Recent glacial recession and its impact on alpine riverflow in the Rwenzori Mountains of Uganda

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\textbf{A B S T R A C T}

The limited number and duration of hydrological measurements in the East African Highlands inhibit current understanding of the impact of glacial recession on alpine riverflow. From historical records and surveys conducted in the dry season of 2005 and wet season of 2007, we report (1) recent changes in the terminal positions of large valley glaciers (Speke, Elena) and (2) spot measurements of alpine riverflow along altitudinal transects of the principal river (River Mubuku) draining alpine icefields in order to assess the relative contribution of icefields and underlying ecotones to river discharge. Observed acceleration in the rates of termini retreat of the Speke and Elena glaciers since the late 1960s is attributed, in part, to the convex–concave slope profile in which these valley glaciers reside. We show that current glacial recession has a negligible impact on alpine riverflow. Spot measurements of meltwater discharges indicate that icefields contribute considerably less than 2% of the river discharge at the base of the Rwenzori Mountains during both dry and wet seasons. An anomalously high specific discharge of the River Mubuku (1730 mm a\textsuperscript{−1}) arises from high rates of precipitation exceeding 2000 mm a\textsuperscript{−1} below alpine icefields within Heath-moss and Montane forest ecotones that occupy more than half of the river’s gauged catchment area. For other tropical alpine icefields representing a tiny fraction (<1%) of alpine river catchment areas (e.g. Irian Jaya, Kilimanjaro, Mount Kenya), glacial meltwater discharges are similarly expected to contribute a negligible proportion of alpine riverflow.

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\section{1. Introduction}

Tropical alpine glaciers form important reservoirs of fresh water that store seasonal inputs of precipitation, associated with the movement of the Inter-tropical Convergence Zone (ITCZ), and sustain meltwater discharges during drier periods. In the South American Andes, glaciers serve to regulate alpine riverflow upon which downstream communities rely for year-round water supplies (Bradley et al., 2006). Meltwater discharges from alpine icefields covering \textasciitilde 10\% of the mesoscale Rio Santo basin of Peru are estimated to provide at least 12\% of the annual river discharge (Mark and Seltzer, 2003) and \textasciitilde 40\% of the dry-season river discharge (Mark et al., 2005). Glacial recession since the 19th century has led to increased seasonality and overall reductions in riverflow (Mark and Seltzer, 2003; Bradley et al., 2006).

In the East African Highlands, the observed reduction in areas covered by glaciers since the early 20th century (e.g. Hastenrath, 1984; Kaser and Noggler, 1996; Kaser and Osmaston, 2002; Taylor et al., 2006) has led to concerns over the impact of deglaciation on river discharge during the dry season (Gasse, 2002; Thompson et al., 2002) and the risk of flooding during the rainy season (Uganda Meteorology Department, 2006). Desanker (2002) asserts that several rivers on Kilimanjaro are drying out during the dry season due to the loss of the frozen reservoir. In contrast, Temple (1968) and Kaser et al. (2004) contend that glacial meltwater discharges provide insignificant contributions to alpine riverflow in the Rwenzori Mountains and Kilimanjaro, respectively.

The limited number and duration of hydrological measurements in the East African Highlands inhibit current understanding of the impact of shrinking icefields on alpine riverflow. In the Rwenzori Mountains, no measurements of riverflow have previously been collected above its base with the exception of a few spot measurements of glacial meltwater discharges summarised by Temple (1968). We report spot measurements of riverflow in the Rwenzori Mountains along altitudinal transects of the principal river (River Mubuku) draining alpine icefields during both dry and wet seasons. We use this new dataset together with historical records to assess the relative contribution of icefields and underlying ecotones to river discharge. We also report on recent changes in the terminal positions of regularly monitored valley glaciers.
2. Hydrology of the Rwenzori Mountains

The Rwenzori Mountains are situated within the western arm of the East African Rift System (Fig. 1a) and comprise an uplifted block (horst) of Precambrian crystalline rocks. Occupying an area of 3000 km², the horst is bounded to the north and south by grabens that contain Lakes Albert and Edward, respectively. The Rwenzori horst tilted up in an ESE to WNW direction (Fig. 2), 4 km above the surrounding peneplain in the Late Pliocene (Taylor and Howard, 1998). Alternating cycles of glacial and fluvial erosion, extensively reviewed by Osmaston (1989), produced deeply incised valleys. Catchment areas draining eastwards are considerably larger than those draining to the west due to the orientation of the horst's tilt. From moraine evidence, Osmaston (2006) estimates that glaciers covered ~260 km² between 10 and 20 ka before present (BP) (Last Glacial Maximum) and ~10 km² between 100 and 200 a BP (Little Ice Age).

