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Hydrological and climatological change associated with glacial recession in the Rwenzori Mountains of Uganda

Final Report
to the Royal Geographical Society

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Final Report to the Royal Geographical Society (EPSRC Small Research Grant 01/07)

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2008

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Cover photo: Melting glacial ice at the terminal of the Elena Glacier on Mount Stanley within the Rwenzori Mountains National Park (Uganda) in April 2007. All photos © ECRC.

EXECUTIVE SUMMARY

The areal extent of tropical icefields in the Rwenzori Mountains of East Africa has reduced steadily over the last century from 7.5 km^2 in 1906 to <1 km^2 in 2003. Considerable debate persists regarding the impact of deglaciation on alpine riverflow and changes in climate driving glacial recession in the East African Highlands. Recent field surveys combined with historical observations reveal continued, rapid retreat in the terminal positions of valley glaciers (Speke, Elena). Observed acceleration in the rate of termini retreat since the 1960s is shown to arise, in part, from the morphologies of the glaciers and the beds within which those glaciers reside. Historical data combined with the first measurements of alpine riverflow in the Rwenzori Mountains show that the contribution of meltwater flows from dwindling icefields to alpine riverflow is negligible, contributing <0.5% of the mean annual river discharge recorded at the base of the mountains. Preliminary high-frequency monitoring of air temperature and humidity in the vicinity of icefields on the Rwenzori Mountains indicates that elevated daily maximum air temperatures coincide with episodic reductions in relative humidity and increased meltwater fluxes observed during the dry season. A sustained reduction in humidity to account for observed deglaciation is not evident from records of lowland precipitation, humidity or river discharge. Lake-level records in East Africa are also inconsistent with a sudden decrease in regional humidity around 1880AD that is proposed to have triggered deglaciation in the East African Highlands. Water levels in the lakes proximate to the icefields of Mount Kenya and Kilimanjaro are rising in the late 19th century when glaciers on these mountains are observed to be in retreat. Lake levels do not, furthermore, indicate that enhanced humidity over the 19th century prior to 1880AD relative to the 20th century. Evidence of warming over the latter half of the 20th century and an earlier onset of deglaciation (~1870AD) from meteorological and palaeolimnological data suggest that the timing and drivers of deglaciation in the Rwenzori Mountains are consistent with the recession of alpine icefields elsewhere in the tropics.

1 Study rationale

The Rwenzori Mountains of East Africa feature one of the last remaining tropical icefields outside of the Andes. Over the last century, the areal extent of its alpine glaciers has reduced steadily from 7.5 km^2 in 1906 to <1 km^2 in 2003 (Fig. 1). Shrinking icefields reflect a negative mass balance between glacial accumulation and ablation. However, resolution of the precise climate drivers of observed deglaciation in the Rwenzori Mountains and other areas of the East African Highlands including Kilimanjaro (Fig. 1) and Mount Kenya, has proved problematic and the subject of debate (e.g. Thompson et al., 2002; Kaser et al., 2004; Mölg et al., 2006; Taylor et al., 2006a; 2006b). Conflicting suggestions have also been made over the direct impact of glacial recession on alpine riverflow in the East African Highlands. In this paper, we assess the impact of glacial recession on alpine riverflow in the Rwenzori Mountains and hydrometeorological trends in western Uganda, inferred from station data, recent monitoring and palaeoenvironmental archives, over the period of observed deglaciation. We report further on recent changes in the terminal positions of regularly monitored valley glaciers in the Rwenzori Mountains.

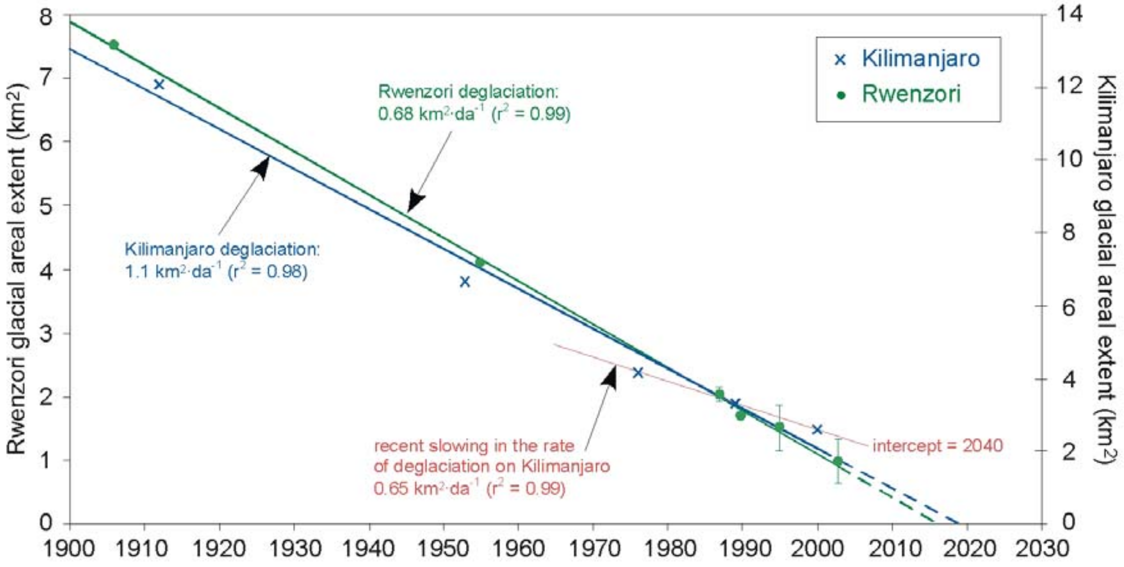

Figure 1. Observed changes in glacial cover on the Rwenzori Mountains and Kilimanjaro over the 20th century. Data for Kilimanjaro and Rwenzori Mountains are given in Thompson et al. (2002) and Taylor et al. (2006a) respectively.

Tropical alpine glaciers can form important reservoirs of fresh water that store seasonal inputs of precipitation, associated with the movement of the Intertropical Convergence Zone (ITCZ), and release meltwaters during drier periods. Consequently, they are able to serve a vital ecological function by regulating alpine streamflow and to aid downstream communities who rely on mountain runoff for year-round water supplies (Bradley et al., 2006). Meltwater discharges from tropical alpine icefields covering ~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 ~40% of the dry-season river discharge (Mark et al., 2005). Increased seasonality and overall reductions in riverflow associated with deglaciation in tropical alpine environments have been reported in the Andes (e.g. Mark and Seltzer, 2003; Bradley et al., 2006) and the Himalayas (e.g. Singh et al., 2004).

The notion that tropical alpine glaciers act as “water towers” (Liniger et al., 1998) has been extended by some workers to the East African Highlands (Gasse, 2002; Thompson et al., 2002; Ugandan Meteorology Department, 2006). Desanker (2002) alleges, for example, that several rivers on Kilimanjaro are drying out in the dry season “due to the loss of the frozen reservoir”. Temple (1968) and Kaser et al. (2004) argue, in contrast, that meltwater discharges provide insignificant contributions to alpine riverflow in the Rwenzori Mountains and Kilimanjaro respectively. Despite the dependence of local communities in the Rwenzori Mountains upon alpine riverflow for the generation of hydro-electric power, no measurements of alpine streamflow have previously been collected above the base of the Rwenzori Mountains with the exception of a few spot measurements of glacial meltwater discharges summarised by Temple (1968).

According to Hastenrath (2001), glacial recession on Mount Kenya was initiated by a sharp reduction in precipitation and humidity in the late 19th century but sustained beyond the early decades of the 20th century by a warming trend that has also increased humidity. As observed in the tropical Andes (Wagnon et al., 1999), a rise in humidity inhibits sublimation and permits more of the sun’s energy to melt glacial ice due to a reduction in latent heat and an increase in sensible heat. For the Rwenzori Mountains, glacial recession over the latter half of the 20th century coincides with rising air temperatures observed regionally both at the base of the mountain range from station records and in the mid-troposphere from radiosonde measurements (Taylor et al., 2006a, 2006b). In contrast, Mölg et al. (2003) have attributed recent glacial recession in the Rwenzori Mountains to a reduction in atmospheric humidity and associated cloud cover that has led to more rapid recession of glaciers on east-facing slopes. This hypothesis draws upon observations on Mount Kenya by Baker (1967) who noted that glaciers on northwest facing slopes are protected from morning sun by the peaks and from afternoon sun by cloud. More recently, Mölg et al. (2006) propose that glaciers in the East African Highlands are relics from more humid conditions during the 19th century. Deglaciation in the East African Highlands is thus considered to have resulted from a proposed shift to less humid conditions at the end of the 19th century.

2 Hydrology of the Rwenzori Mountains

The Rwenzori Mountains (Fig. 2) lie within the western arm of the East African Rift System and comprise an uplifted block (horst) of Precambrian crystalline rocks including gneisses, amphibolites, migmatites, and granites. The Rwenzori horst tilted up in an ESE to WNW direction 4 km above the surrounding peneplain (Fig. 3) known as the 'African Surface' in the Late Pliocene (Osmaston, 1989; Taylor and Howard, 1998). Occupying an area of 3000 km2, the horst is bounded to the north and south by grabens that feature Lakes Albert and Edward respectively. A maximum elevation of 5109 metres above mean sea level (mamsl) is currently reached by Margherita Peak on Mount Stanley. Although the mountain range is only 40 km from the equator, glaciers currently occur on three mountains: Stanley, Speke and Baker, due to a combination of cold temperatures and abundant precipitation (Kaser and Osmaston, 2002).

