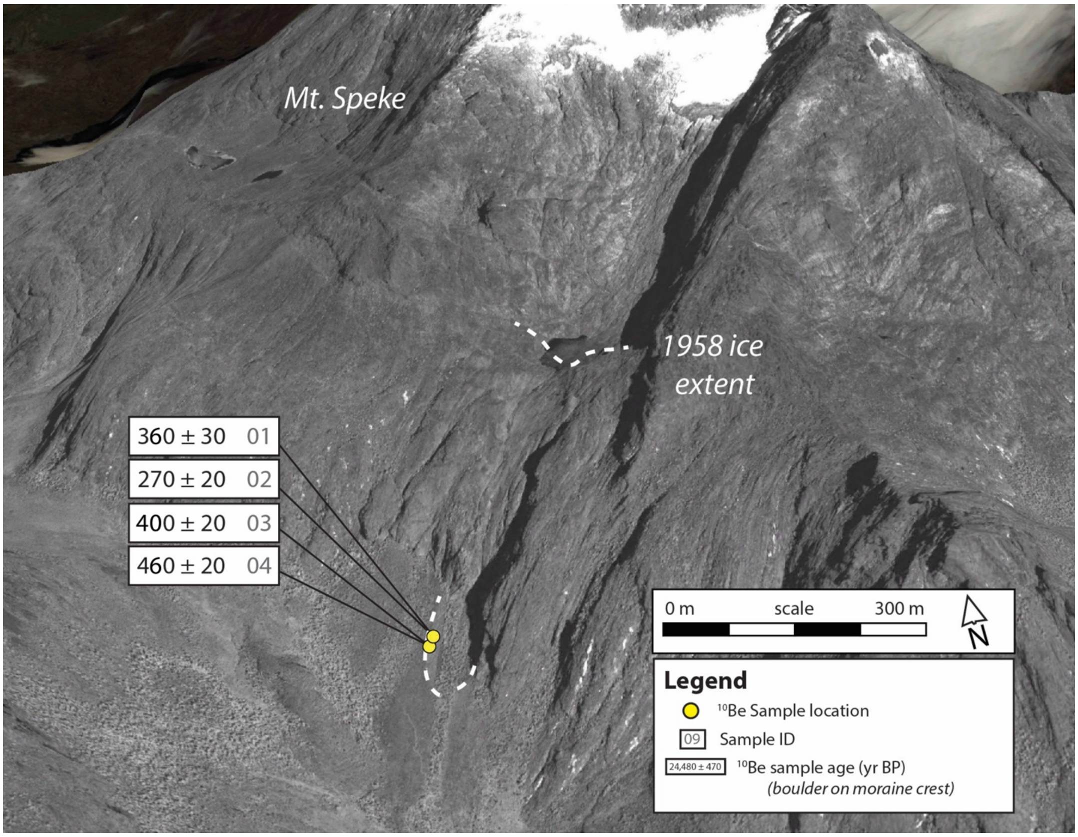

Figure 3. Mount Speke and ^{10}Be ages of the Speke moraine. Ages are shown in black with internal analytical uncertainties. Sample ID numbers as in Tables 1-3 are shown in grey. The ice-contact slope of the Speke moraine is outlined in dashed white, as is the documented 1958 ice margin ~ 300 m upslope (Whittow et al., 1963). Sample locations are mapped onto a 0.5 m-resolution Worldview-1 satellite image.

5.2 Nyamugasani valley

We dated five boulders on bedrock along an elevation transect on the south-facing slope of Mt. Weisman (Figure 4, Tables 1-3). The transect extends from ~4,400 to 4,490 m asl. All samples are from glacially molded, sub-rounded boulders except for sample RZ-15-08 which is from an angular boulder. Based on their size and position on the slope (i.e., away from the valley walls where rockfall may occur), we presume these boulders were deposited by a receding glacier. The two most down valley samples yield ^{10}Be ages of 12.1 ± 0.1 ka (RZ-15-10; 4,397m

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asl) and 11.4 ± 0.1 ka (RZ-15-11; 4,400 m asl). A third sample is located ~170 m up valley at ~4,430 m asl and dates to 10.9 ± 0.1 ka (RZ-15-09). Approximately 250 m farther up valley at ~4,490 m asl, two boulders on bedrock knobs yield ages of 4.5 ± 0.0 ka (RZ-15-07) and 6.5 ± 0.1 ka (RZ-15-08).

