Climate Change and the Aquatic Ecosystems of the Rwenzori Mountains, Uganda

Final Report to the Royal Geographical Society


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EXECUTIVE SUMMARY

The Rwenzori Mountains are home to one of the last remaining tropical icefields outside of the Andes. Over the last century, equatorial icefields of the East African highlands have been steadily shrinking but the precise climate tropical alpine glaciers remain unclear. More than a decade had passed since the last detailed measurements of glacial cover were made in the Rwenzori Mountains. Recent evidence from Kilimanjaro suggests that its icecap will disappear entirely by the year 2020\(^{(1)}\). The Rwenzori glaciers contribute meltwater flows to aquatic ecosystems of the Rwenzori Mountains National Park, a World Heritage Site featuring spectacular, rare Afroalpine flora and fauna, and are headwaters of the River Nile. With the overall aim of assessing the impact of recent climate change on alpine aquatic ecosystems of the Rwenzori Mountains, a collaborative, international research team led by the University College London (United Kingdom) and Makerere University (Uganda), and involving the Institut für Geographie from the University of Innsbruck (Austria) and Water Resources Management Department (Uganda) was assembled in order to pursue three primary scientific objectives:

- to assess the magnitude of current glacial recession;
- to assess the impact of glacial recession on alpine riverflow; and
- to assess recent environmental change from observational datasets and available, environmental archives stored in lake sediment and glacial ice.

The research was supported by grants from the Royal Geographical Society (Ralph Brown Award 2003), The Royal Society, University of London (Central Research Fund, Convocation Trust), University College London (Dean’s Travel Fund, Department of Geography, The Friends Trust), Quaternary Research Association, and Earth and Space Foundation and Rwenzori Beverage Company Limited (Uganda). Institutional support was also provided by the Water Resources Management Department (Uganda), Makerere University, and Uganda Wildlife Authority.

Field research was primarily conducted in June 2003. The international research team comprising 7 researchers and 6 students were supported by 70 porters, guides and rangers making this the largest scientific expedition in the Rwenzori Mountains for half a century. A small follow-up expedition mapping glacial cover and measuring stream discharges was executed in January 2005.

The project made significant progress toward each of its objectives and led to several important findings detailed below.

1. The areal extent of glaciers in the Rwenzori Mountains in 2003 deduced from satellite data and field surveys is 1.0 ± 0.3 km$^2$. Glaciers are receding at a rate of ~0.7 km$^2$ per decade, consistent with a linear trend observed over the last century. Assuming present trends continue, glaciers are predicted to disappear within the next two decades.

2. Deglaciation over the last century is associated with rising air temperatures. Insufficient data exist to quantify the link between changes in climate variables and glacial mass but there is currently greater evidence of trends of increasing air temperature than decreasing humidity to explain recent glacial recession in the Rwenzori Mountains. Changes in humidity and radiative fluxes associated with rising air temperatures are expected to have contributed to observed glacial recession.

3. Glacial recession will have a minimal impact on alpine riverflow. Glacial meltwater flows, based on fluxes during the dry season, constitute a very small proportion (<0.5%) of the total river discharge realised at the base of the Rwenzori Mountains.

4. The lake ecology and flora of Afroalpine areas of the Central Rwenzori Massif have, based on sediment-core archives of diatom and pollen, not undergone significant changes over the period of deglaciation. There is, however, evidence of a recent decline in epiphytic habitats and concomitant increase in algal productivity.

5. Atmospherically deposited mercury, consistent with global trends and emissions, is detected in lake sediment within alpine environments (i.e., Heath-moss Forest zone at 3000 m asl and Afroalpine zone at 4000 m asl) in the Rwenzori Mountains. Trace-metal contamination via atmospheric deposition from more localised sources is observed in the Heath-moss Forest zone from the mid-1950s and coincides with onset of copper mining downslope.

Apart from the scientific outputs from this research, the project initiated a new scientific collaboration in palaeolimnology between the Environmental Change Research Centre, UCL and Department of Geology, Makerere University which included a subsequent visit to the UCL by Dr. Ssemmanda in 2004, funded by the Royal Society, to support palynological research examining Late Holocene changes in alpine vegetation of the Rwenzori Mountains. On-going research includes: (i) further analyses of environmental change based on sediment-core archives from Lakes Kitandara and Mahoma; (ii) a stable-isotope study of meltwater contributions and the origin of rainy season precipitation; and (iii) an altitudinal assessment of stream fluxes during the rainy season.
1 Introduction

1.1 Project rationale and objectives

Alpine aquatic ecosystems in the tropics are in a period of transition. Tropical alpine wetlands, lakes and streams that are supported by glacial meltwater flows, are affected by rapid recession of glaciers in response to global climate change (Thompson, 2000). Glaciers form important reservoirs of fresh water that store seasonal inputs of precipitation and release meltwaters during drier periods. They consequently serve the vital ecological function of regulating alpine streamflow and water levels in lakes and wetlands.

On the Rwenzori Mountains (0º10' to 0º30'N, 29º50' to 30º00'E), which straddle the border between the Republic of Uganda and the Democratic Republic of Congo, alpine wetlands, lakes and streams are supplied, in part, by snowfields that occur primarily on three mountains, Mount Stanley, Mount Speke and Mount Baker (Fig. 1). Glacial meltwater contribute to alpine riverflow upon which downstream BaKonzo and BaAmba communities rely for year-round water supplies and hydro-electric power generation. These aquatic environments, headwaters of the Nile, are home to a diverse range of flora and fauna, many of which are endemic and a few of which are listed in the IUCN Red List of Threatened Animals (Busulwa, 1998; Schmitt, 1998). Spectacular vascular plants include Giant Heather (*Erica spp.*), Giant Lobelia (*Lobelia wollastonii*) and Tree Senecio (*Dendrosenecio adnivalis*). Indigenous fauna include small mammals (*e.g.*, Rwenzori Otter-shrew), fish (*e.g.*, *Varicurhinus rwenzori*) and large mammals such as the Rwenzori Leopard.

By 1990, glaciers on the Rwenzori Mountains had receded to about 40% of their extent recorded in 1955 (Fig. 1) and less than one quarter of that measured by the Duke of Abruzzi in 1906 (Kaser and Osmaston, 2002). Apart from an expedition in 1993 (Talks, 1993), more recent assessments of glacial extent have been hindered by civil unrest in Uganda and conflict in the Democratic Republic of Congo (1998-1999). During the 20th century, glacial recession on the Rwenzori Mountains mirrored recession on Kilimanjaro in Tanzania (Hastenrath and Greischar, 1997) where Thompson *et al.* (2002) predict glaciers will disappear entirely by 2020. With continuing political stability in Uganda, a research project in the Rwenzori Mountains was proposed with the overall aim:

- to assess the impact of recent climate change on alpine aquatic ecosystems of the Rwenzori Mountains.
Three scientific objectives were identified in order to meet the project's overall aim:

1. to assess the magnitude of current glacial recession;

2. to assess the impact of glacial recession on alpine riverflow; and

3. to assess recent environmental change from observational datasets and available, environmental archives stored in lake sediment and glacial ice.

Figure 1. The Central Rwenzori Massif showing alpine lakes, wetlands, streams and the extent of glacial snow cover in 1955 and 1990 (redrawn and adapted from Osmaston and Kaser, 2001).
1.2 Rwenzori Mountains National Park

The Rwenzori Mountains 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 was tilted up in an ESE to WNW direction 4 km above the surrounding peneplain known as the ‘African Surface’ in the Late Pliocene (Figs. 2) (Osmaston, 1989; Taylor and Howard, 1998). Occupying an area of 3000 km$^2$, the horst is bounded to the north and south by grabens that feature Lakes Albert and Edward respectively (Figs. 1 and 3). A maximum elevation of 5109 metres above mean sea level (mamsl) is currently reached by Margherita Peak on Mount Stanley.

The name, “Rwenzori” is a colonial-era corruption of “Rwenzururu” meaning place of snow (“rwe nzururu”). Although the mountain range is only 40km from the equator, glaciers currently occur on three mountains: Stanley, Speke and Baker, due to a combination of cold temperatures and abundant precipitation ranging from 2000 to 2700 mm·a$^{-1}$ (Kaser and Osmaston, 2002). Glaciers also lie at the centre of the traditional belief system of the BaKonzo who have long lived in the foothills of the Rwenzori Mountains (Alnaes, 1998). Snow/ice, "Nzururu", is the 'father' of the BaKonzo deities, "Kitasamba" and “Nyabibuya” who are responsible for human life, its continuity and its welfare. The area now occupied by the Rwenzori Mountains above an approximate elevation of 1700 mamsl in Uganda (996 km$^2$) was gazetted as a national park in 1991. Rwenzori Mountains National Park was subsequently made a World Heritage Site in 1994.

![Figure 2](image-url)

*Figure 2.* 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.
1.3 Project planning

A joint expedition between University College London, UK (UCL) and Makerere University, Uganda (MUK) was first proposed during research visits by Richard Taylor (UCL) to Uganda in 2001 (December) and 2002 (July-August). The broad aim and scientific objectives of the project were established during the latter visit in 2002 and through correspondence with members of the expedition team including primarily Andrew Muwanga, Bob Nakileza and Immaculate Ssemmanda (MUK), Callist Tindimugaya (Water Resources Management...
Department), Neil Rose and Anson Mackay (UCL), and Andrea Fischer (University of Innsbruck). Extensive consultation via electronic mail was also made with members of the expedition advisory panel including most notably Henry Osmaston, Daniel Livingstone, Georg Kaser and Deo Lubega. The programme of research in the Rwenzori Mountains National Park was subsequently approved by the Uganda National Council for Science and Technology (File No. EC 583) and Uganda Wildlife Authority.

Expedition planning began in February 2003 following confirmation that the proposed research had received a grant from the Royal Geographical Society (co-winners of the Society’s 2003 Ralph Brown Award). In April (2003), researchers from Ohio State University including Professor Lonnie Thompson were forced to pull out of the expedition as the American State Department advised American citizens against travel to East Africa due to the threat of terrorist activities associated with the Anglo-American invasion of Iraq. Collection of an environmental archive in glacial ice was consequently abandoned. In this same month, logistical details including a project timetable, equipment needs and division of responsibilities were resolved during a visit by Richard Taylor to Uganda. Food and necessary equipment were subsequently purchased in Uganda and United Kingdom and greatly facilitated by the work of Nelson Kisaka (Makerere University).

1.4 Project team

1.4.1 June 2003 expedition

The project features close collaboration between Ugandan scientists and students from Makerere University and Water Resources Management Department, and their counterparts from University College London (UK) and Institut für Geographie (Austria). To develop new scientists, six students from Makerere University and University College London participated in this expedition. Overall, the team possesses expertise in key fields of hydrology, alpine glaciology, palaeolimnology, palynology, ecology, hydrogeochemistry and geomorphology. Critical logistical support was provided by the Rwenzori Mountaineering Service (guides, cooks, porters) and Uganda Wildlife Authority (project liaison, rangers). Members of the expedition team are listed below.