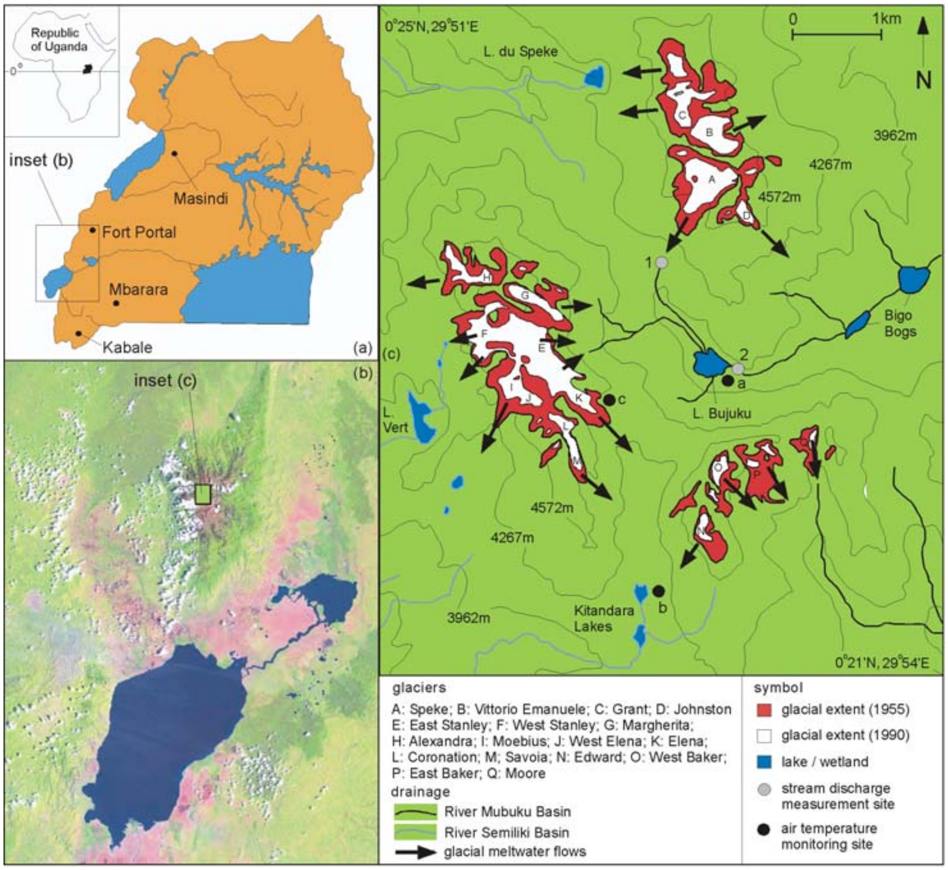

Figure 2. (a) Map of Uganda showing the location of the Rwenzori Mountains in Uganda and local meteorological stations; (b) LandSat7 satellite image showing the Rwenzori horst in relation to Lakes George and Edward; and (c) Map of glacial extent and drainage in the Central Rwenzori Massif (redrawn and adapted from Osmaston and Kaser, 2001) showing the location of stream discharge and meteorological monitoring stations: Lake Bujuku (a), Upper Kitandara Lake (b), and Mbahimba's Pool (c).

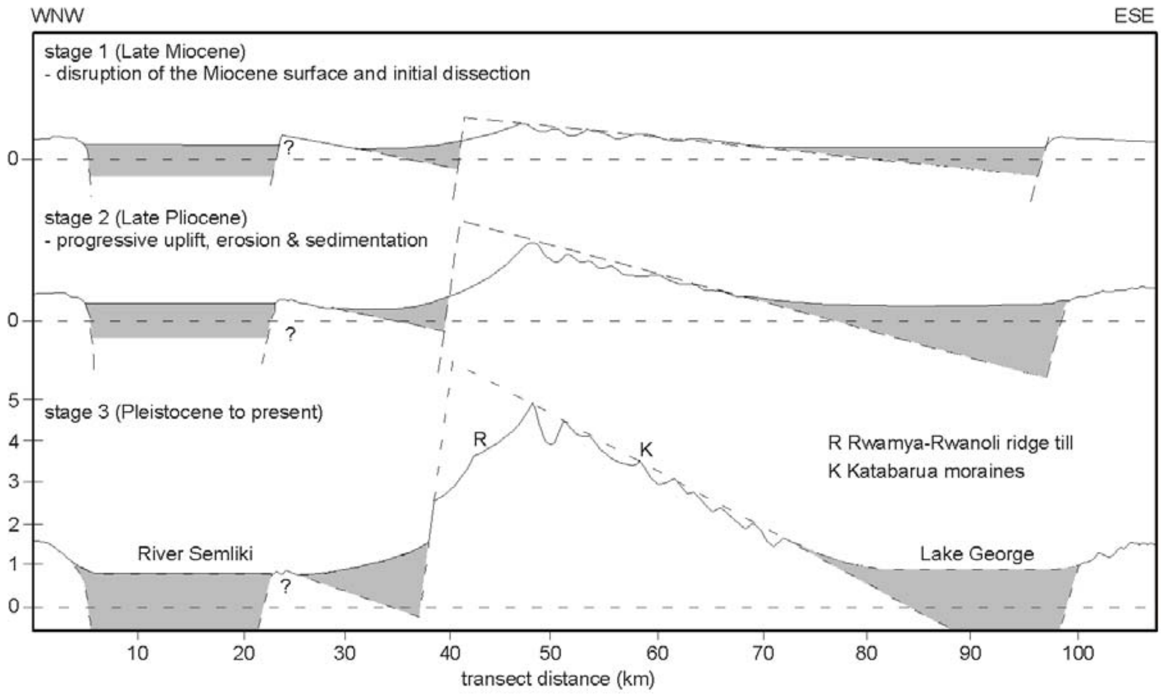

Figure 3. A conceptual representation of the uplift from the Late Miocene to present of the Rwenzori horst tilting upwards from the ESE to WNW (adapted from Osmaston (1989) with approximate ages drawn from Taylor and Howard (1998)). Vertical exaggeration is x 4.

Glaciers have played a major role in shaping the upper slopes of river basins that drain the Rwenzori Mountains (Fig. 4). Alternating cycles of glacial and fluvial erosion, extensively reviewed by Osmaston (1989), have produced glaciated surfaces and deeply incised valleys. The onset of modern glacial recession in the Rwenzori Mountains is unknown but considered by many authors (Hastenrath, 2001; Mölg et al., 2003; 2006; Kaser et al., 2004) to have started around 1880AD 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). The first survey of glacial extent in the Rwenzori Mountains was conducted in 1906 by the Duke of the Abruzzi (1907). Using maps prepared by De Filippi (1909) and photographs taken by Vittorio Sella from the Duke of the Abruzzi expedition, Kaser and Noggler (1996) estimate that, at this time, glaciers covered a total area of approximately 7.5 km^2. Glaciers were primarily restricted to Mounts Stanley, Speke and Baker of the Central Rwenzori Massif (Fig. 2b) but also included small glaciers with a total area of 1.0 km^2 on Mounts Gessi, Emin and Luigi de Savoia (Fig. 4). Glaciers largely existed above 4400 mamsl though some valley glaciers (e.g. Elena, Speke) extended a few hundred metres lower in elevation (Osmaston, 1989). 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., 2006a) confirm a pattern of continuous recession over the last century (Fig. 1).

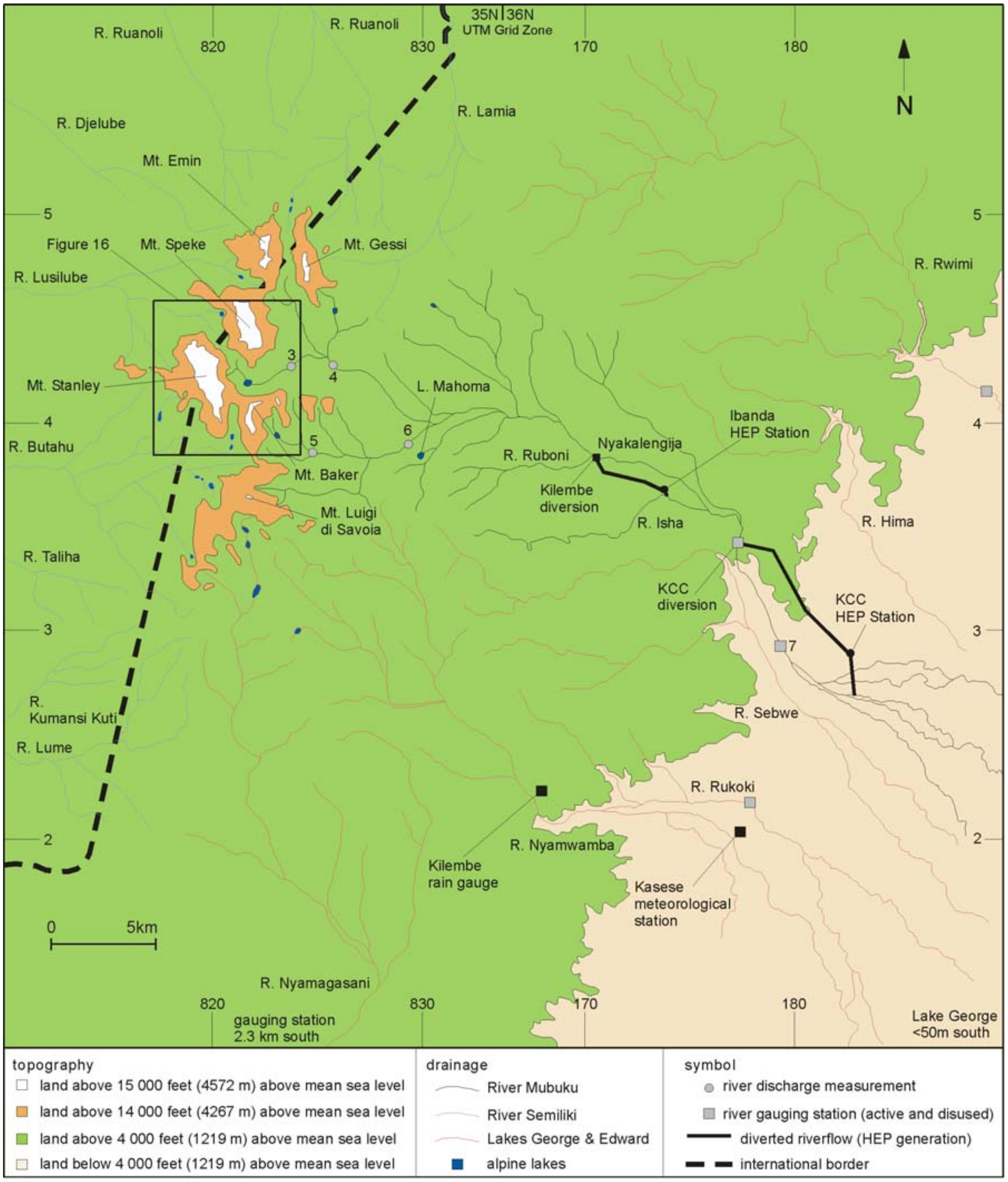

Figure 4. Map of the drainage network for the Rwenzori Mountains. The international border divides the Republic of Uganda to the east and the Democratic Republic of Congo to the west. Redrawn from the Fort Portal (1:250 000) sheet, NA-36-I3 (Lands and Surveys Department Uganda, 1961).