In addition to the elevation transect of boulders on bedrock, we measured ^{10}Be concentrations in three samples of the bedrock floor of the unoccupied cirque below the peak of Mt. Weisman (4,509-4,536 m asl)(Figures 2, 4). We term this feature the 'Thomson cirque'. The bedrock samples from Thomson cirque contain ^{10}Be concentrations between 1.94 and 2.03 x 10^{-12} atoms/gram (quartz), equivalent to ~5.0-5.7 thousand years of exposure (RZ-15-01, 02, 03)(Table 1, 3).

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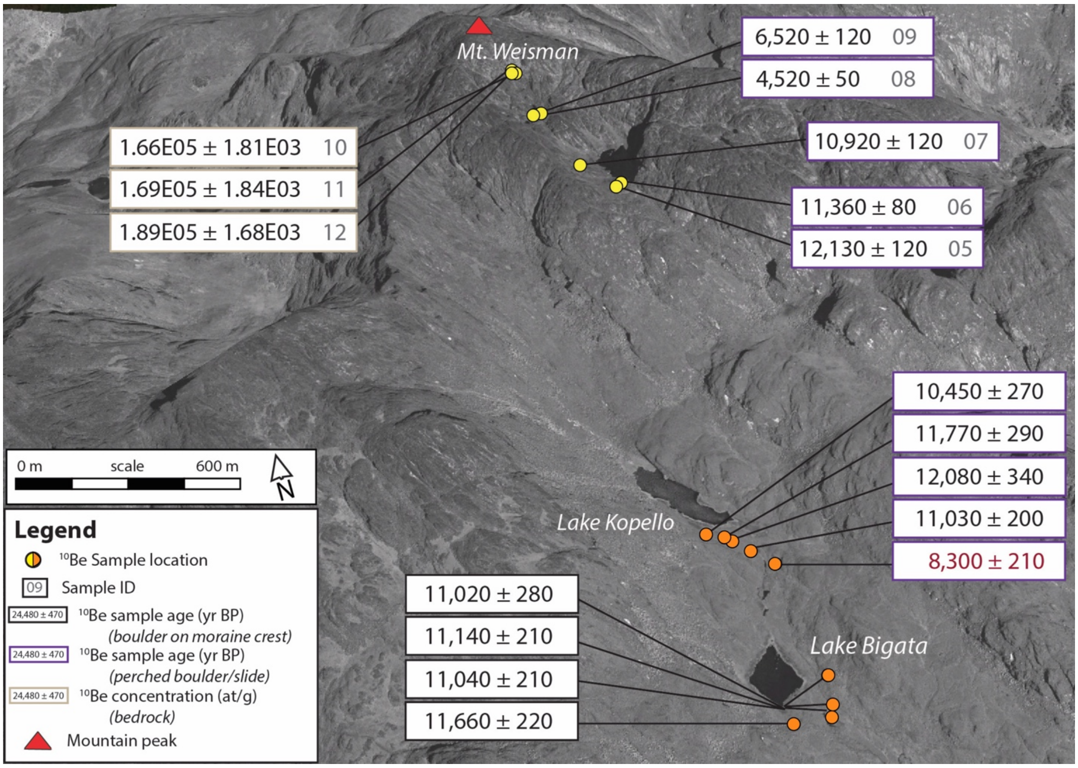

Figure 4. ^{10}Be ages and concentrations in the Nyamugasani valley. Ages are shown in black with internal analytical uncertainties. Sample ID numbers as in Tables 1-3 are shown in grey. Sample locations are marked by yellow circles and mapped onto a 0.5-m resolution Worldview-1 satellite image. Previously reported ^{10}Be ages from the moraine that dams Lake Bigata and from boulders on bedrock near the outlet of Lake Kopello are marked with orange circles (Jackson et al., in review). Ages considered to be outliers are shown in red.