**Department of Geography, University College London (UCL)**
Dr. Richard Taylor (co-expedition leader, hydrologist, geochemist)
Dr. Anson Mackay (palaeolimnologist, diatomist)
Dr. Neil Rose (palaeolimnologist, environmental geochemist)
Lucinda Mileham (student)
Virginia Panizzo (student)
Adinah Shackleton (student)
Departments of Geography and Geology, Makerere University
Dr. Andrew Muwanga (co-expedition leader, hydrologist, geochemist)
Dr. Immaculate Ssemmanda (palynologist)
Dr. Bob Nakileza (alpine geomorphologist)
Nelson Kisaka (student)
Alex Mbonimba (student)
Allen Ndyanabo (student)

Water Resources Management Development (WRMD)
Callist Tindimugaya (isotope geochemist)

Institut für Geographie, University of Innsbruck
Dr. Andrea Fischer (glaciologist)

Uganda Wildlife Authority (UWA)
Aggrey Rwetsiba (project liaison, Kampala)
Baluku Salevano (project liaison, Nyakalengija)
Sinairi Koffi (ranger)
Michael Mugabe (ranger)

Rwenzori Mountaineering Service (RMS)

1.4.2 January-February 2005 expedition

Department of Geography, University College London (UCL)
Dr. Richard Taylor (expedition leader, hydrologist, geochemist)
Lucinda Mileham (student)
Uganda Wildlife Authority (UWA)
Aggrey Rwetsiba (project liaison, Kampala)
Guma Nelson (project liaison, Nyakalengija)

Rwenzori Mountaineering Service (RMS)
Bwambale Jales (guide), Baluku Josephat (guide), Nason Rwaburara (cook),
porters: Cypriano Bwambale, Iseban Gideon, Baluku Simon, Kule Kikumbwa,
Zablan Wilson, Nyamambisi Misaki, Bwambale Zikalia, Baluku Dimiano, Monday
spay, Tsomwa Erineo, Thahimba Erinerico,

1.4.3 Project advisory panel
Henry Osmaston (Cumbria, UK)
Georg Kaser (University of Innsbruck, Austria)
Daniel Livingstone (Duke University, USA)
Lonnie Thompson (Ohio State University, USA)
Deo Lubega (Kampala, Uganda)
Joel Okonga (Water Resources Management Department, Uganda)

1.5 Report layout
The report is grouped into six chapters. Chapters 2 and 3 detail surveys of glacial
extent and changes in climate deduced from meteorological observations over
the last century. Substantial portions of both of these chapters have been
published in the journal, *Geophysical Research Letters* (Taylor et al., 2006a;
2006b). Chapter 4 discusses the impact of glacial recession on alpine riverflow
and investigates trends in hydrological observations coincident with the recent
period of deglaciation. Chapter 5 assesses environmental changes in the
Afroalpine region of the Rwenzori Mountains deduced from environmental
proxies, primarily diatom and pollen, in sediment-core archives from Lake Bujuku
(Fig. 1). A slightly revised version of chapter 5 is expected to appear in a
forthcoming volume of the *Journal of Paleolimnology* (Panizzo et al., in review).
Chapter 6 reviews evidence of pollution from atmospherically deposited trace
metals and fly ash recorded in the sediment of alpine lakes ranging in elevation
from 3000 to 4000 m amsl. This chapter is a revised version of the M.Sc.
deposited pollutants in Rwenzori Mountain lakes, Uganda.*
2 Recent glacial recession in the Rwenzori Mountains and rising air temperatures

2.1 Introduction

Tropical alpine glaciers serve as highly sensitive indicators of tropical climate (Wagnon et al., 1999; Francou et al., 2003) that are particularly valuable in areas where meteorological records are scarce. In the East African Highlands, glaciers have been shrinking over much of the 20th century (Hastenrath and Kruss, 1992; Kaser and Noggler, 1996; Hastenrath and Greischar, 1997; Kaser and Osmaston, 2002; Thompson et al., 2002). Mapping of glacial extent in the Rwenzori Mountains (Fig. 4a), was, however, last conducted more than a decade ago (Kaser and Noggler, 1991; Talks, 1993). There is also uncertainty regarding the nature of climate change in these highlands (Hay et al., 2002; Patz et al., 2002; Kaser et al., 2004).

The first survey of glaciers in the Rwenzori Mountains was conducted in 1906 by the Duke of the Abruzzi (1907) when the glacial cover over the entire range was estimated to be 7.5 km² (Kaser and Noggler, 1996) and the lowest altitude of glaciation is thought to have reached 4400 metres above mean sea level (mamsl) (Osmaston, 1989). Scientific surveys carried out in the 1950s (Menzies, 1951; Bergstrøm, 1955; Whittow et al., 1963) and early 1990s (Kaser and Noggler, 1991; 1996; Talks, 1993) indicate a continuing trend of glacial recession though a brief episode of terminal advance was observed in the early 1960s (Whittow et al., 1963; Temple, 1967). This coincides with a period of anomalously high precipitation when the levels of Lake Victoria rose by 2.5 m (Kite, 1981).

2.2 Field and satellite mapping

Recent glacial recession was assessed by field mapping of the terminal positions of previously monitored 'indicator' glaciers, Elena and Speke (Fig. 4b), and quantitative interpretations of snow and ice cover using optical spaceborne imagery (LandSat5, LandSat7). Field surveys of glacial termini on Mounts Speke and Stanley using a handheld global positioning system (GPS) were conducted in June 2003 and January 2005 (Fig. 5). These included an assessment of the distance between observed termini and the positions of terminus markers set in 1958 (Whittow et al., 1963) and 1993 (Talks, 1993).
Changes in the areal extent of glaciers were assessed using two geometrically corrected LandSat5 (TM) and one systematically corrected LandSat7 (ETM+) optical satellite image accessed from the United States Geological Survey (http://edcdaac.usgs.gov and http://glovis.usgs.gov). Three LandSat images with views of the still glacierised summits unobstructed by clouds were identified in 1987 (7 August), 1995 (17 January) and 2003 (31 January). In the inner tropics where diurnal variations in mean air temperature (~8°C) significantly exceed seasonal variations (~2°C) (Paffen, 1967 cited in Kaser and Osmaston, 2002), ablation on glacial tongues occurs throughout the year. Snow falling below glacial termini in the Rwenzori Mountains is subject to rapid melting through daily ablation during daylight hours and accumulation is confined to high glacial areas during periods of heavy precipitation (rainy seasons). The areal extent of snow and ice inferred from satellite imagery was, therefore, considered to represent glacial cover.
LandSat images were subsampled to create specific images of each mountain in the Central Rwenzori Massif (Fig. 4b). Areal extent of snow and ice was determined using supervised classification (SC) on a false-color composite of bands 2 (visible (green), 0.52-0.60 µm), 4 (near infrared, 0.75-0.90 µm) and 5 (mid-infrared, 1.55-1.75 µm) as this best represents snow (Vogel, 2002). To test the accuracy of estimates derived from SC, the deduced areal extent of glaciers was also calculated using the Normalised Difference Snow Index (NDSI) (eq. 1). The NDSI contrasts the brightness of snow in band 2 with its low reflectivity in band 5. For the most recent (2003) image, field surveys assisted in supervision of classification of glacial cover and confirming the applied NDSI threshold distinguishing glacial cover from rock.

\[
NDSI = \frac{\text{band} 2 - \text{band} 5}{\text{band} 2 + \text{band} 5} \tag{eq. 1}
\]
2.3 Results

2.3.1 Field surveys of glacial extent

Field surveys of the terminal positions of the Speke and Elena Glaciers demonstrate a continuation of the overall trend of recession observed between 1906 and 1990. The terminus of the Elena glacier has retreated by ~400 m since 1906 and 140 m ± 17 m since 1990 (Fig. 4c). Terminal retreat on the Speke glacier is more rapid, ~600 m since 1906 and 311 m since 1993 (Fig. 4d). The contrasting rates are considered to result primarily from differences in the supply of ice to these valley glaciers as a result of their elevation and bed morphology (Fig. 4b). 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) resides above the highest peak on Mount Speke (Vittorio Emanuele), an elevation of approximately 4900 masl. As the equilibrium line altitude (ELA) for each mountain has risen since the last glacial maximum (Mahoma Stage) and particularly over the last century (Osmaston and Kaser, 2001), the supply of ice to Elena Glacier from the Stanley plateau would have continued for longer than that to the Speke Glacier. Mölg et al. (2003) contend that the ELA for Mount Stanley was 4900mamsl in 1955 and conclude that no effective accumulation has occurred on Mount Speke and neighbouring Mount Baker (Fig. 4b) during the 20th century. The impact of ice supply on rates of terminal retreat (i.e., glacial recession) is considered in detail below.

The Speke Glacier is the largest single valley glacier in the Rwenzori snowfield (Fig. 6) and its terminal position has, in a relative sense, been monitored quite frequently. Repeated measurements of the terminal position of the Speke Glacier in relation to a marker established in 1958 (Fig. 6c) show that rates of terminal retreat have increased from 3 m per annum (1962-1977) to 31 m per annum (1993-2003). Similar exponential retreat of glacial termini has 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). As linear rates of recession have been used to predict the lifetime of tropical glaciers (Thompson et al., 2002), these observations appear to suggest that the loss of tropical glaciers may be even more rapid. 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 equilibrium-line-altitude (ELA)\(^1\). 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.

\(^1\) The equilibrium-line-altitude represents the elevation at which glacial accumulation is balanced by ablation. In the wet inner tropics that include the Rwenzori Mountains, high accumulation (as a result of a high precipitation) tends to depress the ELA just below the 0°C elevation (Kaser and Osmaston, 2002).
Depending on the morphology of the glacier and its bed, the rate of retreat of the terminus may directly reflect the rate of volume loss. This is unlikely, except in uniformly sloping valleys, and 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 (Figs. 7 and 8) from which avalanches of snow shed down a steep rock face. 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. Retreat was consequently negligible. Retreat then took place horizontally across the basin, now occupied by a pool (Lake Ruhandika). Although the glacier still sloped down steeply, it was still thick so that retreat occurred at a modest rate. To the northeast of Lake Ruhandika, the bed slopes steeply at approximately the same gradient as did the glacier surface. There is abundant photographic evidence of thinning of the whole Speke Glacier (e.g., Kaser and Noggler, 1996), right up to its highest limits. 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. This 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. Thus, the bed and glacier morphologies are able to explain, in part, the exponentially accelerating rate of terminus retreat that has been observed and the fact that retreat has occurred more rapidly than Elena Glacier on Mount Stanley.

### 2.3.2 Mapping glacial cover by remote sensing

Analyses of LandSat imagery using supervised classification (SC) and NDSI identify a ~50% decrease in the total area of glaciers from 1987 (2.01±0.11 km²) to 2003 (0.96±0.34 km²). Broad agreement exists between estimates of glacial cover (<12% difference) derived from each method (Table 1). The results of the NDSI-classified, LandSat image from 1987 are consistent with historical data derived from aerial and terrestrial photography (Kaser and Noggler, 1996; Kaser and Osmaston, 2002). On all three of the still glacierised mountains in the Central Rwenzori Massif, the estimated areal extent of glaciers in 1987 is less than the area in 1955 but greater than that assessed for 1990 (Table 1). The estimated areal extent of glaciers on Mount Baker derived from LandSat data in 1995 is slightly larger (0.08 km²) but within analytical error of the area estimated from terrestrial photographs in 1990. Outlines of glacial extent on Mount Speke mapped by Kaser and Osmaston (2002) for 1906, 1955 and 1990 are overlain on a subsample of the NDSI-classified LandSat7 image from 2003 in Fig. 4d. High reflectance areas (pixels), classified as glacial cover, clearly demonstrate the loss of glacial cover at lower elevations since 1990.
Table 1. Areal extent of glacial cover (km$^2$) on the Central Rwenzori Massif (Fig. 4b). Estimated errors derive from the classification and geometry of pixels.

<table>
<thead>
<tr>
<th>Year</th>
<th>Method</th>
<th>Baker (km$^2$)</th>
<th>Speke (km$^2$)</th>
<th>Stanley (km$^2$)</th>
<th>Total (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1906$^a$</td>
<td></td>
<td>1.47</td>
<td>2.18</td>
<td>2.85</td>
<td>6.50</td>
</tr>
<tr>
<td>1955$^a$</td>
<td></td>
<td>0.62</td>
<td>1.31</td>
<td>1.88</td>
<td>3.81</td>
</tr>
<tr>
<td>1987$^b$</td>
<td>SC</td>
<td>0.43±0.13</td>
<td>0.65±0.18</td>
<td>1.03±0.25</td>
<td>2.11±0.56</td>
</tr>
<tr>
<td></td>
<td>NDSI</td>
<td>0.38±0.04</td>
<td>0.63±0.02</td>
<td>1.00±0.05</td>
<td>2.01±0.11</td>
</tr>
<tr>
<td>1990$^a$</td>
<td>SC</td>
<td>0.12±0.01</td>
<td>0.56±0.06</td>
<td>1.00±0.10</td>
<td>1.68±0.17</td>
</tr>
<tr>
<td></td>
<td>NDSI</td>
<td>0.21±0.06</td>
<td>0.45±0.11</td>
<td>0.69±0.15</td>
<td>1.35±0.32</td>
</tr>
<tr>
<td>1995$^b$</td>
<td>SC</td>
<td>0.20±0.09</td>
<td>0.44±0.17</td>
<td>0.86±0.10</td>
<td>1.50±0.36</td>
</tr>
<tr>
<td></td>
<td>NDSI</td>
<td>0.16±0.05</td>
<td>0.40±0.08</td>
<td>0.53±0.09</td>
<td>1.09±0.22</td>
</tr>
<tr>
<td>2003$^b$</td>
<td>SC</td>
<td>0.11±0.03</td>
<td>0.35±0.11</td>
<td>0.50±0.20</td>
<td>0.96±0.34</td>
</tr>
</tbody>
</table>

$a$: (Kaser and Osmaston, 2002); $b$: this work

Figure 6. The changing rate of terminus retreat of the Speke Glacier from 1958 to 2003 is shown in the inset of photograph (a). Field survey of terminus retreat in 2003, relative to the 1993 marker (Talks, 1993), 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).
Figure 7. (a) Terrestrial photograph of the Speke Glacier from Mount Stanley in 2005 showing the steep slopes below the glacier’s current and former terminus (photo: Alan Killian). (b) NDSI-classified Landsat7 image from 31 January 2003.