Over the last century, glaciers and their meltwater flows have formed headwaters of primarily three rivers in the Rwenzori Mountains: the River Mubuku that flows in an eastward direction in the Republic of Uganda and Rivers Butawu and Lusilube which drain toward the west in the Democratic Republic of Congo (Figs.

2 and 4). During the Holocene, glaciers and their meltwater flows would also have contributed to Rivers Ruanoli and Nyamagasani (Fig. 4). Ultimately, all of these rivers supply the River Semliki which discharges into Lake Albert, a source of the White Nile. The contribution of the River Mubuku to the flow of the River Semliki occurs via a more circuitous route that includes Lake George, the Kazinga Channel, and Lake Edward (Fig. 2b). The River Nyamugasani discharges directly into Lake Edward.

Of the remaining glaciers in the Central Rwenzori Massif (Fig. 2c), most of the largest including East Stanley, Speke, Vittorio Emanuele, and Margherita glaciers form headwaters of the River Mubuku. The East Stanley, Margherita and Speke glaciers sustain meltwater streams that flow into Lake Bujuku whereas the meltwaters from the Vittorio Emanuele glacier discharge to the east into a northern tributary (Bukurungu) of the River Mubuku (Fig. 2). Meltwater discharges from a comparatively smaller group of glaciers drain westward into headwater basins of the River Semliki. From the Edward, Savoia and Elena glaciers, meltwaters discharge into the Kitandara Lakes that subsequently drain westward as part of the River Butawu basin (Figs. 2 and 4). Meltwater discharges from Moebius, West Elena, West Stanley and Alexandra glaciers also supply the River Butawu. Meltwater discharges from the now fragmented Grant Glacier on Mount Speke form headwaters of the River Lusilube.

Precipitation in the Rwenzori Mountains features a bimodal distribution with wetter periods occurring from March to May and August to November (Fig. 5). The bimodal pattern results from the regional movement of air masses associated with the ITCZ. 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. 4) at an elevation of 1370 mamsl is 1540 $mm·a^{-1}$ whereas this flux drops to 890 $mm·a^{-1}$ just 11km away but 410 m lower in elevation at Kasese Airport (960 mamsl). Osmaston (2006) collected the only sustained measurements of precipitation at four locations in the Rwenzori Mountains at higher elevations than Kilembe and these observations similarly show pronounced variations in mean annual precipitation with altitude from 1951 to 1954 (Fig. 6). 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 annual precipitation of 2600 $mm·a^{-1}$ recorded at 3290 mamsl 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. Monthly precipitation averages at higher elevations follow a temporal pattern similar to the lowlands that reflects the importance of large-scale atmospheric circulation patterns in regulating regional precipitation. Based on the very limited data that are available from the Rwenzori Mountains in the Democratic Republic of Congo, Osmaston (2006) suggests that precipitation is lower on western slopes of the Rwenzori Mountains.

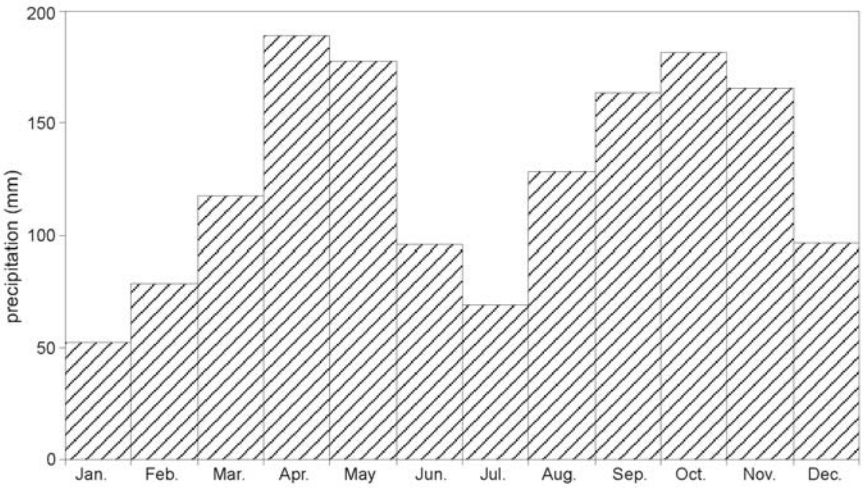

Figure 5. Distribution in mean monthly precipitation recorded at Kilembe, Uganda (0°13'N, 30°00'E) from 1949 to 1996.

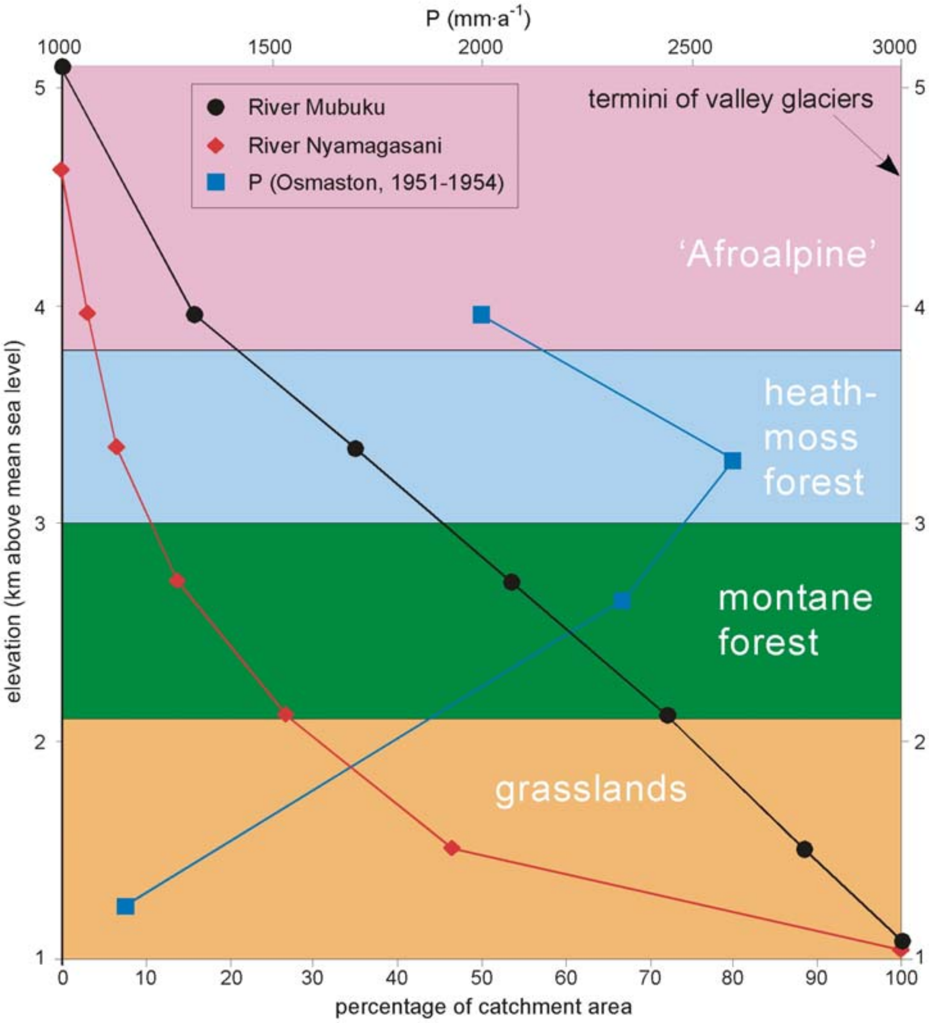

Figure 6. Hypsographic curves of catchment area for the Rivers Mubuku and Nyamagasani plotted alongside observed precipitation from 1951-1954 (Osmaston, 2006). The main vegetation zones (ecotones) are indicated for reference.

3 Methodology

We assessed recent changes in the terminal positions of the two largest valley glaciers remaining in the Rwenzori Mountains (Speke, Elena) through field surveys conducted in June 2003, January 2005 and April 2007. Terminal retreat was measured in relation to past field markers and those established by our surveys. The impact of glacial recession on alpine riverflow was investigated through both an analysis of trends in river discharge for basins receiving meltwater discharges and assessment of altitudinal trends in streamflow from spot measurements conducted during one dry season (January 2005) and one wet season (April 2007). On account of the highly heterogeneous nature of alpine stream reaches that commonly feature large boulders, dilution gauging (Okunishi et al., 1992) was employed rather than the more common, velocity-area approach. We examined hydrometeorological trends associated with glacial recession over the last century using records of precipitation and humidity from station observations at the base of the mountain, recent air-temperature monitoring using StowAway® TidbiT™ temperature loggers installed in shielded locations 1.5m from the ground surface in the Afroalpine zone, and regional hydrological records of both lake levels and river discharge. Trends in regional precipitation over the last two centuries were investigated using both observational datasets (e.g., Hurst, 1925; Hurst and Philips, 1945; Vörösmarty et al., 1998; Nicholson and Yin, 2001) and palaeoenvironmental archives (e.g., Åse, 1987; Verschuren, 1999; Cohen et al., 2005).

4 Results & Discussion

4.1 Retreat of valley glaciers

Field surveys of the terminal positions of the Speke and Elena Glaciers show an acceleration in the rate of recession since the 1960s (Fig. 7). The termini of both glaciers have retreated by nearly 600 m since the early 1960s. Differences between them in the rate of retreat over time may arise from a paucity of observations but are nonetheless strongly influenced by variations in the supply of ice to these valley glaciers as a result of their elevation and bed morphology (Fig. 2c). Hypsographic curves prepared by Kaser and Osmaston (2002) show that between 15 and 20% of the surface area of Mount Stanley (i.e. Stanley Plateau) is above the highest peak on Mount Speke (Vittorio Emanuele), an elevation of approximately 4900 mamsl. As the equilibrium line altitude (ELA) for each mountain has risen since the last glacial maximum and particularly over the last century, the supply of ice to Elena Glacier from the Stanley Plateau would have continued for longer than that to the Speke Glacier. The current elevation of the (mean) 0°C level is 4700 mamsl based on recent data collected from a network air temperature loggers at 14 locations ranging in elevations from 1770 to 4560 mamsl (Eggermont et al., unpublished data).