6 Discussion

6.1 Holocene Glacial Fluctuations in the Rwenzori Mountains

The ^{10}Be ages from the Bujuku and Nyamugasani valleys suggest that glaciers in both catchments retreated rapidly during the Early Holocene. Based on the lack of glacial deposits in the Bujuku valley between the ~11.7 ka moraine and the Speke moraine, and the ~11.0 ka age of the landslide that dams Lake Bujuku (Cavagnaro, 2017), we suggest that the former Bujuku valley glacier retreated up the valley at, or shortly after, the onset of the Holocene. The landslide occurs ~1.5 km up valley of the ~11.7 ka moraine and is undisturbed, indicating that ice had

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retreated at least this distance up valley by ~11 ka and that ice remained up valley of this site throughout the Holocene. Although it is possible that wetland or colluvium deposits on the valley floor buried additional glacial deposits, there are no lateral moraines higher on the valley walls and no evidence of glacial readvance over these colluvial sediments.

The morphology of the Speke moraine in the Bujuku valley, with steep ice-contact slopes and more gentle ice-distal slopes (Figure 2), indicates that the lateral ridges formed as rock-fall debris from the slopes of Mt. Speke fell onto the former Speke Glacier surface and was transported supraglacially to the ice margin. The deposition of this rock-fall debris along the glacier margins produced the fan-like ice-distal slopes of the Speke moraine. Deposition ceased when the glacier receded and the moraine was abandoned at ~270-460 years ago.

Additional evidence for Early Holocene glacial recession in the Rwenzori comes from the Nyamugasani valley. The stratigraphically innermost moraine (i.e., farthest up valley) in the Nyamugasani valley dates to ~11.2 ka (Jackson et al., in review) (Figure 4). Approximately 0.5 km farther up valley, four boulders on a bedrock rise that dams Lake Kopello yield ages between ~12.1 and 10.5 ka (Jackson et al., in review). An additional ~1.6 km up valley from the Lake Kopello bedrock, glacially-transported boulders set down on bedrock yield ages between ~12.1 and 10.9 ka. Based on the statistical similarity of these sample ages, we interpret these samples to reflect rapid glacier recession from the innermost Nyamugasani valley moraine (~11.2 ka) during the Early Holocene. These data suggest that the valley was deglaciated to an elevation of ~4,430 m asl by at least ~10.9 ka.

Farther up valley, bedrock on the floor of Thomson cirque, below the south-facing peak of Mt. Weisman, has ^{10}Be concentrations equivalent to ~5.0-5.7 ka of net exposure (Figure 4). The cirque was occupied by the former Thomson Glacier until at least the mid 20th century

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(Meader, 1937; Whittow et al., 1963; Osmaston and Pasteur, 1972). This implies that the cirque was ice-free for some period of time before its occupation by Thomson Glacier (Doughty et al., in press). If we assume that ice cover during the LGM (Kelly et al., 2014; Jackson et al., 2019) was erosive enough to remove any pre-existing ^{10}Be from the bedrock surface, the measured bedrock ^{10}Be concentrations reflect the total period of exposure of the bedrock (i.e., ice-free conditions) after the LGM. More specifically, based on the Early Holocene age of moraines down valley (Jackson et al., in review), we suggest the Thomson cirque bedrock ^{10}Be concentrations indicate the net duration of bedrock exposure (~5.0-5.7 ka) during the Holocene.

This interpretation, and the observation that the cirque was occupied by Thomson Glacier during the early and middle 20th century, leads to one notable consequence. Namely, if the Thomson cirque was ice-free for ~5.0-5.7 kyr during the Holocene yet occupied by ice during at least a portion of Late Holocene time, this implies that ice had ablated away completely in the cirque at some point earlier in the Holocene before re-nucleating prior to the 20th century. This scenario may include multiple periods of glacial ablation and readvance, or a single period of ice-free conditions followed by Late Holocene re-nucleation. Although the timing of ice recession and re-nucleation within the cirque cannot be established with the data presented here, the bedrock ^{10}Be concentrations suggest that the cirque remained ice-free for a significant portion of the Holocene Epoch.