Figure 8. A conceptual, cross-sectional representation of changes in the profiles of ‘indicator’ valley glaciers (shaded): (a) Elena and (b) Speke in the Rwenzori Mountains from 1991 to 2005 (adapted from Kaser and Osmaston, 2002). Surface profiles are drawn relative to an air-photograph survey of glacier cover in 1955. Glacial thickness and bed topography are not known precisely. Vertical exaggeration is x 2.
The recent field surveys and satellite mapping of glacial cover on the Central Rwenzori Massif show continued rapid reduction in glacial extent (Fig. 9) since the last field measurements were taken in the early 1990s (Kaser and Noggler, 1991; Talks, 1993; Kaser and Noggler, 1996; Kaser and Osmaston, 2002). Measurements over the last century indicate a relatively steady rate of decline in glacial extent though linearity ($r^2 = 0.999$) in the rate of recession may derive, in part, from the limited number and uneven distribution of observations. Advance of the Speke Glacier was, for instance, detected during a period (1961 to 1962) of frequent monitoring and anomalously high precipitation (Temple, 1967). Glaciers in the Rwenzori Mountains are, nevertheless, expected to disappear within the next two decades if deglaciation continues to follow the observed linear trend (Fig. 9).

![Figure 9. Plot of changes in glacial areal extent on the Central Rwenzori Massif since 1906. Data from 1906, 1955 and 1990 derive from Kaser and Osmaston (2002). Remaining observations derive from NDSI classification of Landsat 5 (TM) and Landsat 7 (ETM+) scenes (Table 1).](image)

### 2.4 Meteorological trends

The absence of continuous and proximate meteorological observations in the Rwenzori Mountains prevents direct analysis of the climatic factors driving observed glacial recession. Previous studies of glacial dynamics in the East African Highlands (e.g. Kruss and Hastenrath, 1987; Kaser and Noggler, 1991; Mölg et al., 2003; Kaser et al., 2004) contend that recession over the 20th century arises principally from an abrupt decrease in humidity at the end of the 19th century (ca. 1880). Decreased humidity increases the exposure of glaciers to solar radiation through reduced cloud cover. An associated decline in precipitation lowers accumulation and increases absorption of radiation due to the lower albedo of ice, relative to snow (Mölg et al., 2003; Kaser et al., 2004). As a result, the rate of glacier net mass loss consequently rises.
Hastenrath (2001) citing studies on Mount Kenya (Kruss, 1983; Hastenrath and Kruss, 1992), posits that glacial recession in the East African Highlands beyond the early decades of the 20th century has been promoted by a warming trend that has increased atmospheric humidity. This inhibits sublimation and permits more of the sun’s energy to melt glacial ice due to a saving of latent heat. This has been well demonstrated on the Zongo and Chaccaltaya glaciers in Bolivia where higher melt rates in the wet season (i.e. period of increased humidity) result from reduced sublimation (Wagnon et al., 1999; Francou et al., 2003). Though differential recession of glaciers in response to variations in solar incidence has been proposed for the Rwenzori Mountains (Mölg et al., 2003), the spatially uniform loss of glacial cover in the Rwenzori Mountains at lower elevations over the last decade strongly suggests increased air temperature is the main driver.

Terrestrial observations of air temperature ($T_a$) are consistent with a warming trend indicated by recent glacial recession. Daily records of maximum and minimum air temperature at meteorological stations east of the Rwenzori range between latitudes of 1º41'N and 1º15'S in Uganda (Fig. 4a) show significant (at confidence intervals of 99% or greater) and consistent trends toward increased air temperatures of ~0.5ºC per decade since the last period of glacial advance in the early 1960s (Fig. 10). These data contain, however, significant gaps and are limited in duration. Gridded CRU2 climate data (New et al., 2002) for the grid cell closest to the Rwenzori Mountains (0º50'N, 29º30'E) also demonstrate a small but significant rise in mean surface temperature of 0.15ºC per decade from 1960 to 1998 that is consistent with a regional warming trend of the same magnitude determined by Patz et al. (2002). Because of the thermal homogeneity of the troposphere in the inner tropics (Kaser and Osmaston, 2002; Oerlemans, 2005), the recent (post-1960) rise in air temperature observed at stations between 960 and 1869 mamsl is also expected to occur in areas of glacial cover between 4800 and 5100 mamsl. This assumption is discussed in detail in section 3.2.

The possibility that recent glacial recession arises from a reduction in precipitation is unsupported by station data in western Uganda over the 20th century. Records of annual precipitation demonstrate considerable interannual variability (Fig. 11) which is thought largely to be controlled synoptically by sea surfaces temperatures of the Indian Ocean via the El Niño Southern Oscillation (Ogallo, 1988) and Indian Ocean Dipole (Conway et al., 2007). Mölg et al. (2006) cite historical evidence in support of a reduction in humidity in East Africa beginning around 1880 (Nicholson and Yin, 2001). The evidence is anecdotal and it remains unclear whether the posited change follows a sustained period of greater humidity or a brief anomaly (see sections 3.3 and 4.6). Meteorological records in Uganda begin at the end of the 19th century and are, thus, unable to investigate whether a posited warming trend starting in the 19th century (Oerlemans, 2005) also contributed to the onset of deglaciation in the East African Highlands.
Figure 10. Standardised anomalies in annual mean maximum (solid circles) and mean minimum (open circles) air temperature observed at meteorological stations in western Uganda and annual mean temperature from gridded CRU2 climate data (New et al., 2002) over the 20th century.
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.

2.5 Conclusions

Recent field mapping and analysis of Landsat imagery confirm a rapid decline in the areal extent of glaciers on the Central Rwenzori Massif that is consistent with an overall recessionary trend over the 20th century. Glacial cover on the three remaining glacierised summits (Mounts Stanley, Speke and Baker) has decreased from $2.01 \pm 0.56 \text{ km}^2$ in 1987 to $0.96 \pm 0.34 \text{ km}^2$ in 2003 and is expected to disappear within the next two decades. Field surveys highlight the importance of bed morphology in determining the rates of glacial termini retreat. Climate inferences attributed solely to rates of termini advance or retreat must therefore be regarded with caution. Increased air temperature suggested by the spatially uniform nature of recent loss of glacial cover at lower elevations, is supported by station data in western Uganda and gridded climate data sets. The observed rise in air temperatures over the last four decades is also consistent with warming trends predicted in the tropical troposphere from climate model simulations that incorporate historical increases in greenhouse gases (Santer et al., 2005).
3 Climatological implications of glacial recession in the Rwenzori Mountains

3.1 Introduction

Debate persists as to the extent to which recent glacial recession observed in tropical highlands is driven primarily by changes in air temperature (e.g. Bradley et al., 2006; Thompson et al., 2006) and atmospheric humidity (e.g. Kaser et al., 2004; Mölg and Hardy, 2004). Uncertainty has also been expressed in the relationship between temperature trends at the surface and higher elevations in the tropical free troposphere (e.g. Christy et al., 2003; Christy and Norris, 2004; Douglass et al., 2004; Fu et al., 2004; Tett and Thorne, 2004) where alpine glaciers reside. Although the surface energy balance and mass balance are best able to describe the relationship between climate parameters and glacier change (e.g. Wagnon et al., 1999; Mölg and Hardy, 2004), measurements that would form the basis of a glacier mass balance model of the Rwenzori Mountains do not exist. Although a definitive, quantitative understanding of the climate variables responsible for glacier mass losses in the Rwenzori Mountains remains elusive, we show that trends of increasing air temperature are better supported by currently available evidence than decreasing humidity.

3.2 Relationship between $T_a$ at the surface and mid troposphere

The validity of the assumption that $T_a$ trends observed in gridded CRU TS 2.0 climate data sets (New et al., 2002) and at meteorological stations between 960 and 1869 mamsl, reflect $T_a$ trends in the middle troposphere where glaciers in the Rwenzori Mountains occur, is open to question. Significant uncertainty persists in temperature data for the tropical troposphere whether these derive from satellite-borne Microwave Sounding Unit (MSU) observations or in situ measurements using radiosondes, particularly in data-poor regions like East Africa. Indeed, linear $T_a$ trends in the tropical troposphere can vary significantly based simply upon choice of start and end date as is the case in the paper by Gaffen et al. (2000) using MSU data in which at 500hPa a cooling trend is detected between 1979 and 1997 but an overall warming trend occurs between 1960 and 1997. Nevertheless, recent studies that employ diurnal corrections to MSU observations between 1979 and 2003 (Mears and Wentz, 2005) and homogenized radiosonde datasets (HadAT2) between 1958 and 2002 (Thorne et al., 2005), show that the middle troposphere warmed at a similar or slightly greater rate to the surface in the tropics (Fu and Johanson, 2005; Santer et al., 2005), consistent with the sign and (within error) magnitude of $T_a$ trends (+0.13°C
Upper air temperature records from gridded HadAT2 radiosonde data (Thorne et al., 2005) for the most proximate (and only) grid cell to the Rwenzori Mountains show consistent warming trends in the lower and middle troposphere (700hPa, 500hPa) from 1958 to 2005 (Fig. 12). These warming trends coincide with increased $T_a$ trends at the surface over the second half of the 20th century that have been detected in gridded (homogenized) CRU TS 2.0 datasets (New et al., 2002) at four locations in the East African Highlands by Pascual et al. (2006) and the Rwenzori Mountains (Fig. 10). The increased incidence of malaria observed in the East African Highlands is considered, in part, to arise from rising air temperatures (Pascual et al., 2006) as mosquitoes are able to colonise environments at elevations that previously restricted mosquito populations and, hence, malaria transmission by temperature (i.e., $<15^\circ$C). Local records for Kasese District at the base of the Rwenzori Mountain show over a 6-year period that malaria incidence have risen at a rate of over 24 000 cases per year from 172 992 cases initially recorded in 1998. A peak of 457 601 cases was then recorded in 2004. Other factors, apart from a rise in air temperature, such as the conversion of forest cover to cropland, increased migration, and improved reporting procedures are also considered to have contributed significantly to the observed rise in the incidence of malaria.

A comparison of temperature trends from surface observations at high elevations and free troposphere (radiosonde measurements) indicates more rapid warming of alpine surfaces than the free troposphere (Pepin and Seidel, 2005) though this discrepancy is reduced for mountain peaks and may stem from a systematic cooling bias arising from daytime heating of the radiosonde sensors (Sherwood et al., 2005). Analyses of station data in the tropical Andes (Vuille and Bradley, 2000) and on the Tibetan Plateau (Liu and Chen, 2000) show that $T_a$ trends between 1000 and 5000 masl remain constant in sign (i.e. increasing $T_a$) but can vary in magnitude (+0.1 to +0.3ºC per decade). It is worth noting that a step-wise increase in $T_a$ during the 1970s, noted globally at the surface (Jones and Moberg, 2003) and in the troposphere (Thorne et al., 2005) as well as in the tropical Andes (Vuille and Bradley, 2000), is also observed at the surface in CRU TS 2.0 datasets in the East African Highlands (Fig. 1 in Pascual et al., 2006) and station data in western Uganda (Fig. 10).