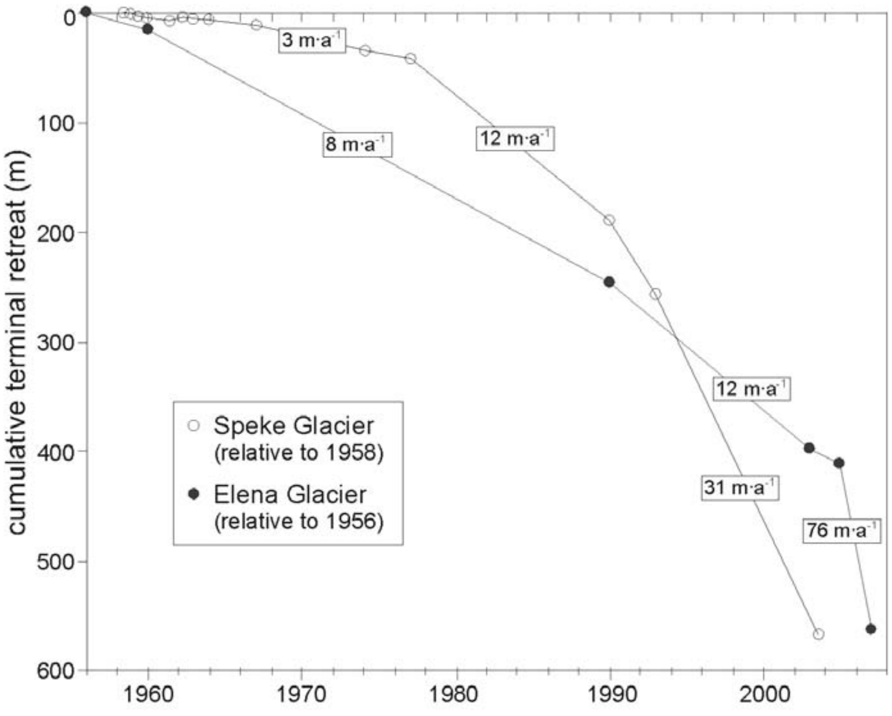

Figure 7. Observed retreat in the terminal positions of the Speke and Elena Glaciers relative to observations in 1958 and 1956 respectively. Data derive from Kaser and Osmaston (2002), Whittow et al. (1963) and this work.

The Speke Glacier is the largest single valley glacier in the Rwenzori icefield and its terminal position has, in a relative sense, been monitored quite frequently (Fig. 7). Repeated measurements of the terminal position of the Speke Glacier in relation to a marker established in 1958 show that rates of terminal retreat have increased from 3 m per annum (1962-1977) to 31 m per annum (1993-2003). Exponential retreat of glacial termini has similarly been observed for the Qori Kalis Glacier (Thompson, 2000), the largest outlet of the Quelccaya ice cap in Peru (13°56'S, 70°50'W). These observations appear to suggest that the loss of tropical glaciers may be occurring more rapidly. These trends can, however, be misleading.

'Glacier retreat', the term used to describe the current behaviour of the termini of many glaciers worldwide, reflects a rise in the ELA. The ELA varies in response to climatic changes, primarily temperature and precipitation. A rise in ELA results in a reduction of total net mass balance and, thus, a progressive reduction in the volume of a glacier. It is this last parameter (volume) that is a true measure of the condition of a glacier and the way in which it is being affected by climate change. It is unlikely that the rate of retreat of the terminus directly reflects the rate of volume loss except in uniformly sloping valleys. The Speke Glacier shows this discrepancy very clearly.

Prior to the 1950s, the terminus of the Speke Glacier lay adjacent to the edge of a steep cliff from which avalanches of snow shed down a steep rock face (Fig. 8a). Substantial volume loss subsequently occurred by thinning since before any significant retreat of the terminus could take place, it had to thin down to the level of the underlying rock. Terminal retreat was consequently negligible. Retreat then took place horizontally across part of the basin, now occupied by a small lake, Ruhandika (Fig. 9a), resulting in a steeply sloping glacier surface parallel to the underlying bed. There is abundant photographic evidence for continued thinning of the whole Speke Glacier (e.g., Kaser and Noggler, 1996), right up to its highest limits (Fig. 9b). The ice lying on this slope thinned fairly uniformly until at a critical thickness it became effectively stagnant, cut off from supply due to the convex-concave slope profile and subject to rapid melting (Fig. 8a). These changes would result in a rapid retreat of the terminus to the change in gradient at the top of the slope where the present thin terminus can be seen. This pattern of rapid terminal retreat following the separation of the valley glacier’s tongue from its ice supply as a result of thinning, has subsequently been observed for the Elena Glacier (Fig. 8b).

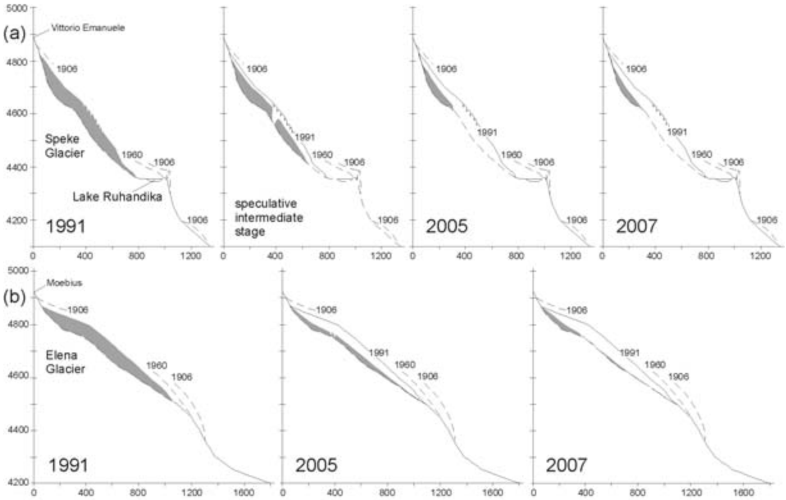

Figure 8. A schematic, cross-sectional representation of changes in the profiles of 'indicator' valley glaciers (shaded): (a) Speke and (b) Elena in the Rwenzori Mountains from 1991 to 2005 (adapted from Kaser and Osmaston, 2002). Glacial thickness and bed topography are not known precisely. Vertical exaggeration is x 2.

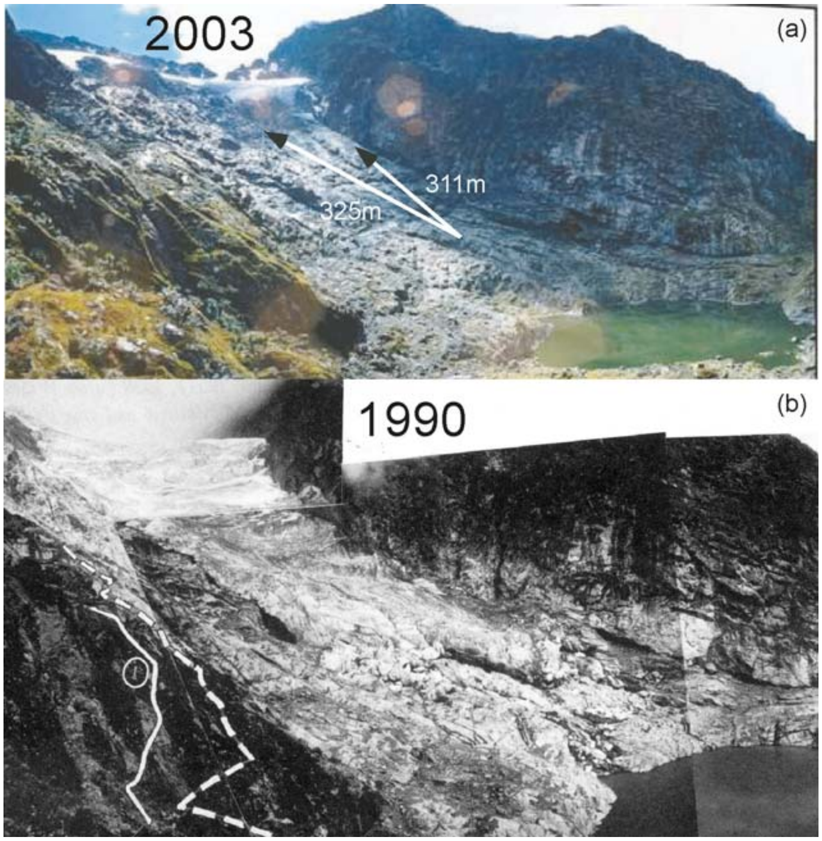

Figure 9. Retreat in the terminus of the Speke Glacier as shown by terrestrial photographs in 2003 (a) and 1990 (b). (a). Field survey of terminus retreat in 2003, relative to the 1993 marker (Talks, 1994), is also shown in photograph (a). Photograph (a) is panoramic image taken by Andrea Fischer on 22 June 2003 whereas the panoramic photograph on 29 January 1990 (b) is from Kaser and Noggler (1991).

The retreat of valley glaciers observed on the Rwenzori Mountains highlights how bed and glacier morphologies can explain, in part, observed acceleration rates of terminus retreat. The monotonic decline recorded in the areal extent of icefields in the Rwenzori Mountains over the last century (Fig. 1) is expected to mask considerable variability in the mass balance of these icefields. For example, frequent measurements of the Lewis Glacier on Mount Kenya show linear decreases in the length and area of the glacier over the 20th century but a variable rate of decline in volume (Hastenrath, 1984; Fig. 5.2.7.1). Caution is therefore required in attributing changing rates of terminal retreat to specific hydroclimatological influences particularly for small dwindling glaciers.

4.2 Impact of glacial recession on alpine riverflow

4.2.1 evidence from historical records of river discharge

Analysis of historical records of river discharge sought to determine whether significant trends in river flow exist over the period of observed deglaciation. Current monitoring of riverflow at the base of the Rwenzori Mountains (Fig. 4) is restricted to the River Nyamagasani though historical records exist for Rivers Mubuku, Semliki, Rwimi and Rukoki that drain alpine areas of the Rwenzori Mountains. Discharge records for the rivers Mubuku, Nyamagasani, and Semliki (Fig. 4) are plotted in Figure 10. Each river is, or was recently, supplied in part by glacial meltwater discharges.