The two boulders on bedrock ~10-20 m downslope of the cirque (dated to ~4.5 and 6.5 ka; RZ-15-07, 08) suggest that the former Thompson Glacier extended to this downslope location during the Middle Holocene. However, the ^{10}Be ages of these boulders are similar to the exposure-age equivalent of the nearby cirque bedrock (~5.0-5.7 ka), which suggests that the boulders may contain inherited ^{10}Be. In this scenario, the boulders would have been plucked

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from the nearby cirque floor and transported a short distance (~100 m) by the former Thomson Glacier during a Late Holocene readvance. Alternatively, the boulders may have fallen onto the ice surface from the valley walls above and escaped sub-glacial erosion prior to deposition. Sample RZ-15-08 (~6.5 ka) is from an angular boulder, which may indicate that it was transported supraglacially after falling onto the former ice surface from the valley headwall. In contrast, sample RZ-15-07 (~4.5 ka) was sub-rounded in appearance and so was presumably eroded during glacial transport. These sampled boulders are located near the early-20th century snow or ice margin, as shown in photographs from 1937 CE (Meader, 1937). The proximity of the samples to the early 20th century snow/ice margin supports the interpretation that the boulders were deposited during a Late Holocene advance of Thomson Glacier, but more data are needed to determine the depositional histories of these samples. Due to the uncertainties associated with these samples, we do not use their ^{10}Be ages in any subsequent interpretations.

Overall, ^{10}Be ages from the Bujuku and Nyamugasani valleys suggest glacial recession occurred in both catchments during the Early Holocene and that glaciers in these valleys then retreated to, or inboard of, their maximum late-19th or early-20th century extents (Figure 5). In the Nyamugasani valley, ^{10}Be concentrations measured in bedrock samples from the floor of Thomson cirque suggest ~5-6 kyr of net exposure of surfaces that were glacierized in the first half of the 20th century. The results do not preclude the possibility that glaciers persisted on the high Rwenzori peaks throughout the Holocene, albeit inboard of their late 19th century positions. However, the data suggest that glaciers in the Bujuku and Nyamugasani valleys did not advance beyond their Late Holocene maximum ice positions during Early or Middle Holocene time.

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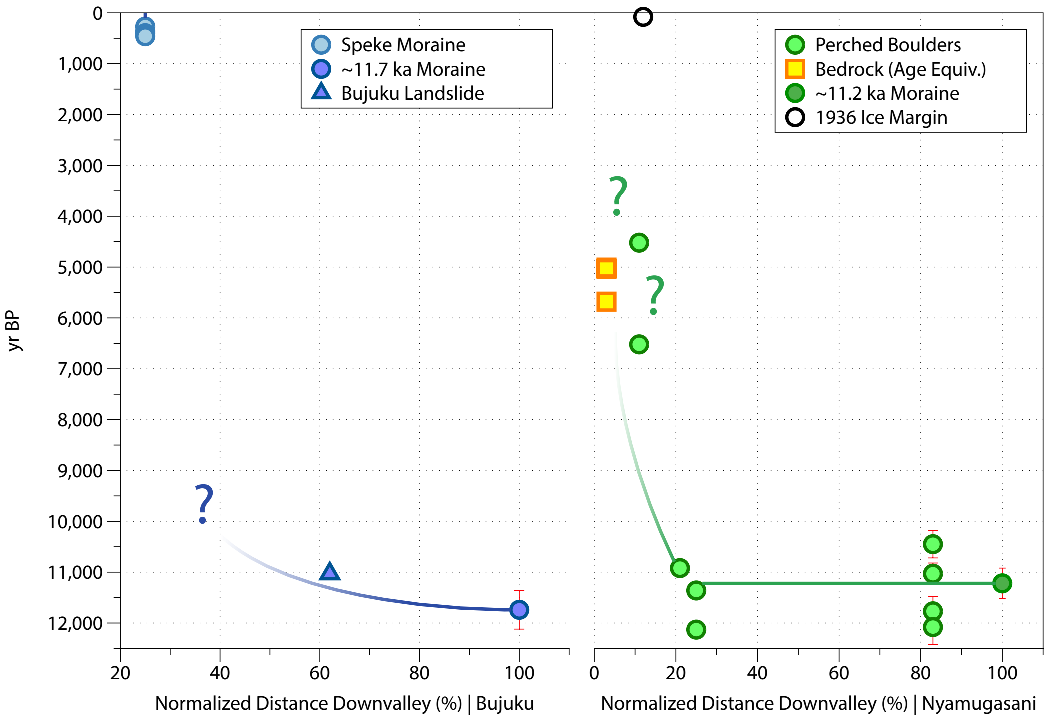