### 3.3 Trends in atmospheric humidity

Mölg et al. (2006) employ NCEP reanalysis data to indicate a trend of decreasing specific humidity in the mid-troposphere (600hPa) from 1948 to 2005. Quite apart from the time-dependent biases in all NCEP data, the reliability of the specific humidity data is particularly questionable as NCEP humidity is a statistically derived parameter. The ability of NCEP humidity data to represent interannual
Figure 12. Time series of monthly air temperature anomalies in the lower and middle troposphere from homogenised radiosonde datasets (HadAT2) (Thorne et al., 2005) at (a) 700hPa and (b) 500hPa for the most proximate grid cell (35ºE, -2.5ºS) to the Rwenzori Mountains. Bold lines in (a) and (b) represent the 12-month running mean.

Figure 13. Time series of mean annual anomalies in (a) vapour pressure (1901 to 1995) and (b) precipitation (1901 to 1998) from gridded CRU TS 2.0 climate data (New et al., 2002) for the most proximate grid cell (29.5ºE, +0.5ºN) to the Rwenzori Mountains.
precipitation anomalies associated with the dominant modes of climate variability in equatorial east Africa does not bear on the reliability of these datasets for trend analyses. Radiosonde-derived humidity from 1965 to 1984 (Hense et al., 1988) cited in support of NCEP specific humidity trends from 1948 to 2005, are in fact uncorrected; systemic dry biases have been carefully removed from more recent corrected datasets (Guichard et al., 2000). A decline in humidity over the 20th century is, furthermore, unsupported by surface CRUTS 2.0 precipitation and vapour pressure datasets (Fig. 13).

Mölg et al. additionally argue that observed glacial recession in the East African Highlands over the last century originates from a drastic reduction in moisture in the late 19th century. This drop in moisture, based on historical evidence of the levels of Lake Victoria and other East African lakes (Nicholson and Yin, 2001), is actually the descending limb of a temporary (less than two decades) high lake stand (Fig. 14). Lake levels, a remote and indirect proxy of regional humidity, are variable during the 19th century prior to their peak in 1880 but comparable to lake levels throughout the 20th century. A modern comparison to the 19th century event is the 2.3 m rise in the level of Lake Victoria between October 1961 and May 1964 (Fig. 14). The implied increase in humidity associated with this lake-level rise coincided with a very brief (1 year) and very marginal advance (3 to 5 m) in the terminal positions of valley glaciers in the Rwenzori Mountains (Temple, 1967). The humidity hypothesis proposed by Mölg et al. (2006) contends that (1) termination of a brief period of accumulation due to enhanced precipitation around 1880 led to continued glacial retreat into the latter half of the 20th century and (2) a trend of decreasing humidity, supported only by NCEP reanalysis data for which trend analysis is inappropriate, has driven glacial recession since 1970. Even ignoring concerns regarding this evidence, the argument that these climate events are responsible for the expected demise of small, fast-responding glaciers that have persisted for at least 5000 years (Thompson et al., 2006) is improbable.

Figure 14. Level of Lake Victoria at Jinja (33.2°E, 0.2°N) from 1800 to 2005 based on historical evidence from 1800 to 1896 (Nicholson and Yin, 2001) and monthly observations from 1896 to 2005.
3.4 Conclusions

Both increasing air temperature and reduced air humidity remain plausible and likely related hypotheses to explain recent glacial recession in the Rwenzori Mountains of East Africa. There are insufficient data to represent the complex interactions of radiant energy and heat at the glacier’s surface and thus quantify the link between changes in climate variables and glacial mass in the Rwenzori Mountains. There is, however, currently greater evidence of trends of increasing air temperature than decreasing humidity to explain deglaciation in the Rwenzori Mountains. This conclusion does not preclude, however, the likelihood that changes in humidity and radiative fluxes associated with rising air temperatures, have also contributed to observed glacial recession.
4 Hydrological implications of glacial recession

4.1 Introduction

The hydrological implications of recent deglaciation in the Rwenzori Mountains outlined in Chapter 2 are unclear. Shrinking icefields not only affect glacial meltwater discharges but also signal a net deficit between accumulation and ablation. Gasse (2002) and Thompson et al. (2002) have expressed concern over the direct impact of glacial recession on alpine riverflow and, thus, freshwater resources in the East African Highlands particularly during dry (low-flow) periods. In the Rwenzori Mountains, communities rely upon alpine riverflow for year-round water supplies and generation of hydro-electric power. Little is known, however, of the characteristics of alpine riverflow in the highland areas due to a near absence of glacial meltwater and stream discharge measurements. Current monitoring of riverflow at the base of the Rwenzori Mountains (Fig. 15) is restricted to the River Nyamagasani though historical records exist for Rivers Mubuku, Semliki, Rwimi, and Rukoki that drain the alpine areas of the Rwenzori Mountains.

Tropical alpine glaciers are highly sensitive indicators of climate change [Kaser, 1999] but, as discussed in Chapter 3, the precise climate signals indicated by shrinking icefields in the East African Highlands that include Mount Kenya, Kilimanjaro and the Rwenzori Mountains, are the subject of much debate [e.g. Thompson et al., 2002; Kaser et al., 2004; Chapter 2). Hastenrath [2001] contends that glacial recession on Mount Kenya was initiated by a sharp reduction in humidity in the late 19th century but sustained beyond the early decades of the 20th century by a warming trend that has 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 saving of latent 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 (Chapters 2 and 3). In contrast, Mölg et al. (2003) argue that recent glacial recession in the Rwenzori Mountains has resulted from 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.

In this chapter, we assess both the impact of glacial recession on alpine riverflow in the Rwenzori Mountains and hydrometeorological trends in western Uganda, indicated by station data and historical evidence, over the period of observed deglaciation.
4.2 Hydrology of the Rwenzori Mountains

4.2.1 Quaternary glaciations

Glaciers have played a major role in shaping the upper slopes of river basins that drain the Rwenzori Mountains (Fig. 16). Alternating cycles of glacial and fluvial erosion, extensively reviewed by Osmaston (1989), have produced glaciated surfaces and deeply incised valleys. Moraine evidence reveals three major Pleistocene glaciations: the Katabarua stage, ca. 300 000 years before present (BP) (glacial cover ~500 km²); Rwimi Stage, ca. 100 000 years BP (glacial cover ~300 km²); and Mahoma stage, ca. 15 000 to 20 000 years BP (glacial cover ~260 km²) (Kaser and Osmaston, 2002). The Katabarua stage occurred on previously undissected land allowing a large plateau ice cap to develop, creating the most extensive glaciers in East Africa (Osmaston and Kaser, 2001). The upward tilt of the Rwenzori horst in a WNW direction (Fig. 2) caused glaciers to develop more extensively on ESE-facing slopes and occupy a large proportion...
(~430 km²) most of what is now demarcated as the Rwenzori Mountains National Park in Uganda.

The incision of drainage during the long cycle of erosion that followed the Katabarua stage meant that subsequent glaciations were significantly smaller and occurred as valley glaciers (Osmaston, 1989). Evidence of the Mahoma Stage is most abundant on the mountain with large moraines in all of the main valleys. Ice tongues at this time extended to 2000 mamsl and pollen evidence suggests that temperatures were 4 to 6 ºC colder than present (Kaser and Osmaston, 2002). Caution is, however, required in drawing simple associations from the past between the elevation of glacial cover and temperature. As highlighted by Osmaston and Kaser (2001), ELAs of former glaciers on the Rwenzori Mountains, estimated using the area-height-accumulation method, are consistently asymmetrical from east to west (Fig. 17). This asymmetry indicates that local climatic conditions are favourable for the formation of glaciers at lower elevations in the east than the west. Similarly, the lower limit of moraines on east-facing slopes is lower than west-facing slopes due, in part, to larger catchment areas in the east. According to Osmaston (1989), this combination of larger catchments and more favourable climatic conditions on the east-facing slopes of the Rwenzori Mountains enabled glaciers to reach elevations far lower than anywhere else in the East African Highlands. Following the Mahoma stage, alpine glaciers in the Rwenzori Mountains have, however, been in retreat apart from two short intervals of advance ca. 10,000 years BP and 100 to 700 years BP, known respectively as the Omurubaho (70 km²) and Lac Gris (10 km²) stages (Fig. 15).

4.2.2 Modern glacial recession

Modern glacial recession in the Rwenzori Mountains is considered to have started during the late 19th century (ca. 1880) following an abrupt reduction in precipitation at the end of the Little Ice Age (LIA) (Kruss, 1983; Hastenrath, 2001; Nicholson and Yin, 2001; Mölg et al., 2003; Kaser et al., 2004). The first survey of glacial extent in the Rwenzori Mountains was conducted in 1906 by the Duke of the Abruzzi (1907). At this time, Kaser and Noggler (1996) estimate that glaciers covered a total area of approximately 7.5 km² using maps prepared by De Filippi (1909) and photographs taken by Vittorio Sella from the pioneering Duke of the Abruzzi expedition. Glaciers were primarily restricted to Mounts Stanley, Speke and Baker of the Central Rwenzori Massif (Fig. 3b) but also included small glaciers with a total area of 1.0 km² on Mounts Gessi, Emin and Luigi de Savoia (Fig. 16). Glaciers largely existed above 4400 mamsl though some valley glaciers (e.g. Elena, Speke) extended a few hundred metres lower in elevation (Osmaston, 1989). As reviewed in Chapter 2, field research carried out in the 1950s (Menzies, 1951; Bergström, 1955; Whittow et al., 1963), early 1990s (Kaser and Noggler, 1991; 1996; Talks, 1993) and most recently (Chapter 2) confirm a pattern of continued recession over the last century (Fig. 9). The terminal positions of some valley glaciers advanced, however, during the early
1960s. This brief period coincides with both frequent measurements of glacial termini positions (Temple, 1967) and anomalously high precipitation across East Africa when the level of Lake Victoria and the River Nile in Uganda rose by 2.5 m (Lamb, 1966; Kite, 1981).

Figure 16. 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).
4.2.3 Glacial meltwater drainage

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 easterly direction in the Republic of Uganda and Rivers Butawu and Lusilube which drain toward the west in the Democratic Republic of Congo (Figs. 16 & 18). Under Lac Gris and Omurubaho glaciations during the Holocene, glaciers and their meltwater flows would also have contributed to Rivers Ruanoli and Nyamagasani. Ultimately, all of these rivers supply the River Semliki which discharges into Lake Albert, a source of the White Nile. As such, the drainage confirms the prescient claim of Claudius Ptolemy who wrote in 150 A.D. "... the Mountains of the Moon, whose snows feed the lakes, sources of the Nile." (cited in Osmaston, 2006). 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. 3). The River Nyamugasani discharges directly into Lake Edward.

Of the glaciers that presently remain in the Central Rwenzori Massif (Fig. 18), 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. 16). 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 (Fig. 16).
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.

**Figure 18.** Map of glacial extent and drainage in the Central Rwenzori Massif. Glaciers occur on Mounts Speke (north), Stanley (west) and Baker (southwest). Redrawn and adapted from Osmaston and Kaser (2001).

### 4.2.4 Precipitation

Precipitation in the Rwenzori Mountains occurs primarily during two pronounced seasons from March to May and August to November (Fig. 19). The bimodal pattern results from the regional movement of air masses associated with the inter-tropical convergence zone (ITCZ). Unlike typical monsoon climates that are derived from a reversal of wind currents from the northeast in January to the
southwest in July, a north-south reversal in east Africa causes the heavy rains to occur in April and October.

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. 14) 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). The only sustained measurements of precipitation within alpine areas of the Rwenzori Mountains were collected by Osmaston (2006). Mean annual precipitation at four locations from 1951 to 1954 similarly show pronounced variations with altitude (Fig. 20). 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 (Fig. 18) within the Central Rwenzori Massif.