The precise onset of modern glacial recession in the Rwenzori Mountains remains unclear. Several authors (Hastenrath, 2001; Mölg et al., 2003, 2006; Kaser et al., 2004) contend that deglaciation started around 1880 AD as a result of an abrupt reduction in precipitation inferred from a reconstruction of the levels of Lake Victoria over the 19th century (Nicholson and Yin, 2001). Recent palaeolimnological evidence (Russell et al., 2008) suggests that glacial recession started slightly earlier between 1860 and 1870 AD similar to other tropical alpine icefields. Field research carried out in the 1950s (Menzies, 1951; Bergstrøm, 1955; Whittow et al., 1963), early 1990s (Kaser and Noggler, 1991, 1996; Talks, 1993) and from 2003 to 2005 (Taylor et al., 2006) indicate that the area covered by alpine glaciers has reduced from 7.5 km² in 1906 to <1 km² in 2003.

Glaciers currently occur on three mountains: Stanley, Speke and Baker. Over the last century, glaciers and their meltwater flows formed headwaters of primarily three rivers in the Rwenzori

![Diagram showing drainage and glaciers in the Rwenzori Mountains](image_url)

**Fig. 1.** (a) Map of Uganda showing the location of the Rwenzori Mountains in Uganda and regional meteorological stations; (b) Landsat7 satellite image showing the Rwenzori horst in relation to Lakes George and Edward as well as the orientation of the cross-section (X-X') in Fig. 2; and (c) map of glacial extent and drainage in the Central Rwenzori Massif (redrawn and adapted from Osmaston and Kaser, 2001) showing the direction of meltwater discharges and location of river discharge monitoring stations.
Mountains: the River Mubuku that flows eastward in the Republic of Uganda and Rivers Butawu and Lusilube which drain westward in the Democratic Republic of Congo (Figs. 1c and 3). Of the remaining glaciers in the Central Rwenzori Massif (Fig. 1c), most of the largest including East Stanley (E), Speke (A), Vittorio Emanuele (B), and Margherita (G) glaciers form headwaters of the River Mubuku.

Precipitation in the Rwenzori Mountains is bimodal; wetter periods occur from March to May and August to November. Apart from the seasonal control on precipitation exerted by movement of the ITCZ, there is a strong orographic effect on local precipitation. Mean annual precipitation from 1964 to 1995 recorded at Kilembe (Fig. 3) at an elevation of 1370 m above mean sea level (mamsl) is 1540 mm a\(^{-1}\) whereas this flux drops to 890 mm a\(^{-1}\) just 11 km away but 410 m lower in elevation at Kasese Airport (960 mamsl). Osmaston (1989) collected the only sustained measurements of precipitation at four locations in the Rwenzori Mountains from 1951 to 1954 at higher elevations than Kilembe. These observations similarly show pronounced variations in mean annual precipitation with altitude from 1951 to 1954 (Fig. 2). From the base of the mountains around 1250 mamsl, precipitation was observed to increase with rising elevation from 1150 mm a\(^{-1}\) to a maximum of 2600 mm a\(^{-1}\) at Lake Bujuku in the Afroalpine zone. Above this, precipitation decreased to 2000 mm a\(^{-1}\) at Lake Bujuku in the Heath-moss forest zone. Above this, precipitation decreased to 2000 mm a\(^{-1}\) at Lake Bujuku in the Afroalpine zone (3990 mamsl) within the Central Rwenzori Massif.