Figure 5. Normalized glacial extent in the Bujuku and Nyamugasani valleys during the Holocene. Lines indicate reconstructed glacial extent, question marks highlight periods where glacial extent is uncertain. (left) In the Bujuku valley, the maximum dated Holocene position (~11.7 ka moraine; Jackson et al., in review) is roughly 1.5 km down valley of the ~11 ka landslide which dams Lake Bujuku (Cavagnaro, 2017) and over 3 km down valley from the Speke moraine. (right) In the Nyamugasani valley, the most up valley moraine in the catchment dates to ~11.2 ka. Boulders set down on the Kopello ridge yield ages between ~12.1-10.5 ka. The Nyamugasani transect boulders yield similar ages to those on the Kopello ridge, but are 1.8 km farther up valley. Yellow squares mark the exposure-age equivalents (^{10}Be concentration) of samples of bedrock from Thomson cirque, although we emphasize that these ages represent the cumulative exposure duration (likely since the LGM), and do not necessarily reflect the most recent period of exposure.

6.2 Patterns of East African Glaciation and Temperature during the Holocene

Although sensitive to precipitation, humidity, aspect, and hypsometry, glaciers in the 'humid' inner tropics (~10ºN-10ºS) are influenced primarily by temperature (e.g., Sagredo et al., 2014). This includes glaciers in the Rwenzori (Taylor et al., 2006; Russell et al., 2009; Kelly et al., 2014; Doughty et al., in press). The hypothesis that glacial fluctuations in the Rwenzori during the Holocene are controlled by temperature is supported by a comparison of our data with

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paleolimnological records of regional precipitation and temperature (Figure 6). Organic geochemical (branched glycerol dialkyl glycerol tetraethers; brGDGTs) proxy temperature records from four East African lakes and the Congo River Basin indicate temperatures warmed by ~1 ºC from ~12-11 ka, were similar to Late Holocene values from ~11 to 8 ka, and then rose to a mid-Holocene thermal maximum between 6 and 5 ka, before cooling to Late Holocene values (Ivory et al., 2017, and references therein). The Early Holocene is also marked by the African Humid Period (AHP; ~11.6-5.0 ka), a time of elevated precipitation across tropical Africa (Garcin et al., 2007) reflected in precipitation reconstructions from Lakes Victoria and Tanganyika, the Nile River Delta, and at the foot of the Rwenzori Mountains at Lake Edward (Russell et al., 2003a; Buening and Russell, 2004; Tierney et al., 2008; Berke et al., 2012; Weldeab et al., 2014). Declining precipitation associated with the end of the AHP began at ~5.2 ka in western Uganda, recorded by rising salinity in Lake Edward (Russell et al., 2003b, Russell and Johnson, 2006), roughly coincident with the onset of cooling in East Africa. Rwenzori glaciers thus retreated during a wet and warming Early Holocene and remained near or inboard of their Late Holocene maxima during the warm, drying Middle Holocene. The end of the AHP and the onset of cooler conditions in East Africa broadly coincides with the transition to more erosive glacial margins on Mt. Kenya (Karlen at el., 1999) and with the beginning of extended net accumulation on the Kilimanjaro Ice Cap after ~4 ka (Gabrielli et al., 2014). We suggest that regional temperatures were sufficiently high during the Early and Middle Holocene to dominate glacial mass balance in the African tropics in spite of elevated precipitation.

The pattern of Holocene glacial fluctuations inferred in the Rwenzori is broadly consistent with reconstructed glacial histories from elsewhere in East Africa. In Ethiopia, Uganda, and Kenya, glaciers retreated either during or prior to the Early Holocene (Hamilton and

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Perrot, 1982; Shanahan and Zreda, 2000; Tiercelin et al., 2008) and remained near or inboard of reconstructed Late Holocene positions throughout Holocene time. Although disputed (Mahaney, 1989), there is some evidence for a Middle Holocene readvance of glaciers on Mt. Kenya (Perrot, 1982; Johansson and Holmgren, 1985; Karlen et al., 1999). The ages of ~4.5-6.5 ka of perched boulders in the Rwenzori's Nyamugasani valley may indicate a similar Middle Holocene readvance, but to a position near or inboard of the maximum Late Holocene extent (Meader, 1937; Osmaston and Pasteur, 1972). Acknowledging this uncertainty, we suggest that the Rwenzori chronology is generally representative of Holocene glacial fluctuations in tropical Africa.