Based on very limited data that are available from the west side of the Rwenzori in the Democratic Republic of Congo, Osmaston (2006) suggests that precipitation is lower on west side of the Rwenzori Mountains. Reduced precipitation would explain the higher elevation of ELAs from contemporaneous glaciations on the west-facing slopes (Fig. 17) and may reflect a ‘rain shadow’ assuming that the dominant source of precipitation to the Rwenzori Mountains derives from the east (Indian Ocean). Fluctuations in sea surface temperatures of the Indian Ocean are thought to account largely for the observed interannual variability in East African precipitation (section 2.4). The source of precipitation to alpine areas of the Rwenzori Mountains remains, however, complicated by the fact that air currents of a different origin and direction than those at low elevations are frequently observed in the mid-troposphere (Whittow, 1960).

Figure 19. Annual distribution in precipitation recorded at Kilembe, Uganda (0º13’N, 30º00’E) from 1949 to 1996.
4.3 Methodology

The impact of glacial recession on alpine river riverflow was investigated through both an analysis of trends in river discharge for basins receiving meltwater discharges and an assessment of altitudinal variations in streamflow from spot measurements. Apart from a few spot measurements of glacial meltwater discharges summarised by Temple (1967), no measurements of alpine streamflow have previously been collected at elevations above the river gauges.
at the base of the Rwenzori Mountains (Fig. 15). Spot measurements of streamflow conducted under this research project have, to date, been restricted to dry seasons in June 2003 and January 2005. On-going research is assessing how streamflow varies with elevation during the rainy season and apply stable-isotope tracers of water movement to supplement physical measurements. Accurate measurement of streamflow is hindered by the highly heterogeneous nature of alpine stream reaches that feature large ice-rafted boulders (Fig. 21). As a result, it was necessary to employ dilution gauging (Okunishi et al., 1992) rather than the more common, velocity-area method. Analysis of potential hydrometeorological trends associated with glacial recession over the last century included records of precipitation and humidity from station observations at the base of the mountain and regional hydrological records of lake levels and river discharge. Trends in regional precipitation over the last two centuries were investigated using both observational datasets and historical evidence.

Figure 21. Photograph of the confluence of the River Mubuku and its main tributary the River Bujuku at sampling site no. 4 (Fig. 16). The widespread occurrence of ice-rafted boulders produces complex stream reaches necessitating the use of dilution gauging to measure alpine streamflow.
4.4 Longitudinal trends in alpine riverflow

Discharge records for the rivers Mubuku, Nyamagasani, and Semliki (Fig. 15) are plotted in Figure 22. Each river is, or was recently, supplied in part by glacial meltwater discharges. Records of river discharge have not been found for the Rivers Butawu and Lusilube in the Democratic Republic of Congo and simply may not exist. An unpublished report on hydrological measurements in the Rwenzori Mountains by Kayondo (1967), cited by Temple (1967), has not been located.

4.4.1 River Mubuku

The flow of the River Mubuku has for several decades been diverted for generation of hydro-electric power (HEP) at an intake in Nyakalengija (Fig. 16). Diverted flow is directed via a conveyor to the Ibanda HEP generating facility and returned to the River Mubuku via one of its tributaries, the River Isha. Sluices and drains at the Nyakalengija diversion permit peak flows to continue along the river channel. A time lag in the response of the river gauge downstream (river gauge site no. 16 in Fig. 16) to precipitation is expected as a result of the longer and more circuitous route taken by diverted flow. The virtual elimination at the beginning of the calendar year 1966 of a difference between maximum and minimum flows casts doubt on the reliability of discharge records available from 1966 to 1971 and limits analysis of these records to a period from 1954 to 1965 inclusive. A second diversion of the River Mubuku for HEP generation by the Kasese Cobalt Company Limited (KCCL) occurs at Bugoye, downstream of the confluence of the River Mubuku and its tributary, the River Isha, but upstream of gauging station no. 16 (Fig. 16). Records of river discharge begin in early 2000 but feature several gaps. At Bugoye, diverted flow is conveyed to the KCCL HEP generating facility east of the River Mubuku downstream and returned to the outlet of the River Mubuku (Figure 16) in the floodplain east of the Rwenzori horst that includes Lake George (Fig. 2).

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$^3$s$^{-1}$ or a depth equivalent over the catchment of 1730 mm·a$^{-1}$. Although this period includes the anomalously wet period of 1961 to 1963, the depth equivalent of mean annual catchment riverflow is exceptionally high (1730 mm·a$^{-1}$), three to five times that of other basins (e.g., Nyamagasani) during the same period and of a comparative size with similar evaporative channel losses. Indeed, this observation may have led many to presume a significant contribution of glacial meltwaters to riverflow. However, as altitudinal trends in riverflow indicate (section 4.5), the anomalously high, depth equivalent of catchment riverflow arises primarily from the fact that the catchment features very high, orographic precipitation that ranges from 2 to 3 m per year (Fig. 20), the highest annual flux in Uganda. Records of river discharge (Fig. 22) show considerable interannual variability but are too limited in
duration to permit trend analyses. The anomalously wet conditions of the early 1960s are well represented in the discharge of the River Mubuku and Rivers Nyamagasani and Semliki. As a result, the mean discharge for this period may be slightly in excess of the long-term mean. For comparison, the mean discharge of the River Mubuku for the slightly smaller catchment gauged by KCCL was 12 m$^3$·s$^{-1}$ over the calendar year 2000.

4.4.2 River Nyamagasani

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. 15). Available records of discharge from 1955 to 1978 are presented in Figure 22. A long gap in observations begins in 1979 and lasts until November 1998. An automated recording gauge then operated at this site for more than two years before being destroyed by flooding in 2001. The station was rehabilitated on September 4, 2001. Similar to the River Mubuku, discharge records (Fig. 22) are too limited in duration to permit trend analyses. In a qualitative sense, there is no evidence of a clear decrease or increase in river discharge. 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. 15). No significant temporal trends (at a 95% confidence interval) in precipitation are evident over a 50-year period (1949 to 1998) at Kilembe and 38-year period (1964 to 2001) at Kasese Airport.

4.4.3 River Semliki

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. 15 and 16). A continuous record of river discharge is available over a 26-year period from 1952 to 1977 (Fig. 22). Although direct inspection of the gauge for the River Semliki has not yet been undertaken, all river discharge records in Uganda have recently been subjected to a quality control analysis by the Water Resources Management Department (Uganda). The anomalously wet conditions from 1962 to 1964, clearly represented in the discharge record, complicate the assessment of any underlying trends in river discharge. Indeed, a statistically significant trend at a 95% confidence interval is not observed ($p = 0.077$). Overall, the observations point to a weak trend ($r = 0.35$) of increasing riverflow (1.3% or 2.7 mm·a$^{-1}$ per annum) over the 27-year period.
Figure 22. 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. Data compiled by the Water Resources Management Department of Uganda.

4.5 Altitudinal trends in riverflow from spot measurements

Altitudinal trends in the flow of the River Mubuku basin, deduced from spot measurements collected during the season in January 2005, are plotted in Figure 20. These data show that contemporary glacial meltwater discharges aggregated at Lake Bujuku represent a tiny fraction (<0.2 m³·s⁻¹) of the mean river discharge (14 m³·s⁻¹) recorded from 1954 to 1971 at the base of the Rwenzori Mountains (Fig. 15). The altitudinal profile of river discharge highlights, furthermore, the relative increase in river discharge that occurs below the glaciers (>4500 m a.s.l)
in the Heath-moss and Montane forest zones between 2000 and 4000 m asl as the catchment area expands and where precipitation is highest. The minimal influence of glacial meltwaters on alpine riverflow in the East African Highlands is contrary to speculation (Gasse, 2002; Thompson et al., 2002) but consistent with a previous suggestion by Temple (1967) and evidence from Kilimanjaro (Kaser et al., 2004). The conclusion that recent glacial recession has had a negligible impact on alpine riverflow is sensible in light of the fact that less than 0.5% (1.0±0.3 km²) of the River Mubuku basin (256 km²) is covered by glaciers. Ongoing research seeks to confirm these deductions by taking measurements during the rainy season in April 2007.

4.6 Meteorological trends over the last century

As glacial recession does not constitute a direct threat to the magnitude of alpine riverflow, research then focused on the possibility that receding glaciers signal a reduction in alpine precipitation, potentially lowering riverflow, and/or humidity. The former would reduce glacial accumulation whereas the latter may reflect a decrease in cloud cover that increases the exposure of glaciers to solar radiation that enhances ablation. Records of river discharge for the Mubuku basin are, however, inadequate to permit analysis of longitudinal trends and thus represent potential changes in alpine precipitation. Analysis of the only long-term records of precipitation in western Uganda which is restricted to stations in lowland areas <2000 m asl (Fig. 10), highlights significant interannual variability discussed in section 2.4. Significant downward trends in precipitation are not realised at any of the four stations. Small but significant trends of increasing precipitation (at a 95% confidence interval) are observed at two stations (Fort Portal, Mbarara).

Daily measurements of relative humidity are available over two continuous periods from 1967 to 1974 and 1991 to 2000 at the base of the Rwenzori Mountains in Kasese (Fig. 15). Although these records are too brief to permit an analysis of temporal trends, a comparison of mean values of relative humidity as well as mean minimum and mean maximum relative humidity for these two periods fails to support the decline in relative humidity (Table 2) proposed by Mölg et al. (2006) based on reanalysis datasets. Marginal increases in relative humidity are uniformly observed.

A key limitation in the relationship between lowland and alpine precipitation presumed in the above analyses is that the source of precipitation remains the same. As noted by Whittow (1960), air currents of a different origin and direction than those at low elevations are frequently observed in the mid-troposphere in the Rwenzori Mountains. Current research seeks to trace the origin of precipitation in lowland and alpine areas on both sides of the Rwenzori Mountains using the stable isotopes of O and H.

Table 2. Mean, mean minimum, and mean maximum relative humidity (%) from measurements available over two continuous periods, 1967 to 1974 and 1991 to 2000, at Kasese (Fig. 15). Data
derive from daily measurements recorded at 9AM and 3PM. The standard deviation in each mean value is given in parentheses.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>mean - 9AM</td>
<td>80 (6)</td>
<td>84 (5)</td>
</tr>
<tr>
<td>mean minimum – 9AM</td>
<td>63 (8)</td>
<td>66 (9)</td>
</tr>
<tr>
<td>mean maximum – 9AM</td>
<td>94 (4)</td>
<td>97 (3)</td>
</tr>
<tr>
<td>mean – 3PM</td>
<td>52 (7)</td>
<td>54 (7)</td>
</tr>
<tr>
<td>mean minimum – 3PM</td>
<td>34 (8)</td>
<td>37 (7)</td>
</tr>
<tr>
<td>mean maximum – 3PM</td>
<td>82 (10)</td>
<td>86 (10)</td>
</tr>
</tbody>
</table>

4.7 Hydrological trends over the two centuries

According to Mölg et al. (2006), glaciers in the East African Highlands are relics from more humid climatic conditions during the 19th century. Although this hypothesis might explain the monotonic decline in glacial cover in East African Highlands over the 20th century (Fig. 23), there is currently no compelling evidence (e.g. measurements of precipitation or humidity during the 19th century) to support it. As recognised by Kaser and Osmaston (2002), the apparent linearity in rate of decline in glacial cover over the 20th century may stem from the limited number of measurements. More frequent observations of glacial cover on Kilimanjaro toward the end of the 20th century reveal, for instance, a slowing the rate of loss of glacial cover (Fig. 23) and raise the possibility that glaciers there may persist up to ~2040 rather than ~2020 suggested by Thompson et al. (2002).