3. Methodology

Historical records of riverflow draining alpine areas of the Rwenzori Mountains were supplied by the Water Resources Management Department of Uganda. Spot measurements of riverflow in the River Mubuku were collected at six locations ranging in elevation from 2845 to 4104 mamsl (Figs. 1 and 3) during one dry season in 2005 (25 January–2 February) and one wet season in 2007 (20–24 April). Due to the highly turbulent nature of alpine stream meandering, hydraulic geometry was typically 100–500% greater than background. EC was reliably measured using an electrical conductivity (EC) meter. All EC measurements were compensated for substantial changes in water temperature (3–22 °C) within the alpine environment and were recorded in terms of a standard temperature of 25 °C. Calibration of the EC meter was conducted daily against prepared standards (10, 20, 50 and 100 mg L\(^{-1}\)) in order to account for potential drift in meter readings. Background EC measurements of riverflow varied from 9 to 61 µS cm\(^{-1}\) depending upon season and river elevation. Pre-weighed, dry quantities of NaCl ranging from 0.25 to 0.50 kg were injected to the river inducing peak EC measurements that were typically 100–500% greater than background. EC was recorded every 10 s at a distance of 20–25 m downstream from injection (equivalent to 20–30 channel widths). All salt dilution gaugings were done in duplicate; calculated uncertainty in flow estimates was ±10%. Changes in the terminal positions of the two largest valley glaciers in the Rwenzori Mountains (Speke, Elena) were surveyed in relation to past field markers as well as those established by our surveys using a measuring tape and hand-held GPS (Etrex Summit).

4. Results and discussion

4.1. Retreat of Speke and Elena valley glaciers since 1990

Continued retreat of the terminal positions of the Speke and Elena glaciers is observed (Fig. 4) relative to positions reported in 1990 (Kaser and Noggler, 1991, 1996; Kaser and Osmaston, 2002). The Speke Glacier has retreated 380 m between 1990 and 2003 whereas the Elena Glacier has retreated 320 m between 1990 and 2007. For the more frequently monitored Speke Glacier, acceleration in the rate of termini retreat is evident from the late 1960s to present. The implication that the rate of glacier mass losses in the Rwenzori Mountains has recently increased is not, however, supported by changes in glacial area reported by Taylor et al. (2006). These data show that the rate of decline in glacial extent since 1990 is consistent with the overall trend of ~0.7 km\(^2\) per decade since 1906. Rapid retreat in the terminus of the Speke Glacier followed prolonged thinning over the entire glacier (Kaser and Noggler, 1996) which, residing on a convex–concave slope profile, eventually resulted in the separation of the valley glacier’s tongue from its area of accumulation (Fig. 5). A similar sequence of thinning followed by rapid terminal retreat (76 m a\(^{-1}\) from 2005 to 2007) has more recently been observed for the Elena Glacier.
4.2. Contributions of receding glaciers to alpine riverflow

Regular monitoring of riverflow at the base of the Rwenzori Mountains is currently restricted to the River Nyamagasani though historical records exist for Rivers Mubuku, Rwimi and Rukoki (Fig. 3). Inconsistencies and gaps identified in these records (Taylor and Aggrey, 2004) limit the analysis of historical data to Rivers Mubuku and Nyamagasani (Fig. 6). The old gauge for the River Mubuku (station 7 in Fig. 3) has a catchment area of 256 km² with a mean discharge from 1954 to 1965 of 14 m³ s⁻¹ (data gaps occur during the years 1955, 1959 and 1960). This period includes the anomalously wet conditions from 1961 to 1963 when the level...
of Lake Victoria and the River Nile in Uganda rose by 2.5 m (Lamb, 1966; Kite, 1981). As a result, the mean discharge of the River Mubuku over this period may slightly exceed the long-term mean. Based on a complete record of observations in 2000 for a slightly smaller catchment area (246 km²) gauged at Bugoye (station 8 in Fig. 3), mean discharge of the River Mubuku is 12 m³ s⁻¹. Over the period between these observations, no significant temporal trends (at a 95% confidence interval) in precipitation are evident from records at Kilembe (1949–1998) and Kasese (1964–2006) (stations 9 and 10 in Fig. 3). The mean specific discharge of the River Mubuku from 1954 to 1965 is 1730 mm a⁻¹, more than three times that of the River Nyamagasani (493 mm a⁻¹) to the south (Fig. 3) over the same period. As the River Mubuku is the primary catchment still to have its headwaters supplied by glacial meltwaters, the presumption that a substantial proportion of the river’s discharge derives from glacial meltwater discharges (e.g. Uganda Meteorology Department, 2006) likely derives from its disproportionately high specific discharge. Spot measurements of alpine riverval flow summarised in Fig. 7 and Table 1, challenge this assumption.