Our comparison of Rwenzori glacier extents with regional GDGT-based temperature records indicates that ice masses did not respond linearly to temperature. For example, GDGT temperature reconstructions suggest regional temperatures at ~11 ka were similar to temperatures at ~1 ka-present (Ivory et al., 2017). In contrast, glacial margins during the Early Holocene were ~330 m lower in the Nyamugasani valley and ~490 m lower in the Bujuku valley than during the Late Holocene (Figure 6). This difference may be due to the fact that there was more substantial, if retreating, ice volume in the Rwenzori at ~11 ka relative to the Late Holocene, and that Late Holocene ice was re-nucleating or re-advancing after a period of sustained ablation. Alternatively, this difference may reflect two distinct equilibrium glacial mass balances at similar temperatures but with different precipitation regimes and radiative boundary conditions. Modeling suggests that past changes in Rwenzori equilibrium-line altitude are only weakly influenced by precipitation amount, and that the large (~60% increase; Buening and Russell, 2004) changes in precipitation in western Uganda during the AHP are insufficient to explain the large downslope movement of Rwenzori glaciers observed at ~11 ka (Doughty et al., in press).

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Early Holocene glacial recession is coincident with both increasing atmospheric CO_2 (Monnin et al., 2001)(Figure 6), which increases surface longwave radiation, and with rising mean-annual equatorial insolation after ~10 ka (Berger and Loutre, 1991). Because tropical glaciers undergo ablation throughout the year, mean-annual radiation (both insolation and longwave) influences glacial mass balance in the tropics (Kaser and Osmaston, 2002) and may have played a role in Holocene glacial extents. However glaciers in the Rwenzori and elsewhere in East Africa apparently re-nucleated or readvanced during the Late Holocene, whereas atmospheric CO_2 and mean annual insolation continued to rise. Alternatively, seasonal, rather than mean-annual, insolation is another potential forcing mechanism for tropical glacial fluctuations. The sun passes directly over the equator twice each year in September and March, coincident with the twice-annual equatorial wet season (Sept.-Nov. and March-May) and the passage of the Intertropical Convergence Zone over the equator (Singarayer and Burrough, 2015). Modeling studies of ice cliffs on Kilimanjaro (Mölg et al., 2003a) and of modern Rwenzori glaciers (Mölg et al., 2003b) suggest that a transition to more regionally arid conditions after ~1880 CE reduced cloud cover and increased the amount of net annual solar radiation impacting glacier surfaces during dry seasons, which may have encouraged further ablation after the initiation of recent Rwenzori deglaciation ~1870 CE (Russell et al., 2009). Neither of the Rwenzori dry seasons (June-Aug and Dec-Feb) had insolation minima during Middle Holocene (Figure 6), and so the Late Holocene re-nucleation or readvance of African glaciers is difficult to reconcile with this mechanism. Elevated wet season (Sept.-Nov.) insolation could play a role, but Sept. and March insolation trends counteract each other during the Holocene. More work is needed to determine the discrete influences on glacial mass balance over millennial timescales during the Holocene in the East African tropics.