The River Mubuku has a catchment area of 256 km^2 with a mean discharge from 1954 to 1965 (no totals for 1955, 1959 and 1960) of 14 $m^3 \cdot s^{-1}$ or a depth equivalent over the catchment (specific discharge) of 1730 $mm \cdot a^{-1}$. The period of observation includes the anomalously wet conditions from 1961 to 1963 that are well represented in the discharge record of the River Semliki but only partially reflected in the discharge of the River Nyamagasani due to missing data. As a result, the mean discharge of the River Mubuku over this period may slightly exceed the long-term mean. For comparison, the mean discharge of the River Mubuku for the slightly smaller catchment (246 km2) gauged at Bugoye by KCCL (Fig. 4) is 12 $m^3 \cdot s^{-1}$ (1560 $mm \cdot a^{-1}$) over the calendar year 2000.

The specific discharge of the River Mubuku is in the order of 1560 to 1730 $mm \cdot a^{-1}$ and at least three times that of the River Nyamagasani over the same period (493 $mm \cdot a^{-1}$). As the River Mubuku is one of the last remaining basins still to have its headwaters supplied by glacial meltwaters, the basin's proportionately high discharge led some (e.g., Uganda Meteorology Department, 2006) to presume that a significant proportion of the river's flow derives from glacial meltwater flows. 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 $mm \cdot a^{-1}$. 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 = 2030 mm·a^{-1}), compared with the River Nyamagasani 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 ~10ºC and more than half of the River Nyamagasani lies below 1500 mamsl where water temperatures are ~17ºC, 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.

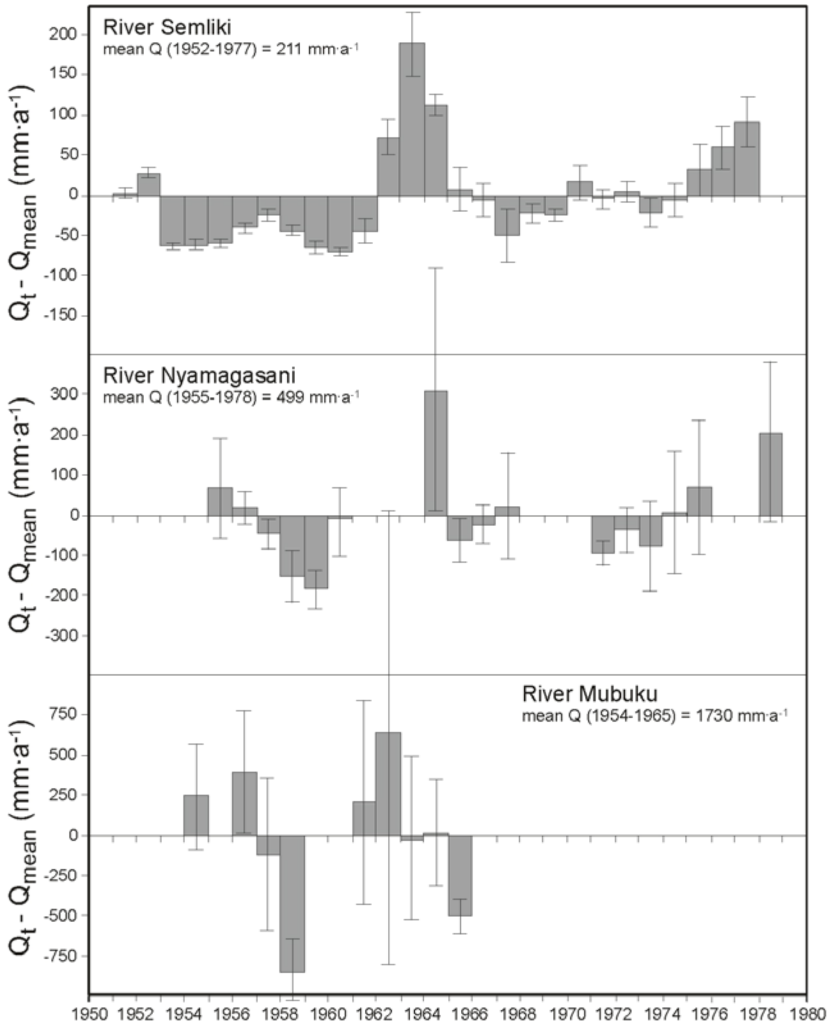

Figure 10. Longitudinal trends in deviations from mean riverflow observed at the base of the Rwenzori Mountains from 1952 to 1978. Missing data for the Rivers Mubuku and Nyamagasani reflect incomplete discharge records for these calendar years. Calculated errors derive from uncertainty in the derivation of the rating curve.

Records of river discharge for the Rivers Mubuku and Nyamagasani (Fig. 10) show considerable interannual variability but are too limited in duration to permit trend analyses. The River Nyamagasani has a catchment area of 507 km^2 and is the only river draining the Rwenzori Mountains (in Uganda) that is currently monitored (Fig. 4). From records of discharge available from 1955 to 2002 (Fig. 10), a long gap in observations begins in 1979 and lasts until November 1998. Qualitatively, there is no evidence of a decrease or increase in river discharge either annually or in terms of the lowest daily flow recorded each year. Positive deviations in mean annual discharge in the calendar years 1964 and 1978 are consistent with anomalously high precipitation recorded locally at Kilembe and Kasese Airport (Fig. 4). No significant temporal trends (at a 95% confidence interval) in precipitation are evident over a 50-year period (1949 to 1998) at Kilembe and 43-year period (1964 to 2006) at Kasese (Fig. 4).

The River Semliki has a catchment area of 23 621 km^2 and is the net recipient of the discharges from all rivers and lakes draining the Rwenzori Mountains and the surrounding region (Figs. 2 and 4). A continuous record of river discharge is available over a 26-year period from 1952 to 1977 (Fig. 10). The anomalously wet conditions from 1962 to 1964, clearly represented in the discharge record, complicate assessment of underlying trends in river discharge. A statistically significant trend at a 95% confidence interval is not observed in either annual flow or in terms of the lowest flow recorded each year over the 27-year period.

4.2.2 evidence from spot measurements of alpine riverflow

Analysis of altitudinal trends in stream and river discharge in the River Mubuku basin provides an indication of the relative contributions of the icefields and underlying ecotones (e.g. Heath-moss forest) to the cumulative basin discharge observed at the base of the Rwenzori Mountains. Spot measurements, collected during the dry season (January 2005) and wet season (April 2007), are summarised in Table 1. Direct contributions of meltwaters from glaciers on Mounts Speke and Stanley that cover an area of just under 0.5 km^2 to the River Mubuku, are difficult to estimate due to the decreasing accessibility of glacial termini (Speke, East Stanley Glaciers). Spot measurements of glacial meltwater fluxes from the Speke Glacier (station 1, Fig. 2), the largest valley glacier in the Rwenzori Mountains, comprise 0.02 to 0.1 % of the river discharge recorded at the base of the Rwenzori Mountains (site 7 in Fig. 4). Meltwater discharges to the River Mubuku basin from glaciers, together with contributions from the remaining, non-glaciated catchment area of 4.9 km^2 aggregated at Lake Bujuku (site 2 in Fig. 2), represent < 2% of the river discharge recorded at the base of the Rwenzori Mountains. High annual precipitation rates in the Lake Bujuku catchment imply that glacial meltwater must amount to considerably less than 2% of the Lake Bujuku's outflow (0.06 to 0.30 $m^3 \cdot s^{-1}$) and almost certainly less than

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. 4) are considered.

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 parantheses are given in Figures 2 and 4.

Tributary (site)	Elevation (mamsl)	Q (dry)[1] ($m^3 \cdot s^{-1}$)	Q (wet)[2] ($m^3 \cdot s^{-1}$)	Catchment area (km^2)	Q (dry)[1] ($mm \cdot a^{-1}$)	Q (wet)[2] ($mm \cdot a^{-1}$)	Glacial[3] area (%)
Speke (1)	4104	0.0017	0.017	0.6	89	890	33
Bujuku (2)	3918	0.06	0.30	5.3	360	1800	8.1
Bujuku (3)	3520	0.18	0.43	9.6	590	1400	4.5
Bujuku (4)	3321	0.41	1.0	32.6	400	970	1.3
Mubuku (5)	3580	0.20	0.22	10.0	630	690	1.7
Mubuku (6)	2845	1.1	6.2	35.0	990	5600	0.5
Mubuku (7)[4]	1095	*10*	*18*	256	*1280*	*2230*	0.2

1: January 25 – February 2, 2005; 2: April 20 – 24, 2007; 3: 2003 (Taylor et al., 2006a); 4: mean dry Q (February, 1954-1965), mean wet Q (October, 1954-1965)

The altitudinal profile of River Mubuku (sites 5 and 6 in Fig. 4) discharge highlights, furthermore, the substantial increase in river discharge that occurs below the glaciers in the Heath-moss forest zone (3000 to 4000 mamsl) where the catchment area expands from 15% to 46% (Fig. 7) and precipitation is highest (2600 $mm \cdot a^{-1}$). The deduction that recent glacial recession has had a negligible impact on alpine riverflow is sensible in light of the fact that less than 0.2% of the River Mubuku basin (256 km^2) is covered by glaciers. Indeed, the mean annual flux of the River Mubuku (~0.4 $km^3 \cdot a^{-1}$) is approximately 80 times larger than a conservative estimate of the volume (water-equivalent) of the remaining glacial reservoir (<0.005 km^3). The infinitesimal 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. On Kilimanjaro, Hemp (2005) cites an unpublished estimate of an annual meltwater discharge of 106 $m^3 \cdot a^{-1}$ (~0.03 $m^3 \cdot s^{-1}$) from the Southern Icefields that are similar in size (~1.3 km^2) to the Rwenzori icefields.

4.3 Hydrometeorological trends associated with modern glacial recession

4.3.1 evidence from meteorological datasets since 1900

Concurrent with the period of accelerated terminal retreat (Fig. 7), Taylor et al. (2006a, 2006b) report significant increases in lowland air temperature in western Uganda (+0.15 $K \cdot decade^{-1}$ from 1960 to 1998) and free air temperatures of the mid-troposphere from limited radiosonde measurements in East Africa (+0.12 K·decade^{-1} from 1958 to 2005). The relationship between these observations and temperature trends experienced at the icefields in the Rwenzori Mountains remains, however, uncertain. It is also unclear whether possible changes in alpine air temperatures alone account for the rapid rates of observed glacial recession (Figs. 1 and 7). As argued by Mölg et al. (2006; in press) in relation to observed deglaciation on Kilimanjaro, receding glaciers may also signal a reduction in alpine precipitation and/or humidity. The former would reduce glacial accumulation and surface albedo whereas the latter may reflect a decrease in cloud cover that increases the exposure of glaciers to solar radiation that enhances ablation.