Figure 23. Observed changes in glacial cover on the Rwenzori Mountains and Kilimanjaro over the 20th century. Data for Kilimanjaro are given in Thompson et al. (2002). Rwenzori data from 1906, 1955 and 1990 derive from Kaser and Osmaston (2002). Remaining Rwenzori data derive from NDSI classification of two Landsat 5 (TM) and one Landsat 7 (ETM+) scenes (Table 1).
Changes in the lake levels, an indirect and imperfect proxy of regional humidity, are often cited (e.g. 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 (ca. 1880). Nevertheless, historical evidence of changes in the level of Lake Victoria (Fig. 24), speculative as the data may be, indicate that for all but two decades of the 19th century, the level of Lake Victoria was lower than, or commensurate to, its level throughout the 20th century. A very similar rise and fall in the level of Lake Tanganyika during the latter half of the 19th century is also suggested from historical evidence (Nicholson and Yin, 2001). During the 20th century, lake levels and the discharge of major river systems draining East Africa (i.e., Rivers Nile and Congo) exhibit remarkable consistency in their response to years or seasons of anomalously high precipitation (e.g. 1917, 1961-1964, 1969, 1979). These records are, furthermore, consistent with observations from meteorological stations in western Uganda in that they show strong interannual variability but provide no evidence of a decline in precipitation or by speculative inference, atmospheric humidity, over the 20th century.

### 4.8 Concluding Discussion

Meltwater flows from glaciers in the Rwenzori Mountains do not contribute significantly (> 0.5%) to alpine riverflow. This conclusion, based on stream fluxes measured during the dry season, is consistent with suggestions from Temple (1967) and Osmaston (2006), and a similar assertion by Kaser et al. (2004) based on observations on Kilimanjaro. There is, furthermore, no evidence of a decline in precipitation over the 20th century in lowland station records from western Uganda and regional hydrological records. Based on historical evidence of changes in the levels of Lake Victoria and Tanganyika over the 19th century (Fig. 24), the dramatic shift in atmospheric humidity purported to have initiated glacial recession in the late 19th century is actually the descending limb of a brief, high lake stand which lasted for less than two decades. Lake levels do not signal a sustained shift from a more humid climate to a subsequent, less humid one.

Insufficient data exist to verify local reports in Uganda (Kasese District) of an increased frequency and magnitude of flood events at the base of the Rwenzori Mountains. Changes in land use and land pressures outside of the Rwenzori Mountains National Park (i.e., below 1700 mamsl) in the River Mubuku basin may account, in part, for the perceived increase in flood risk.
5 Recent changes in aquatic productivity of Lake Bujuku

5.1 Introduction

Alpine environments are hotspots of biodiversity and considered among the most sensitive to climatic changes occurring on a global scale (Diaz et al. 2003). Recent warming observed in tropical alpine regions (e.g. Liu and Chen, 2000; Vuille and Bradley, 2000), has been linked to increased incidence of malaria in the East African Highlands (Pascual et al. 2006) and rapid retreat of glaciers (Bradley et al. 2006; Thompson et al. 2006; Taylor et al. 2006a). Because tropical alpine glaciers are highly sensitive to changes in climate, they serve as important indicators of environmental change in these regions (Kaser et al. 2004) where meteorological observations are often limited. Rapid glacial retreat over the 20th century has been observed on all three ice-fields in the East African Highlands including Kilimanjaro (e.g. Thompson et al. 2002), Mount Kenya (e.g. Hastenrath and Kruss, 1992) and the Rwenzori Mountains (Chapter 2, Fig. 23). Environmental changes associated with the recession of alpine glaciers in East Africa remain unclear. In contrast to long-term monitoring records (including documentary evidence) from alpine regions in temperate latitudes (e.g. Koining et al. 1998, 2002; Lotter and Bigler, 2000; Psenner and Schmidt, 1992), there is a paucity of similar datasets in tropical alpine regions of Africa (Verburg 2003; Verschuren 2003). In light of rapid tropical glacier recession, well-resolved, high quality palaeolimnological records from African lakes are especially important (ibid.).

This chapter investigates the recent palaeolimnological record from Lake Bujuku, a high altitude lake adjacent to the ice-fields in the Rwenzori Mountains (Fig. 18). Reconstructions focus on the recent past (ca. 150 years) when the glaciers here have been in significant retreat, and for which we are able to produce a robust chronology using radiometric $^{210}$Pb and $^{137}$Cs analyses. We adopt a multiproxy approach, based on algal production within the lake and vegetation changes in the immediate catchment (diatoms, pollen and organic carbon isotope composition, including TOC, C:N and $\delta^{13}$C. The aim of this paper is to investigate the sensitivity of remote, tropical, alpine lakes in documenting environmental and to thereby provide a case study and palaeoecological context for 20th century climatic change observed in East Africa.

5.2 Study site

Lake Bujuku (0º22'N and 29º54'E) lies at an altitude of 3960 metres above sea level (alpine) within the Rwenzori Mountains National Park (RMNP). The lake’s catchment features steep, scree slopes in its upper reaches (Fig. 25) and is partly fed by meltwater flows from the East Stanley and Speke glaciers. The lake
is surrounded on three sides by the last remaining mountains that support ice-fields (Mount Baker, Stanley and Speke) (Fig. 18). Rainfall in the order of 2000 mm·a⁻¹ is controlled by the seasonal displacement of the Inter Tropical Convergence Zone [ITCZ] which predominantly falls during the region’s wet seasons (March to May and August to November) (Osmaston, 2006). The lake is located within the Afro-alpine zone that is characterised by vegetation dominated by *Lobelia wollastonii* (giant lobelia), *Dendroscenecio advinalis* (tree senecio) and *Erica spp.* (including giant heather). At the edges of the lake, sedges and grasses dominate. Both lake inflows and outflow pass through an extensive *Carex runssoroensis* bog, with the outflow feeding through the cascading system of bogs (Fig. 18). Diurnal temperatures change from a mean minimum to mean maximum of -1°C to 10°C which contributes to the polymictic nature Lake Bujuku’s water column (Temple, 1967). Due to its tropical location, the site receives near constant annual solar radiation (Livingstone, 1967).

Figure 25. Photograph of Lake Bujuku from the Speke Glacier (June 22, 2003).
5.3 Methodology

5.3.1 Field Methods

A bathymetry of Lake Bujuku was created by making a number of traverses across the basin while recording water depth with a Plastimo echosounder and simultaneous location using a hand-held e-Trex Summit GPS. Data were interpolated using ArcView. Although a maximum depth of 14.5 m was recorded in the lake, a more uniformly flat region at a depth of 13.5 m (Fig. 26) was selected for coring. Four cores (Buju1-4) were collected using a Glew gravity corer (Glew, 1991). The longest sequence retrieved was 40.5 cm (Buju3) and is used in this study for all analyses. Extrusion was conducted in the field at a resolution of every 2.5 mm (from 0 to 10 cm) and thereafter every 5 mm. An assessment of the contemporary characteristics of the lake was also made. Eight diatom samples were collected from littoral regions of the lake, including epilithic, epipsammic and epiphytic habitats (Fig. 26). Core site water temperature readings gave a spot reading at the time of coring of 8.1°C ± 2.1°C, a pH of 7.2 ± 0.3 units and a Secchi-disc depth reading gave an estimate of light penetration of 4.5 m.

Figure 26. Digitised image of Lake Bujuku bathymetry, inflows, outflow and bog region. Numbers refer to contemporary diatom sampling sites (Table 3) and X refers to core location of Buju3.
5.3.2 Laboratory methods

5.3.2.1 Chronology

Sediment samples were dated using $^{210}\text{Pb}$ and $^{137}\text{Cs}$ by non-destructive gamma spectrometry (Appleby and Oldfield, 1992) at the Centre for Environmental Research, University of Sussex. Twelve core sub-samples were counted for at least 8 hours on a Canberra well-type ultra-low background HPGe gamma ray spectrometer to determine the activities of $^{137}\text{Cs}$, $^{210}\text{Pb}$ and other gamma emitters. Sediment accumulation rates were determined using the ‘simple model’ of $^{210}\text{Pb}$ dating (e.g. Robbins, 1978), where sedimentation rate is given by the slope of the least squares fit for the natural log of the $^{210}\text{Pb}$ excess activity versus depth.

5.3.2.2 % DW and LOI analyses

Eighty samples (every 5 mm) were analysed for wet densities (WD), percentage dry weight (%DW) at 105°C and percentage loss-on-ignition at 550°C (% LOI) as an estimate of organic carbon. Calculations followed procedures outlined by Charles et al. (1994) and Bengtsson and Enell (1986).

5.3.2.3 Organic geochemistry

C:N ratios were calculated to examine the relative importance of autochthonous and allochthonous sources of organic material within Lake Bujuku sediments whereas the stable isotope ratios of carbon ({$^{13}\text{C}/^{12}\text{C}$}) were analysed to trace the dominant plant source of carbon in the lake (Talbot and Laerdal, 2000). Bulk carbon samples at a resolution of every 5 mm were prepared by placing 2 g of wet sediment overnight in 50 ml of 5% hydrochloric acid to remove carbonates. Subsequently, they were washed using deionised water through Whatman No. 41 filter papers and dried in air at 40°C. Once ground into a fine powder, $^{13}\text{C}/^{12}\text{C}$ analyses were performed by combustion using a Carlo Erba NA1500 (series 1) on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer, with $\delta^{13}\text{C}$ values calculated to the VPDB scale using a within run laboratory standard calibrated against NBS19 and NBS22. C/N ratios were determined by reference to an Acetanilide standard, and replicate analyses of well-mixed samples indicate a precision of + <0.1 ‰ (1 S.D.).

5.3.2.4 Diatom analyses

Procedures for diatom analysis followed those outlined by Battarbee (1986) involving digestion of 0.1 g of wet sediment in 30% H$_2$O$_2$ and HCl before mounting on slides with Naphrax (Renberg, 1990). Resolution followed every 5mm between depths 0 and 1 cm, every 10 mm between 1 and 20 cm and every 20 mm between depths 20 and 40 cm. A known concentration of microspheres was added to samples in order to calculate diatom concentrations. Diatoms were
counted using oil immersion phase contrast Leica Axioskop light microscopy at x1000 magnification. At least 300 valves were counted for each sample, revised to a maximum of 500 valves when dominating *Fragilaria sp.* represented > 70% of sample assemblages. Taxa were identified according to a range of published papers and books including Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b), Camburn and Charles (2000) and those with tropical African taxonomy (Gasse, 1986). The resultant stratigraphy, created using C2 v1.4 (Juggins, 2004) and displayed on the constructed time scale, was divided into zones using stratigraphically constrained cluster analysis by incremental sum of squares (CONISS) using the programme ZONE Version 1.2 (Juggins, 1992).

### 5.3.2.5 Pollen analysis

Approximately 0.05 g of freeze dried sediment was weighed and tablets containing a known number of Lycopodium spores were added to calculate pollen concentrations (Stockmarr, 1972). The samples were further processed using standard methods (Faegri and Iversen, 1975). Resolution followed every 5 mm between depths 0 and 1 cm, every 10 mm between 1 and 4 cm and every 20 mm between depths 4 and 40 cm. Between 500 and 1000 terrestrial pollen grains and spores were counted using a Zeiss D-7082 microscope (identified at x1000 under oil immersion). The total terrestrial plant pollen and spore sum was used for pollen calculation of all terrestrial taxa. Aquatic pollen is also expressed relative to this terrestrial sum. Species were retained when they were > 5% abundance and grouped according to their ecological affinities. C2 v1.4 was used to construct the stratigraphy and diatom zonation was applied to aid interpretation.

### 5.3.2.6 Multivariate Analyses

Statistical analyses were carried out on diatom and pollen taxa present in samples with an abundance of > 2%. Unconstrained (detrended correspondence analysis - DCA) and principal components analysis (PCA) ordinations were carried out on Buju3 diatom and pollen data using the software package CANOCO 4.5 (ter Braak and Šmilauer, 2002). The principal gradients of floristic variation within the core were assessed prior to ordination analysis using DCA, with detrending by segments, non-linear scaling of axes, square-root transformation of species data and down-weighting of rare species. A first axis gradient of 1.067 SDs was obtained for diatom data and 0.621 for pollen, thus core data were subsequently analysed using the linear ordination technique of PCA (ibid.). Axes 1 and 2 of the diatom data were further analysed with broken-stick analysis to test their significance (Jollife, 1986).
5.4 Results

5.4.1 Contemporary diatom ecology

*Fragilaria pinnata, F. construens* and *A. minutissima* are represented in littoral samples (Table 3). However, *T. flocculosa* dominates 61% of the total valve abundance at site 6 and is present at all the sites apart from the epipsammic sample (site 8). Littoral habitats are more diverse than suggested by the surface sediment sample from Buju3 (Table 3). For example, neither *Tabellaria flocculosa* nor *Synedra spp.* are represented in Buju3 yet they represent a large proportion of the species abundances in the contemporary assemblages. *Synedra tenera* and *S. linearis* also appear in the contemporary sites, not represented in Buju3, and account for 58% of assemblage abundance at site 5. The representivity of modern assemblages is addressed more fully in the discussion.