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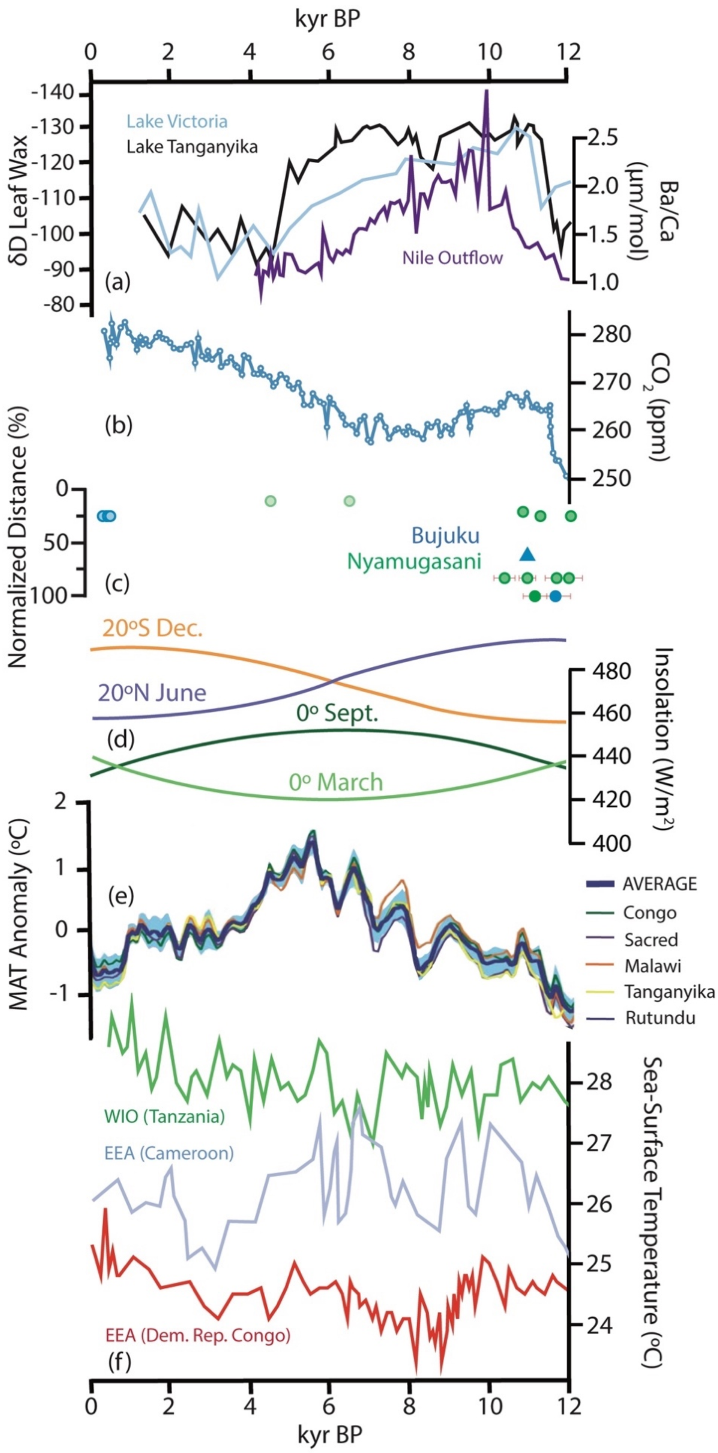

Figure 6. East African climate during the Holocene. (a) Precipitation (δD leaf wax) records from Lakes Victoria (light blue) and Tanganyika (black) and East Asian monsoon intensity (purple; Ba/Ca) from the Nile Delta (Tierney et al., 2008; Berke et al., 2012; Weldeab et al., 2014); (b) Atmospheric CO_2 (Monnin et al., 2001); (c) Normalized glacier distance down valley in the Nyamugasani (green) and Bujuku (blue) valleys in the Rwenzori Mountains as in Figure 5.; (d) Tropical Holocene insolation at 20ºN (June; blue), 20º S (Dec.; orange), and º0 (Sept. (dark green) and March (light green) (Berger and Loutre, 1991); (e) Holocene terrestrial temperatures reconstructed from organic lacustrine sediments, bootstrapped and plotted as anomaly using the mean value over the last 2 ka (Ivory et al., 2017); (f) Sea-surface temperature records from the equatorial Western Indian Ocean (WIO; green; Romahn et al., 2014) and the Eastern Atlantic (EEA; light blue, red; Weldeab et al., 2005).