Analysis of records of precipitation in western Uganda (Fig. 2a) over the 20th century is restricted to stations at elevations of <2000 mamsl. Significant downward trends in precipitation are not realised at any of the four stations (Fig. 11); in fact, small but statistically significant trends of increasing precipitation (at a 95% confidence interval) are observed at Fort Portal (1903 to 1978) and Mbarara (1904 to 1999). These observations contrast with a decline in lowland precipitation of between 27% and 38% over the last century reported by Hemp (2005) for three stations around the base of Kilimanjaro (Moshi, Kilema Mission, Kibosho Mission). Apart from divergent temporal trends in lowland precipitation, substantial differences between the alpine climates of Kilimanjaro and the Rwenzori Mountains are also apparent from limited monitoring of alpine precipitation. Though observations are separated by nearly half a century, Osmaston (2006) recorded nearly four times as much precipitation (2000 mm·a^{-1}) at 3990 mamsl on the Rwenzori Mountains from 1951 to 1953 compared to that (540 mm·a^{-1}) recently reported by Hemp (2005) at 4000 mamsl on Kilimanjaro.

Differences between the environments of Kilimanjaro and the Rwenzori Mountains extend to recent changes in land use. On Kilimanjaro, rapid loss of montane and cloud forest has reduced both fog interception and canopy water storage (Hemp, 2005). Deforestation in catchments downslope of the icefields in the Rwenzori Mountains (Figs. 3 and 4) has largely been prevented as land above 1700 mamsl 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. Daily measurements of relative humidity at the base of the Rwenzori Mountains in Kasese (Fig. 4) are available over two continuous periods from 1967 to 1974 and 1991 to 2000. The brevity of these records does not permit analysis of temporal trends. Comparison of mean values of relative humidity as well as mean minimum and mean maximum relative humidity for the two periods (Table 2) does not, however, signal a decline in relative humidity over the latter half of the 20th century proposed by Mölg et al. (2006); marginal increases in relative humidity are observed.

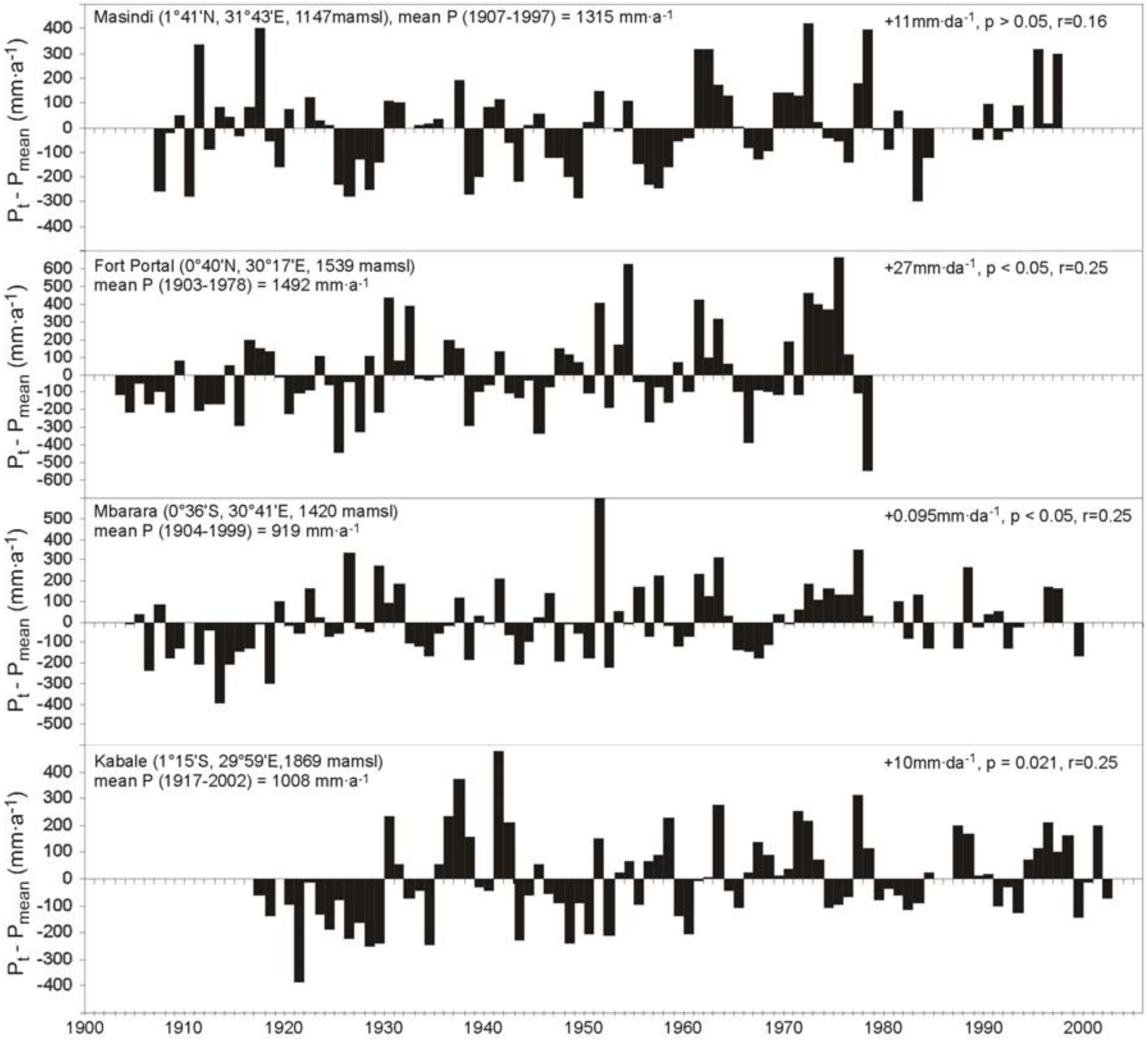

Figure 11. Longitudinal trends in annual precipitation, plotted as deviations from the mean, for stations at meteorological stations in western Uganda over the 20th century.

Table 2. Measurements of relative humidity (%) available over two continuous periods, 1967 to 1974 and 1991 to 2000, at Kasese (Fig. 4). Data derive from daily measurements recorded at 9AM and 3PM. The standard deviation in each mean value is given in parentheses.

relative humidity	**1967 – 1974**	**1991 – 2000**
mean - 9AM	80 (6)	84 (5)
mean minimum – 9AM	63 (8)	66 (9)
mean maximum – 9AM	94 (4)	97 (3)
mean – 3PM	52 (7)	54 (7)
mean minimum – 3PM	34 (8)	37 (7)
mean maximum – 3PM	82 (10)	86 (10)

Recent installation of temperature loggers within the Rwenzori Mountains provides the first, continuous (every 2 hours) record of air temperature (T_a) in the vicinity of the icefields (Fig. 12). Diurnal variations in T_a from May 2005 to January 2008 at three locations (Fig. 2c) show a strong relationship to available moisture. During the dry season from December to February (Figs. 5 and 12), the amplitude of diurnal temperature changes rises considerably with substantial increases observed in daily maximum temperature. Since May 2007, both temperature and humidity have been monitored at one alpine location (Mbahimba's Pool). These data reveal a clear temporal relationship between sub-daily episodes of reduced humidity during the dry season and increased maximum T_a (Fig. 13). The magnitude of observed maximum air temperatures that occasionally exceed 20ºC at this location (4550 mamsl) suggests contamination of the temperature record by solar radiation may have occurred.

Strong diurnal variations in meltwater fluxes from the Speke Glacier have been observed by Whittow et al. (1963, Fig. 20). Meltwater fluxes recorded overnight increase three-fold by late afternoon (4pm). Their observations, though limited, show further that the mean meltwater flux from the Speke Glacier during the dry season (0.02 $m^3 \cdot s^{-1}$) is an order of magnitude greater (0.003 $m^3 \cdot s^{-1}$) than during the rainy season when diurnal temperature fluctuations are lower. These contemporary and historical observations highlight the interdependence of humidity and temperature on ablation as increasing air temperatures and meltwater fluxes can clearly result from reduced humidity.