Measured glacial meltwater fluxes down gradient from the Speke Glacier (station 1, Fig. 1), the largest valley glacier in the Rwenzori Mountains, on 28 January 2005 (dry season) and 21 April 2007 (wet season) are 0.002 and 0.017 m³ s⁻¹, respectively. Measurements were taken during the late afternoon (3–4 pm) when meltwater discharges are generally highest and follow by 1–3 h diurnal maxima in temperature and insolation (Whittow et al., 1963).
Spot observations are generally consistent with, but slightly lower than, historical data from Whittow et al. (1963) who observed a mean meltwater discharge of 0.019 m$^3$s$^{-1}$ over a 12-day period during the dry season in 1959. Assuming that our observations are within an order of magnitude of the seasonal mean flux, these fluxes represent between 0.01% and 0.2% of the mean discharge of the River Mubuku recorded at the base of the Rwenzori Mountains (station 7 in Fig. 3) during the dry season (18 m$^3$s$^{-1}$), and wet season (10 m$^3$s$^{-1}$), respectively. Cumulative meltwater discharges from approximately half of the remaining icefields in the Rwenzori Mountains to the River Mubuku together with contributions from a non-glaciated catchment area of 4.9 km$^2$ are aggregated at Lake Bujuku (Fig. 1c). Spot measurements of the discharge at the lake’s outlet (station 2 in Fig. 1c) during the dry and wet season constitute between 0.5% and 2% of the river’s mean discharge (Fig. 7). With an estimated annual precipitation of 2000 mm a$^{-1}$ at Lake Bujuku (Fig. 2), meltwater contributions from glaciers necessarily amount to considerably less than the measured outflow from Lake Bujuku (0.06–0.30 m$^3$s$^{-1}$) and are expected to be <0.5% of the river’s discharge at the base of the mountain even if limited glacial meltwater contributions from Mount Baker (site 5, Fig. 3) as well as the Vittorio Emanuele and Johnston glaciers on Mount Speke are considered.

The discharge profile of River Mubuku (Fig. 7) reveals a substantial increase in discharge below the glaciers in the Heath-moss forest zone (3000–4000 mamsl) where the catchment area expands from 15% to 46% and precipitation is highest (2600 mm a$^{-1}$). Hypsographic curves of catchment area for the Rivers Mubuku and Nyamagasani basins (Fig. 6) show that >70% of the River Mubuku basin resides within the Montane forest, Heath-moss forest and Afroalpine ecotones where mean annual precipitation exceeds 2000 mm a$^{-1}$. In comparison, >70% of the River Nyamagasani basin lies below these ecotones within the grasslands where mean annual precipitation is 1150 mm a$^{-1}$. The relatively higher proportion of orographic precipitation that falls in the River Mubuku basin (mean catchment $P = 1540$ mm a$^{-1}$), accounts, in part, for observed differences in river discharge. As more than half of the River Mubuku basin lies above 2800 mamsl where observed water temperatures are ~10 °C and more than half of the River Nyamagasani lies below 1500 mamsl where water temperatures are ~17 °C, proportionately greater evaporative losses in the River Nyamagasani are also expected to account for some of the difference in the mean discharge between these neighbouring catchments.

The negligible contribution of glacial meltwaters to alpine riverflow deduced in the Rwenzori Mountains is expected to apply to other tropical alpine catchments where glaciers occupy a tiny proportion (<1%) of the basin area (i.e. Irian Jaya, Kilimanjaro, Mount Kenya). On Kilimanjaro, Hemp (2005) cites an unpublished estimate of an annual meltwater discharge of $10^6$ m$^3$a$^{-1}$ (~0.03 m$^3$s$^{-1}$) from the Southern Icefields that are similar in size (~1.3 km$^2$) to the Rwenzori icefields. Reported reductions in dry-season riverflow on Kilimanjaro (Desanker, 2002) are, therefore, likely to derive from declining rainfall and changes in land use. Hemp (2005) reports declining lowland precipitation of between 27% and 38% over the last century for three stations around the

**Fig. 6.** Longitudinal trends in deviations from mean riverflow observed at the base of the Rwenzori Mountains from 1952 to 1978. Missing data for the Rivers Mubuku and Nyamagasani reflect incomplete discharge records for these calendar years. Calculated errors derive from uncertainty in the derivation of the rating curve.
base of Kilimanjaro (Moshi, Kilema Mission, Kibosho Mission). In contrast, analysis of lowland (<2000 masl) records of precipitation in western Uganda (Fig. 1a) over the 20th century fails to detect significant downward trends (Fig. 8). Small but statistically significant trends of increasing precipitation (at a 95% confidence interval) are observed at Fort Portal (1903–1978) and Mbarara (1904–1999). On Kilimanjaro, rapid loss of montane and cloud forest has also reduced both fog interception and canopy water storage (Hemp, 2005). In contrast, deforestation within catchments downslope of the icefields on the Rwenzori Mountains has largely been prevented as land above 1700 masl has been protected from encroachment through its designation as a National Park and World Heritage Site in 1991 (Osmaston, 2006) and, prior to this, as a forest reserve.