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6.3 Tropical South American Glacial Fluctuations and Implications for Holocene Climate

Reconstructions of Holocene glacial fluctuations in South America show broad similarities in the timing and magnitude of tropical Andean glacial extent change with records of glacial extent from tropical Africa. Glaciers in the northern and southern tropical Andes retreated during the Early Holocene and remained near or within their Late Holocene extents throughout much of the Holocene Epoch (e.g., Jomelli et al., 2014; Stansell et al., 2017). ^{10}Be dating of Late Holocene moraines documents glacial advances in the South American tropics after ~2-1 ka (Solomina et al., 2015), and many glaciers only reached their Late Holocene maximum extents within the last ~700-500 years (Licciardi et al., 2009; Jomelli et al., 2011; Jomelli et al., 2014; Stansell et al., 2015; 2017). Sediment-flux analyses and radiocarbon dating of glacially influenced lake sediments, however, indicate that glaciers were more erosive, and perhaps more extensive, after ~5 cal kyr BP relative to earlier Holocene time (e.g., Rodbell et al., 2008). Lake sediment records from sites in the Eastern Cordillera and Cordillera Blanca of Peru suggest that glaciers in these regions advanced and retreated multiple times during the Holocene, with more advanced ice positions taking hold after ~4-2 cal kyr BP (Rodbell et al., 2008; Stansell et al., 2015; 2017). ^{10}Be dating and geomorphic mapping of moraines from these sites also suggest that glaciers generally remained inboard of their Late Holocene maxima until at least ~1 ka (Stansell et al., 2015; 2017). Altogether these data suggest that, after a period of Early Holocene retreat, glacial margins in the South American tropics were more dynamic after ~ 5 ka relative to the Early Holocene but did not achieve their maximum extents until after ~1 ka.

The broad similarity of Holocene glacial fluctuations in tropical East Africa and South America suggests that tropical glaciers responded to a common, pan-tropical forcing mechanism during the Holocene. Based upon prior observational and modeling work assessing controls on

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glacial mass balance across the South American Cordillera (Sagredo and Lowell, 2012; Sagredo et al., 2014), we suggest that temperature was the primary control on glacial extents across the low latitudes during the Holocene. This hypothesis requires that Holocene temperatures were similar across the tropics, and that whatever mechanism or mechanisms affected temperatures in one region had similar impact elsewhere. As in East Africa, radiative forcing from atmospheric CO_2 and mean-annual or seasonal equatorial insolation cannot easily explain the pattern of glacial fluctuations in the South American tropics. This highlights an avenue for future research through both ground-based geologic investigation as well as through climate and mass-balance modeling. Determining the mechanisms that influence temperatures in the low latitudes is crucial for understanding better the context for modern warming and the sensitivity of tropical glaciers to future climate change.

7 Conclusions

Twelve new ^{10}Be ages of glacial features in the Rwenzori Mountains indicate that glaciers retreated rapidly during the Early Holocene and remained near or within their Late Holocene extents through much of the Holocene Epoch. These results are broadly similar to records of past glacial fluctuations elsewhere in tropical East Africa. Based on a comparison of tropical East African glacial fluctuations with regional climate records, we suggest that temperature acted as the primary control on glacial fluctuations throughout the Holocene.

Glacial chronologies from tropical Africa and South America indicate that Early Holocene glacial recession was followed by a period of generally restricted ice extents until at least ~ 1 ka. The coherence of tropical African and South American glacial fluctuations suggests that glaciers across the low latitudes responded to a common forcing during the Holocene, which

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we suggest was most likely temperature. However the ultimate driver of Holocene temperatures, and thus glacial extent, remains enigmatic. Understanding the controls on low-latitude temperature is crucial for assessing and contextualizing modern climate variability and for determining the sensitivity of tropical glaciers to changing climate conditions. Although more work is needed to assess the sensitivity of low-latitude temperature to discrete forcing mechanisms, the results presented here highlight the utility of glacial records in assessing past terrestrial temperature change in tropical regions.

Data Availability

All analytical information and metadata associated with newly reported cosmogenic nuclide measurements are included within the manuscript tables (Tables 1-3). All reported cosmogenic nuclide ages are as calculated using the ICE-D calibration database (calibration.ice-d.org) and version 3 of the online exposure-age calculator as described by Balco et al., 2008 and subsequently updated (hess.ess.washington.edu).

Author Contribution

MK, JR, and AD designed the project. BN coordinated the project in Uganda. MJ, AD, JR, and MK collected samples. MJ and JH processed samples for ^{10}Be dating and SRHZ measured beryllium ratios. MJ, MK, AD, and JR analyzed results. MJ wrote the paper with contributions from all authors.

Competing Interests

The authors declare that they have no competing interests.

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