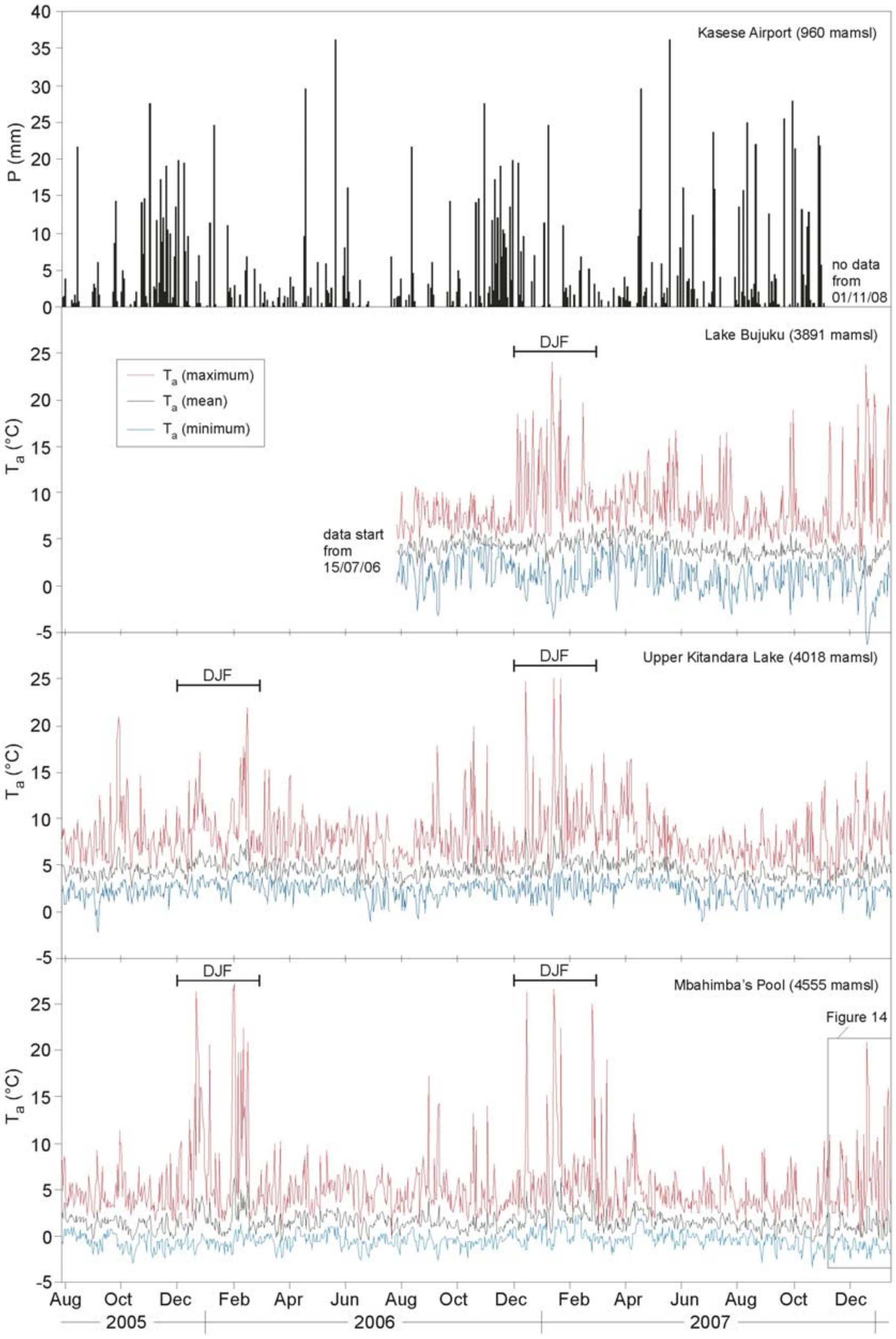

Figure 12. Daily (lowland) precipitation at Kasese (960 mamsl; Fig. 4) and daily mean, maximum and minimum air temperature observed at 3 locations in the Afroalpine zone (Fig. 2) from July 15 2006 to January 12 2008.

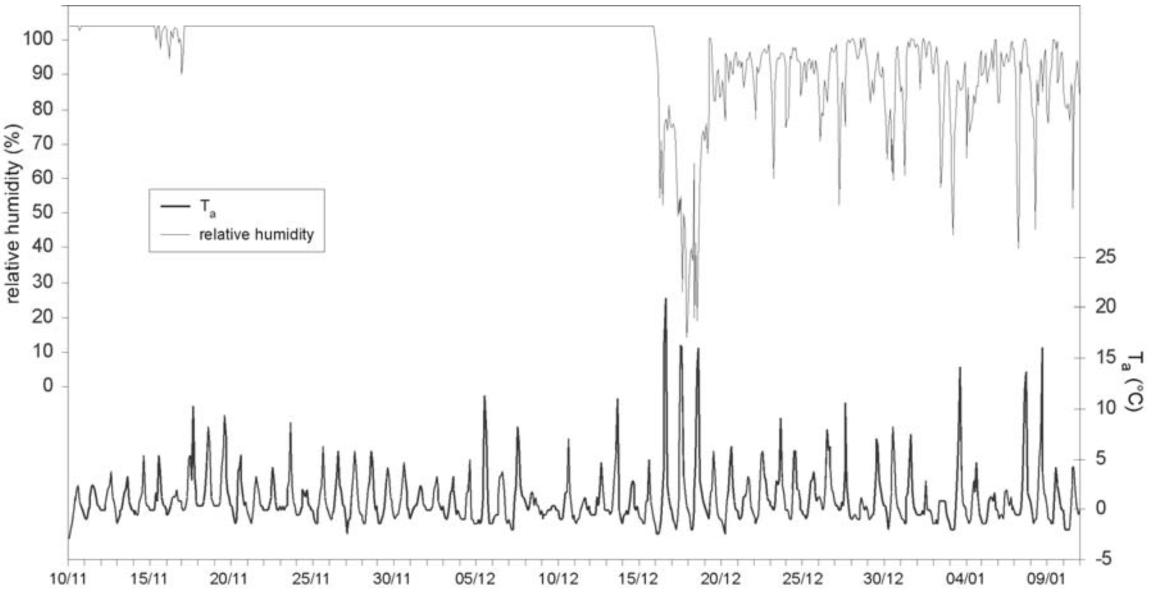

Figure 13. Air temperature and relative humidity observed every 2 hours at Mbahimba's Pool (Fig. 2) from November 10 2007 to January 10 2008.

4.3.2 evidence from regional hydrological records since 1800

The hypothesis of Mölg et al. (2006) that glaciers in the East African Highlands are relics from more humid climatic conditions during the 19th century, may explain the apparent monotonic decline in glacial cover in the East African Highlands over the 20th century (Fig. 1). There is, however, currently no compelling hydrological evidence to support it. The apparent linearity in rate of decline in glacial cover over the 20th century may, as recognised by Kaser and Osmaston (2002), stem from a paucity of measurements. More frequent observations of glacial cover on Kilimanjaro toward the end of the 20th century reveal, for instance, a slowing rate of loss of glacial cover (Fig. 1) and raise the possibility that glaciers there may persist up to ~2040 rather than ~2020 suggested by Thompson et al. (2002).

Changes in the lowland lake levels, an indirect and imperfect proxy of alpine humidity, are often cited (e.g. Kaser et al., 2004; Mölg et al., 2006) in support of the assertion of that a dramatic reduction in humidity in East Africa occurred towards the end of the 19th century (c. 1880AD). Lake level records throughout the East Africa Rift System (EARS) (Fig. 14) indicate that for all but two decades of the 19th century, lake levels were lower than, or similar to, their levels throughout the 20th century. A sharp decline in the reconstructed level of Lake Victoria during the late 19th century (Nicholson and Yin, 2001) that is presumed to reflect a dramatic reduction in regional humidity and to have initiated glacial recession (e.g., Mölg et al., 2006), is actually the descending limb of a brief, high lake stand lasting less than two decades. The sudden drop in the level of Lake

Tanganyika in 1877 is considered to result from erosion of the lake's outlet at River Lukuga, rather than a decline in precipitation (Evert, 1980; cited in Cohen et al., 1997).

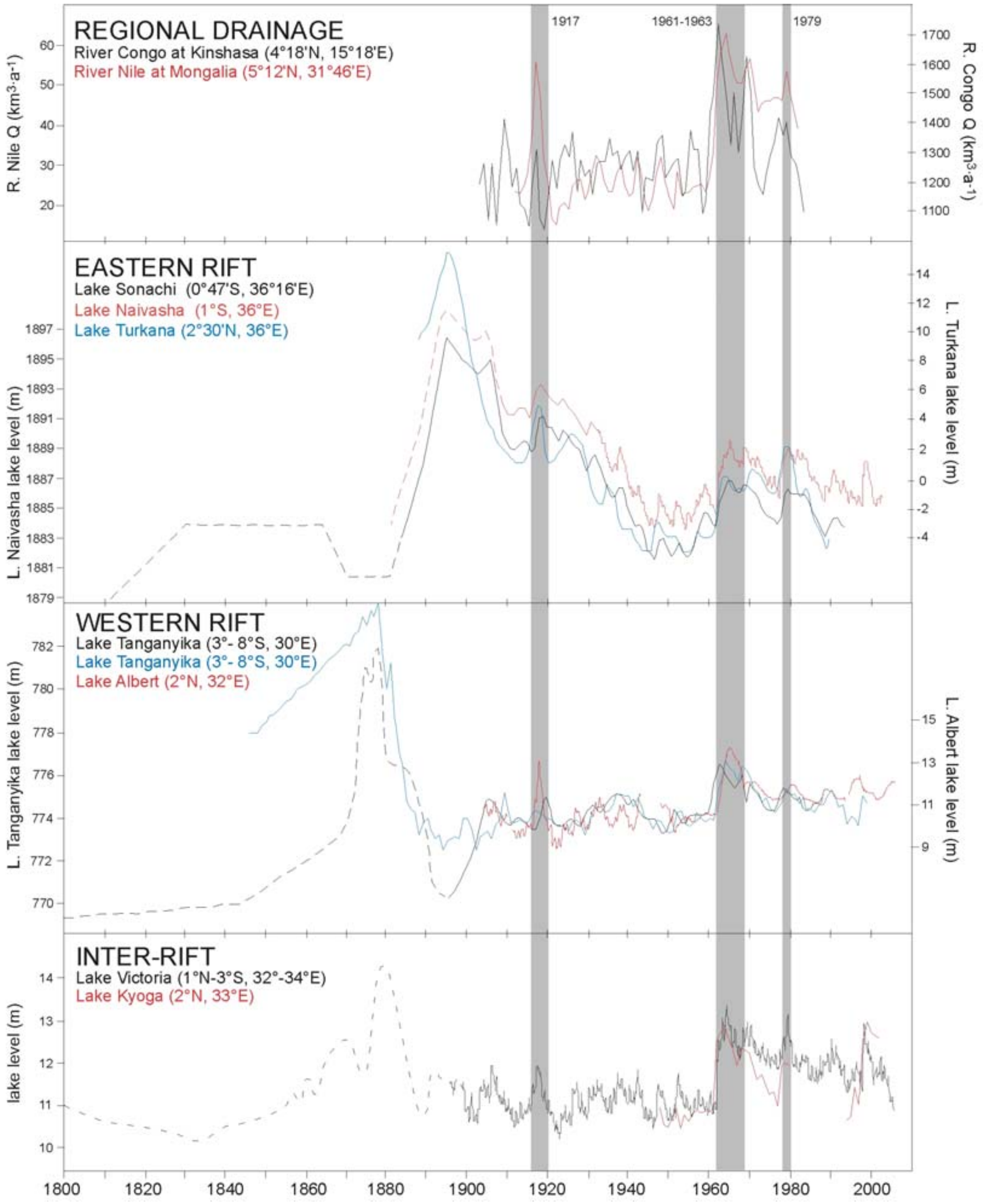

Figure 14. Regional hydrological trends in lake levels and river discharge in East Africa since 1800. River discharge records derive from Vörösmarty et al. (1998). Reconstructions (dashed line) and observations (solid line) of the lake levels in East Africa include Lake Naivasha (Åse, 1987; Lukman, 2003), Lake Sonachi (Verschuren, 1999), Lake Turkana (Kolding, 1992), Lake Tanganyika (Nicholson and Yin, 2001; Cohen et al., 2005), Lake Albert (Hurst, 1925; Hurst and Phillips, 1945; Directorate of Water Resource Management, Entebbe), Lake Victoria (Nicholson and Yin, 2001; Directorate of Water Resource Management, Entebbe) and Lake Kyoga (Directorate of Water Resource Management, Entebbe).