*Table 3.* Summary of diatom assemblage compositions from contemporary sampling at eight sites around the shore of Lake Bujuku. Only the most abundant species, and their relative abundances, at each of the sites is displayed.

<table>
<thead>
<tr>
<th>Site 1 epilithic</th>
<th>Achnanthes minutissima (70%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Synedra linearis (12%)</td>
</tr>
<tr>
<td></td>
<td>Tabellaria flocculosa (8%)</td>
</tr>
<tr>
<td>Site 2 epiphytic</td>
<td><em>Fragilaria</em> capucina (13%)</td>
</tr>
<tr>
<td></td>
<td>F. pinnata (7%)</td>
</tr>
<tr>
<td></td>
<td>S. linearis (20%)</td>
</tr>
<tr>
<td></td>
<td>S. tenera (14%)</td>
</tr>
<tr>
<td></td>
<td>T. flocculosa (35%)</td>
</tr>
<tr>
<td>Site 3 epilithic</td>
<td><em>A. minutissima</em> (14%)</td>
</tr>
<tr>
<td></td>
<td>Brachysira brebissonii (5%)</td>
</tr>
<tr>
<td></td>
<td>F. construens (5%)</td>
</tr>
<tr>
<td></td>
<td>F. pinnata (31%)</td>
</tr>
<tr>
<td></td>
<td>T. flocculosa (11%)</td>
</tr>
<tr>
<td>Site 4 epiphytic</td>
<td><em>A. minutissima</em> (14%)</td>
</tr>
<tr>
<td></td>
<td>B. brebissonii (6%)</td>
</tr>
<tr>
<td></td>
<td>F. pinnata (7%)</td>
</tr>
<tr>
<td></td>
<td>S. tenera (18%)</td>
</tr>
<tr>
<td></td>
<td>T. flocculosa (22%)</td>
</tr>
<tr>
<td>Site 5 epiphytic</td>
<td><em>F. capucina</em> (5%)</td>
</tr>
<tr>
<td></td>
<td>Gomphonema parvulum (5%)</td>
</tr>
<tr>
<td></td>
<td>S. linearis (26%)</td>
</tr>
<tr>
<td></td>
<td>S. tenera (32%)</td>
</tr>
<tr>
<td></td>
<td>T. flocculosa (18%)</td>
</tr>
</tbody>
</table>
### Site 6
**Epiphytic**

- **Eunotia bilunaris** (4%)
- **F. capucina** (4%)
- **S. linearis** (8%)
- **S. tenera** (8%)
- **T. flocculosa** (61%)

### Site 7
**Epilithic**

- **E. bidens** (9%)
- **F. pinnata** (12%)
- **S. linearis** (7%)
- **S. tenera** (16%)
- **T. flocculosa** (16%)

### Site 8
**Episammic**

- **A. minutissima** (7%)
- **E. bidens** (7%)
- **F. capucina** (12%)
- **F. contruens** (7%)
- **F. pinnata** (21%)
- **G. parvulum** (26%)

### 5.4.2 Chronology

$^{210}$Pb activity in Buju3 shows a broadly exponential decline with depth (Fig. 27). The $^{210}$Pb derived sediment accumulation rate, based on a constant rate of sedimentation, was $2.9 \text{ mm} \cdot \text{a}^{-1}$ (2 SD range = $2.5 - 3.4 \text{ mm} \cdot \text{a}^{-1}$). $^{137}$Cs shows a clear subsurface maximum in activity at 10 cm in Buju3 that is most likely a stratigraphic marker for 1963, the year of peak global $^{137}$Cs fallout from atmospheric nuclear weapons testing (Fig. 27a). This therefore suggests an accumulation rate of $2.6 \text{ mm} \cdot \text{a}^{-1}$ from the base to the uppermost sediments. Both are in good agreement therefore and suggest that Buju3 spans ca. 140 years based on a continuous rate of deposition, dating back to 1860 ± 20 years (Figure 27b).

### 5.4.3 Organic geochemistry

For explanatory purposes, the four diatom zones have also been applied to the organic geochemistry and lower resolution pollen stratigraphies (Fig. 28). C2 v. 1.4 was also adopted to create stratigraphies for organic geochemistry (Juggins, 2004).

### 5.4.4 % TOC

In the case of Buju3 there has been a gradual increase with time in %TOC, from ca. 6% at the base of the core to ca. 13% at the surface. This increase has been predominantly steady (apart from a more rapid increase in values between c. 1895 and 1910 of ca. 3%) and suggests a gradual increase in productivity in the sequence, especially from ca. 1930 onwards.
Figure 27. (a) $^{137}$Cs apex acts as a stratigraphic marker for 1963; (b) plot of age versus depth for Buju3, based on the simple model of $^{210}$Pb dating. Error bars shown are calculated using the 2 SD error on the gradient of the linear regression fit of ln$^{210}$Pb excess vs. depth.

Figure 28. Age (depth) profiles of bulk organic carbon analyses: $\delta^{13}$C ($\%$), C/N and % TOC. Zones are defined by diatom data.
5.4.5 C/N ratios

C/N ratios for the Buju3 sequence remain between 12 and 17 indicating a predominantly submerged macrophyte and/or aquatic algal source for carbon in Lake Bujuku (Meyers and Teranes, 2001). C/N ratios increase to 16.5 during the % TOC peak in zone III between ca. 1895 and 1910. This peak, although consistent with a signature of submerged and aquatic vegetation, may also represent a mixed aquatic allochthonous source event in the record here. After ca. 1975 there is a shift in C/N values suggesting an increase in algal dominance in the lake (12.4).

5.4.6 Stable isotopes of carbon

$\delta^{13}$C shows a gradual lowering in values over the period of reconstruction from -25‰ to -27.5‰. C/N ratios suggest that this carbon source is autochthonous (algal predominantly) and corroborates increasing % TOC values in Buju3. Assuming no significant plant community change within the lake (and significant changes in the inwash of terrestrial material can be discounted by the C/N ratio data) then one interpretation is that this represents an increase in productivity at Bujuku.

5.4.7 Diatoms

Throughout the diatom record three species dominate, *F. construens* and *A. minutissima* and *F. pinnata*, with the latter being the most abundant (Fig. 29). In zone IV *F. pinnata* accounts for > 40% of total species abundances although during this zone *F. construens* is also shown to increase to between c. 15-20% abundance. These increases in the dominance of *F. construens* are concurrent with reductions in the relative abundance of *F. pinnata*. The increasing trend seen from zone IV by *F. construens* continues throughout the record until zone I. PCA axis 2 displays the shift between these Fragilaria species. Diatom concentrations and flux rates decline in number from the base of the core ca. 1860 from $19 \times 10^5$ (valves g per wet weight) and $4.9 \times 10^5$ g⋅cm$^{-1}$⋅a$^{-1}$ respectively. After that, they begin to increase at ca. 1880 and towards zone III once again.

Flux rates and concentrations show a double peak in values at ca. 1900 ($2.3 \times 10^5$ g⋅cm$^{-1}$⋅a$^{-1}$ and 8.9 x 105 valves g per wet weight respectively) and 1930 ($2.0 \times 10^5$ g⋅cm$^{-1}$⋅a$^{-1}$ and 7.7 $\times 10^5$ valves g per wet weight respectively) with a fall in numbers c. 1920. By ca. 1960 there is also an increase in *F. capucina*, which by 1970 declines once again. By 1975 and towards the transition with zone I, this species increases once more reaching 10%. The dominance of *F. pinnata* increases after c. 1975 once more (accounting for >60%), with an increase of 23% in the space of 3 years. This change is reflected by PCA axis 1 scores shifting to positive values. *F. pinnata* values then begin to decline after ca. 1990 while an increase in *F. construens* (up to 20%) and *A. minutissima*, the former
Figure 29. Diatom stratigraphy as percentage abundances for Buju3. Valve concentrations, diatom flux rates and PCA axes scores 1 and 2 are also shown. Zones applied are derived from constrained cluster analysis.
recovering from its lowest abundances in the profile, is seen. Once again valve concentrations increase within the profile at c. 1990 (11.3 \times 10^5 \text{ valves g per wet weight}), as do valve accumulations $2.9 \times 10^5 \text{ (valves g cm}^{-1} \text{ cm}^{-1} \text{ yr}^{-1})$ although these values drop slightly towards the present day.

### 5.4.8 Pollen

A total of 89 pollen and spore types were identified (Fig. 30), although here we have classified the taxa into the following groups: non-local trees, local trees, herbs, aquatics and spores (mainly from undifferentiated ferns and Sphagna). The pollen group stratigraphy shows little variation during zone IV, with indications of non-local and local tree pollen decreasing after ca. 1880, while herbs remain dominant (between 34 and 44\%). Aquatic pollen shows an increase in numbers concomitant with the fall in diatom flux rates, after which they begin to increase towards zone III.

Pollen results show that aquatic pollen shows that greatest change during zone III (from ca. 5 to 20\%), with PCA axis 2 scores also reflecting this increasing trend. This is most noted after ca. 1900. Herbs show little change until ca. 1920 after which values begin to fall to < 30\% and a temporary increase is seen in local terrestrial pollen. However, during zone III there is a gradual decline in aquatic pollen that can be seen after ca. 1950 concomitant with the fall in diatom concentrations. This is again reflected by the pollen PCA axis 2 scores. After ca. 1980, aquatic pollen shows small, fluctuations towards the present day concomitant with variations in \textit{F. construens} and \textit{F. pinnata} valve abundances.

### 5.5 Discussion

Despite evidence that glaciers in the RMNP have undergone rapid retreat since their first documented measurement in 1906 (Kaser and Osmaston, 2002), catchment and limnological changes recorded in Lake Bujuku have been more subtle. Central to our interpretations are the limnological controls on diatom species representation and abundance within the sedimentary record, and these are addressed first here.

The limnology of Lake Bujuku has major consequences for diatom presence and distribution in the lake, related to the lake’s location and altitude. As highlighted above, Lake Bujuku is polymictic and subject to diurnal temperature fluctuations that are more pronounced than annual changes. Temperature readings conducted by Livingstone (1967) found that the difference between top and bottom waters was insufficient to maintain stratification, whereas exposure to strong winds (due to minimal geostrophic influence in the tropics) will also be responsible for the limited development of thermal stratification in this lake (Talling and Lemoalle, 1998).
Figure 30. Pollen stratigraphy from Buju3 as percentage abundances. Results are grouped according to their family for ease of interpretation and displayed with PCA axes scores 1 and 2. Zones applied are derived from constrained cluster analysis carried out on diatom data to aid interpretation.
Adaptive *Fragilaria* sp. can take advantage of dynamic water columns. Continual turnover allows the recycling of oxygen and nutrients from the profundal zone, which was confirmed by Richardson (1968) who demonstrated that high amounts of oxygen occurred at the bottom of Lake Bujuku. A further ecological preference associated with oxygen charged bottom waters is associated with the species *A. minutissima*, which is regarded as the best indicator of oxygen rich conditions (Gasse, 1986). Evidence for the polymictic nature of Lake Bujuku can account for the presence of these i) non-planktonic species (with requirements of high oxygen values) and ii) tychoplanktonic species (readily adaptive to dynamic thermal characteristics and to both benthic and planktonic environments (Barker et al., 1994) within the sediment profile.