Fig. 7. Spot measurements of river discharge during the dry season (2005) and wet season (2007) as a percentage of mean discharge for the dry season (February, 1954–1965) and wet season (October, 1954–1965); hypsographic curves for the Rivers Mubuku and Nyamagasani are plotted along the same ordinate axis. The number of each river discharge measurement station (locations in Figs. 1 and 3) is given in parentheses by elevation.

Table 1
Spot measurements of surface discharge (Q) in the River Mubuku basin together with the proportion of the catchment covered by glaciers. Site locations in parentheses are shown in Figs. 1 and 3.

<table>
<thead>
<tr>
<th>Tributary (site)</th>
<th>Elevation (m als)</th>
<th>Q (dry) (m³ s⁻¹)</th>
<th>Q (wet) (m³ s⁻¹)</th>
<th>Catchment area (km²)</th>
<th>Q (dry) (mm a⁻¹)</th>
<th>Q (wet) (mm a⁻¹)</th>
<th>Glacial area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speke (1)</td>
<td>4104</td>
<td>0.002</td>
<td>0.017</td>
<td>0.6</td>
<td>89</td>
<td>890</td>
<td>33</td>
</tr>
<tr>
<td>Bujuku (2)</td>
<td>3918</td>
<td>0.06</td>
<td>0.30</td>
<td>5.3</td>
<td>360</td>
<td>1800</td>
<td>8.1</td>
</tr>
<tr>
<td>Bujuku (3)</td>
<td>3520</td>
<td>0.18</td>
<td>0.43</td>
<td>9.6</td>
<td>590</td>
<td>1400</td>
<td>4.5</td>
</tr>
<tr>
<td>Bujuku (4)</td>
<td>3321</td>
<td>0.41</td>
<td>1.0</td>
<td>32.6</td>
<td>400</td>
<td>970</td>
<td>1.3</td>
</tr>
<tr>
<td>Mubuku (5)</td>
<td>3580</td>
<td>0.20</td>
<td>0.22</td>
<td>10.0</td>
<td>630</td>
<td>690</td>
<td>1.7</td>
</tr>
<tr>
<td>Mubuku (6)</td>
<td>2845</td>
<td>1.1</td>
<td>6.2</td>
<td>35.0</td>
<td>990</td>
<td>5600</td>
<td>0.5</td>
</tr>
<tr>
<td>Mubuku (7)d</td>
<td>1095</td>
<td>10</td>
<td>18</td>
<td>256</td>
<td>1280</td>
<td>2230</td>
<td>0.2</td>
</tr>
</tbody>
</table>

° 2003 (Taylor et al., 2006a).
5. Conclusions

Glaciers in the Rwenzori Mountains continue to recede rapidly. Observed acceleration in the rates of termini retreat of two valley glaciers since the late 1960s is attributed, in part, to the convex–concave slope profile in which the valley glaciers reside. Current glacial recession has a negligible impact on alpine riverflow. Spot measurements of meltwater discharges indicate that icefields contribute considerably less than 2% of the total discharge of the principal river receiving meltwater discharges (River Mubuku) at the base of the Rwenzori Mountains during both dry and wet seasons. The anomalously high specific discharge of the River Mubuku (1730 mm a\(^{-1}\)) arises from high rates of precipitation (2340–2600 mm a\(^{-1}\)) below alpine icefields within Heath-moss and Montane forest ecotones that occupy more than half of the river’s gauged catchment area. Our conclusion in the Rwenzori Mountains that glacial meltwater discharges contribute negligibly to alpine riverflow is expected to apply to other tropical alpine glaciers outside of the South American Andes (i.e. Irian Jaya, Kilimanjaro, Mount Kenya) where icefields represent a tiny fraction (<1%) of alpine river catchment areas.

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Fig. 8. Longitudinal trends in annual precipitation, plotted as deviations from the mean, for regional meteorological stations in western Uganda over the 20th century.