Lake levels and the discharge of major river systems draining East Africa (i.e., Rivers Nile and Congo) exhibit remarkable consistency over the 20th century in their response to years of anomalously high precipitation (e.g. 1917, 1961-1964, 1979) (Fig. 14). These records are, furthermore, consistent with observations from meteorological stations in western Uganda (Fig. 12) in that they demonstrate strong interannual variability but provide no evidence of a decline in precipitation or by speculative inference, atmospheric humidity, over the 20th century. Of significance is the highly muted response of frequently monitored alpine glaciers on the Rwenzori Mountains (Speke, Elena) and Mount Kenya (Lewis Glacier) to the most extreme hydrological event of the 20th century in East Africa when the level of Lake Victoria and the River Nile in Uganda rose by 2.5 m (Lamb, 1966; Kite, 1981). Despite the sharp and sustained rise in precipitation suggested regionally by large, coincidental increases in lake levels and river discharges during the early 1960s (Fig. 14), the Speke Glacier experienced a brief (< 1 year) and marginal advance (~3 m) whereas the Elena Glacier advanced ~5 m over a two-year period (Temple, 1968). On Mount Kenya, Hastenrath (1984) reports of a slight thickening of upper reaches of the Lewis Glacier from 1963 to 1974 but the total length, area and volume of the glacier continue to decline over this period. If lowland lake levels are a proxy of alpine precipitation and humidity, glaciological observations suggest that these icefields are relatively insensitive to changes in humidity and precipitation.

The apparent inconsistency between the observed stability in lowland lake levels and steady shrinkage of alpine glaciers in East Africa extends to the 19th century. The earliest accounts of glacial extent on Kilimanjaro are provided by Meyer (1891, 1890; cited in Young and Hastenrath, 1992) who observed the separation of glacial ice inside and outside of the Kibo caldera between 1889 and 1900. The first surveys of the Lewis and Tyndall Glaciers on Mount Kenya revealed a recessionary trend by 1893 (Hastenrath, 1984). The observed recession of glaciers in both icefields coincides with rising water levels in Lakes Sonachi and Naivasha (Fig. 14) that are located in the same (eastern) arm of the EARS as the receding alpine glaciers. The lake-level record of Lake Navaisha is considered to provide a better indicator of changes in alpine precipitation than the more commonly cited record of Lake Victoria as strong correlations between local alpine precipitation and changes in the level of Lake Naivasha have been observed by Vincent et al. (1979).

Rising lake levels in the eastern arm of the EARS during the late 19th century and early 20th century contrast strongly with the falling and low lake levels observed both between the rift valleys (inter-rift) and within the western arm of the EARS (Fig. 14). As gauge readings for Lakes Naivasha and Victoria begin in 1909 and 1898 respectively, this brief divergence in lake level records in East Africa is considered to reflect different hydrological conditions rather than to question necessarily the reliability of anecdotal evidence. A recent palaeolimnological study in both eastern and western arms of the EARS (Bessems et al., 2008) shows a coincidental, extreme drought at the end of 18th century during which crater lakes in western Uganda (Chibwera, Kanyamukali) and Lake Baringo in Kenya dried up. Subsequent refilling of these lakes in the early 19th century is consistent most notably with the proxy record of Lake Sonachi that also derives from sediment-core archives (Verschuren, 1999).

The observed variability in lake levels in East Africa at the end of the 19th century and uncertain relationship noted between lowland lake levels and alpine icefields question the purported onset of modern deglaciation in the East African Highlands that is based on the posited decline in the level of Lake Victoria around 1880 (e.g., Hastenrath, 2001; Mölg et al., 2006). Outside of the East African Highlands, modern recession of tropical alpine glaciers in the is widely considered to have begun during the middle of the 19th century (Kaser, 1999; Hastenrath, 2001; Oerlemans, 2005; Thompson et al., 2006). As previously speculated by Hastenrath (2001), deglaciation in the East African Highlands may similarly have started during the middle of the 19th century but been interrupted by a brief period of anomalously high precipitation during the latter half of the 19th century. In the Rwenzori Mountains, Russell et al. (in press) observe decreases in the siliciclastic content of sediment in alpine lakes directly supplied by glacial meltwaters that suggest that deglaciation began prior to 1880AD (~1870AD).

The absence of sustained, long-term meteorological measurements in alpine areas and uncertainty in the relationship between lowland and highland hydrology highlight the importance of sediment-core archives of environmental change from alpine lakes in deducing the timing and drivers of deglaciation in the Rwenzori Mountains. Recent modelling of the mass balance of the Kersten Glacier on Kilimanjaro using meteorological and glaciological observations collected from February 2005 to January 2006 indicates that the glacier's mass balance is currently more sensitive to changes in precipitation than temperature (Mölg et al., in press). The relationship between these current calculations on Kilimanjaro and changes in temperature and precipitation experienced by icefields of the Rwenzori Mountains that are ~1 km lower in elevation and receive 3 to 4 times as much precipitation, remains uncertain. A multi-proxy palaeolimnological record spanning the last ca. 150 years from Lake Bujuku (Fig. 4) provides strong evidence of increased primary productivity (Panizzo et al., in press) that is consistent with evidence of recent warming (Taylor et al., 2006a).

5 Conclusions

Recent field surveys combined with historical observations confirm a continuation of rapid glacial recession in the Rwenzori Mountains. Observed acceleration in the retreat of the terminal positions of valley glaciers (Speke, Elena) since the 1960s results partly from the morphologies of the glaciers and beds within which the valley glaciers reside. Historical records combined with the first measurements of alpine riverflow in the Rwenzori Mountains show that the contribution of meltwater flows from dwindling icefields to alpine riverflow is negligible, <0.5% of the mean annual river discharge recorded at the base of the mountains.

Hydrometeorological changes associated with deglaciation in the Rwenzori Mountains have yet to be fully resolved. Limited observations of lowland humidity and river discharge at the base of the Rwenzori Mountains over the latter half of the 20th century provide no evidence of a reduction in alpine precipitation or humidity which has been proposed to explain observed glacial recession elsewhere in the East African Highlands (e.g. Kilimanjaro). A reduction in lowland precipitation that has been observed at the base of Kilimanjaro is not, however, evident over the 20th century from station observations around the Rwenzori Mountains. Previously reported increases in lowland air temperatures at the base of the Rwenzori Mountains, supported by very limited radiosonde measurements of temperature in the free troposphere, are consistent with palaeolimnological evidence of late 20th century warming in the Afroalpine zone indicated by a rise in alpine lake productivity. Recent monitoring of air temperature in the vicinity of icefields on Rwenzori Mountains show large increases in maximum daily air temperatures that coincide with episodic reductions in relative humidity and increased meltwater fluxes observed during the dry season.

Lake-level records in East Africa are inconsistent with a sudden decrease in regional humidity around 1880AD that is proposed to have triggered deglaciation in the East African Highlands. Water levels in Lakes Sonachi and Naivaisha, the most proximate lake records to the icefields of Mount Kenya and Kilimanjaro, rose at the end of 19th century when glaciers on both these mountains are observed to be in retreat. A rapid decline in the reconstructed level of Lake Victoria during the late 19th century that is presumed to reflect a dramatic shift in regional humidity, is the descending limb of a brief, high lake stand. Lake levels do not, furthermore, indicate that humidity over the 19th century prior to 1880AD is greater than during the 20th century. On the Rwenzori Mountains, warming over the latter half of the 20th century and an earlier onset of deglaciation (~1870AD) are suggested by available meteorological and palaeolimnological evidence. The timing and climate drivers of deglaciation in the Rwenzori Mountains are, therefore, broadly consistent with the recession of alpine icefields elsewhere in the tropics.

6 Dissemination & knowledge transfer

The dissemination of research findings and transfer of knowledge gained through this research project to local stakeholders and wider scientific community have been achieved through a variety of mechanisms including stakeholder meetings, scientific journals, popular press, conference presentations, and speaking invitations.

6.1 stakeholder meetings

Focused meetings were held to discuss the findings of research and solicit input from local stakeholders including Kasese District Council, Uganda Wildlife Authority, Rwenzori Mountaineering Service and Directorate of Water Resources Management (Uganda). In April 2007, discussions were held with the District Water Officer and District Environment Officer regarding the impact of glacial recession on streamflowe and the principal climate drivers of glacial recession in the Rwenzori Mountains. At this time, discussions were also held with the Chief Warden of Rwenzori Mountains National Park (Nelson Guma), the Rwenzori Mountaineering Service and local BaKonzo elders pertaining to (i) current glacial extent and the rate of glacial recession, (2) the implications of glacial recession on the safe movement of visitors and their support teams from UWA and RMS, (3) the factors, both local and regional, driving glacial recession, (4) the impact of glacial recession and related climate change on the Afroalpine environment and alpine rvierflow, and the impact of glacial recession on the traditional cultural beliefs of the BaKonzo. In July 2008, a draft copy of this report was delivered to the Chief Warden, Nelson Guma, of Rwenzori Mountains National Park.

6.2 scientific publications

Taylor, R.G., J. Russell, H. Eggermont, L. Mileham, C. Tindimugaya, D. Verschuren, M. Todd and L. Mwebembezi, *in review*. Hydrological and climatological change associated with glacial recession in the Rwenzori Mountains of Uganda. *Journal of Hydrology*

6.3 conference presentations and speaking invitations

Taylor, R.G., L. Mileham, C. Tindimugaya, and M. Leng, 2007. Hydrological implications of glacial recession in the Rwenzori Mountains of Uganda. *AGU Annual Congress* (San Francisco, USA)

Taylor, R.G., 2007. “Hydrological implications of deglaciation in the Rwenzori Mountains of East Africa” Department of Biology, University of Gent (Belgium)

6.4 popular press

01/06/2007 “Climate change and the BaKonzo” BBC Radio Science in Action

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