The contemporary ecology of Lake Bujuku shows the presence of many of the abundant species within the stratigraphy and particularly the surface sediments of Buju3 (Table 3). Although common taxa include *A. minutissima, F. pinnata, F. construens* and *F. capucina*, several abundant species in the littoral habitats (*Tabellaria flocculosa, Synedra tenera and S. linearis*) are poorly represented within the sub-surface samples. It is possible that these taxa are not present in the sub-surface layers as a result of ecological change in recent years. However, it is also possible that these species are under-represented in the stratigraphy because of i) taphonomic processes such as dissolution, which can preferentially impact finely silicified taxa such as *Synedra* (Ryves et al. 2001) and ii) core location with respect to the basin morphology of the lake and relative size of the littoral shelf in comparison to lake volume (Jones and Flower 1986). It is important to appreciate that taphonomic processes, determining the formation of fossil diatoms, are often site specific and are issues overlooked in the field (Cameron, 1995).

Taxa, such as *T. flocculosa, S. linearis*, and *S. tenera* dominate macrophyte habitats in littoral margins (Werner, 1977). Small chain forming Fragilaria species which dominate Buju3, (including *Fragilaria pinnata*) are regarded as R-strategist, benthic taxa, meaning they are able to reproduce at a comparatively higher rate than other taxa when environmental conditions rapidly change (Lotter and Bigler, 2000). As a result, they often dominate dynamic environments. Moreover, they have often been classified as tychoplanktonic (Sayer, 2001), showing the adaptive nature of the genus that takes advantage of both benthic and planktonic environments (when nutrients are more limiting; Barker et al. 1994). Unfortunately, little is documented on the individual ecologies of *Fragilaria* species. Moreover, due to its cosmopolitan nature, a multiplicity of evidence exists regarding their optimal ecology, thereby complicating palaeolimnological interpretations when they dominate sequences. Nevertheless, *F. pinnata* appear to tolerate harsher conditions than other species, and is often regarded as a disturbance indicator, found in benthic environments growing on sediments (Barr, pers. comm.). Other species such as *F. capucina* require high amounts of light
penetration for growth (Sweets pers. commun.). Palaeoenvironmental interpretations below are based in part on these observations.

The photic depth of Lake Bujuku is argued to be a significant factor accounting for the dominance of benthic taxa in Bujuku. Although Secchi-disc depth readings obtained at the core site define the photic zone to be 4.5 m deep, Cole (1975) suggests that the photic zone of a lake may be greater than this. Here, diffusive light remains in the water column which is scattered by particulate matter, causing deeper light. In the case of oligotrophic lakes such as Lake Bujuku, factors of 2.7 to 3.0 times Secchi-disc depths have often been found to be a better estimated depth of the photic zone (Davis and Brinson, 1980). As a result, the photic depth of Lake Bujuku could reach in excess of 13 m, signifying that a large proportion of the water column and therefore lake basin is within the photic zone. Furthermore, Kinzie et al. (1998) argue that high ultraviolet radiation (UVR) irradiance incident on tropical mountain ecosystems, has a greater negative effect on photosynthetic aquatic communities than at a lower elevation. The amount of UVR exposure can be up to 20% higher than at sea level of comparable latitude (ibid.). Such exposure may be one reason why the stratigraphy of Bujuku displays predominantly benthic, R-strategist taxa, as phytoplankton cells in frequently circulating waters cannot spend extended periods of time exposed to UVR. Indeed, Vinebrooke and Leavitt (1996) state that the periphytic species *A. minutissima* in alpine lakes is sensitive to increases in UVR due to its inability to migrate upon its substrates for refuge, compared with other periphytic species. Such decreases in this species, towards the latter part of the 1990s at Bujuku, may suggest that UVR has indeed been increasing in this region.

5.5.1 Palaeolimnological reconstruction over period of glacial retreat

Over the period of observed glacial retreat since 1906 in the Rwenzori Mountains, the diatom record of Lake Bujuku contains only relatively subtle responses to global warming and glacier recession in comparison to its higher latitude alpine counterparts (e.g. Koining et al. 1998, 2002; Lotter and Bigler, 2000; Psenner and Schmidt, 1992). Meyers and Teranes (2001) highlights that C/N ratios can be used to distinguish between algal and higher plant carbon sources in lake sediment sequences. In particular, as in this case, levels between 10 and 20 are typical of a mixed source of lacustrine algae (< 10 – 12) and submergent/floatine aquatic macrophytes (Tyson, 1995). Over the whole period, organic carbon isotope analysis demonstrates a gradual, but distinct, increase in productivity in the lake as a whole (i.e. a shift to more negative δ¹³C values and increasing % TOC). Leng et al. (2006) highlight that such periods of increased productivity are explained due to the preferential uptake of δ¹²C by aquatic plants during photosynthesis; as this increases, the carbon pool in the water is enriched in δ¹³C. C/N ratios indicate that productivity has been largely dominated by aquatic macrophytes, until ca. the last 30 years, when ratios highlight a shift in algal productivity dominating the ecosystem. This change, although not reflected
in the aquatic pollen record, is accompanied by the largest shift in diatom assemblage composition in the core where \textit{F. construens} abundances show a marked decline at this time, to be replaced by \textit{F. pinnata}.

The possible habitat changes associated with this shift are not able to be discussed here. Indeed, it is difficult to elucidate whether the species change after 1975 is due to inherent within-lake variability or a more direct response to environmental change in the region, as the glaciers at this time undergo a continuous recessional trend (Taylor et al. 2006a). In relation to taphonomy and representation issues at Bujuku, littoral coring and macrophyte analyses would be valuable in order to investigate macrophyte and submergent community change at this time, allowing for a more comprehensive investigation of the changes observed here.

It is evident therefore that both catchment changes (as evidenced by the pollen record) and diatoms, which have continued to be dominated by benthic Fragilaria species, may simply be insensitive to the relatively subtle changes that may have occurred in temperature, humidity and solar radiation which have driven glacial recession. Such changes (e.g. small change in temperature requiring ice to melt) may not have readily affected catchment vegetation and the limnology of Lake Bujuku. At this stage, we cannot rule out issues of taphonomy and representivity dampening any potential impacts from glacial recession on aquatic responses in the lake, but we are as yet unable to quantify these. For example, during the early 1960s, unusually high precipitation levels led to a 2.5 m rise in the level of Lake Victoria (Kite, 1981) and a small advance in the terminal positions of glaciers in the Rwenzori Mountains (Temple, 1967), yet even these extreme events are not documented in the palaeolimnological record from Lake Bujuku. Moreover, although there is a distinct increase in TOC in the profile (accompanied by a small increase in C/N ratio) between c. 1890 - 1910, these changes are again not reflected in either the diatom or pollen records.

There is unambiguous evidence of rapid glacial mass loss in east Africa and other alpine regions of the tropics yet the precise nature of climatic change and its historical context over the past two centuries remain poorly resolved. This emphasises the need for high resolution, multiproxy palaeoecological studies to resolve this. Interestingly, it would appear that at least the pollen records at Lake Bujuku do not record the dramatic recession of the East Stanley and Speke glaciers, despite the lake’s geography (high, remote catchment, partially fed by retreating glaciers), although organic carbon isotope analysis suggests an increase in lake productivity, possibly in response to warming over the last 150 years.
5.6 Conclusions

Analysis of diatom and pollen assemblages in Buju3 have shown that, unlike the glacial archives (Chapter 2), the Afroalpine lake ecology and flora have not undergone dramatic changes over the last century and a half. This is most likely due to the limnology of Lake Bujuku and highly adaptive nature of its dominating diatom species (*Fragilaria sp.*). Changes in diatom species after ca. 1975 suggest, however, that there has been a perturbation lasting over 25 years superimposed upon the general trend of increasing lake productivity. These trends in diatom flora later begin to reverse in the last few years of the record. Although reasons for such an ecological change are unclear at the moment, the responses indicate a shift to a decline in epiphytic habitats and a concomitant increase in algal productivity. Overall, the palaeoenvironmental record shows only subtle and gradual changes in response to observed glacial retreat.
6 Lake-sediment archives of atmospherically deposited pollutants in the Rwenzori Mountains

6.1 Introduction

6.1.1 Atmospheric pollution

Atmospherically transported pollutants have reached all parts of the globe and nowhere can now be classed as truly pristine. Both the Arctic and Antarctic are known to have been impacted by trace metals (e.g., Boutron 1982; Hermanson 1993; Wolff and Suttie 1994; Wolff et al. 1999), persistent organic pollutants (POPs) (e.g., Macdonald et al. 2000; Borghini et al. 2005) and fossil-fuel derived particulates (e.g., Murphey and Hogan 1992; Rose et al. 2004) and the record stored in lake sediments and ice cores demonstrates that fluxes have increased over recent decades. More volatile contaminants (e.g. some POPs; Hg) are preferentially deposited in colder regions and this effects polar zones by movement latitudinally (Wania and Mackay 1996) as well as areas that are colder by virtue of their altitude (Grimalt et al. 2001). As a consequence, these contaminants have been shown to have bioaccumulated to significant levels in the sediments (e.g., Fernández et al. 1999; 2000) and ecosystems (e.g., Vives et al. 2004a, b) of remote, high altitude European and Arctic lakes.

Mountain lakes are therefore particularly relevant to assessments of atmospheric deposition because they are not directly (i.e. within the catchment) affected by human activities and all contamination enters via the atmosphere. In this respect they can often act as ‘early warning indicators’ for lower altitude environments or for sites directly affected by human activities. Despite growing interest in atmospheric contaminants in mountain lakes, very little work has been undertaken in the tropical mountain lakes of central Africa. This study employs a palaeolimnological approach to investigate atmospherically deposited trace metals and fly-ash in three remote mountain lakes in the Rwenzori Mountains of Uganda. The aims of this study were:

- to determine the temporal trends of pollutant deposition of three mountain lakes and identify direction and rates of change; and
- to assess possible sources of any contamination.

6.1.2 Trace metals

Trace-metal background concentrations in sediments are mainly driven by the weathering of bedrock. Worldwide emission inventories have been developed by Pacyna (1986) assessing both natural and anthropogenic sources. It is worth noting that soil-derived dust accounts for over 50% of the total Cu, Mn and V
emissions, as well as for 20 to 30% of the Cu, Mo, Ni, Pb, Sb and Zn released annually to the atmosphere. Biogeochemical processes within lakes and their catchments may also affect trace metal background concentrations in sediments. Soils consist of heterogeneous mixtures of different organic and inorganic-mineral substances, crystalline and clay minerals, oxides and hydroxides of Fe, Mn and Al, and other solid components as well as a variety of soluble substances. Increases in the transport of catchment-derived material to a lake can lead to enhanced levels of trace metals. Hence, it is often difficult to differentiate between naturally-derived and anthropogenic trace metals. It is consequently important to consider methods of identifying possible natural and human sources when analysing lake sediment records.

Anthropogenic sources of trace metals to the atmosphere include a wide range of industrial activities including, electricity generation, metallurgical industries, mining and smelting, chemical and electronic industries, waste disposal, transport and agricultural practices. Once emitted to the atmosphere, these contaminants can travel very long distances prior to deposition. In the case of Hg, the volatile nature of the element means that it has an atmospheric life-time of ca. 1 year and sources of contamination to even the remotest of regions must be considered on an hemispherical or global scale.

6.1.3 Fly ash

Fly-ash particles are produced by the combustion of fossil-fuels at industrial temperatures and at a high rate of heating (Rose, 2001). This process produces spheroidal carbonaceous particles (SCPs), which are mainly composed of elemental carbon, and inorganic ash spheres (IASs) which are formed from the mineral component of the original fuel (Fig. 31). SCPs were used in this study because they have no natural sources and are not produced from the burning of wood, biomass or charcoal. SCPs are, therefore, an unambiguous indicator of deposition from industrial combustion of fossil fuels. Due to their composition, SCPs are chemically robust and can easily be extracted from lake sediments (Rose, 1994).

Figure 31. Spheroidal carbonaceous particles (SCP) under an electron microscope (Rose, 2004).
Most studies on SCPs have been focused within Europe where the temporal record stored in lake sediments faithfully reflects historical patterns in fossil-fuel combustion. Other studies have been undertaken in lakes from China, Siberia, the USA, and in circum-polar Arctic regions. However, no studies of this nature have been undertaken in central Africa.

6.2 Study areas

Sediment cores were taken from three alpine lakes in the Rwenzori Mountains: Lower Kitandara Lake, Lake Bujuku and Lake Mahoma (Fig. 32). Kitandara Lake is situated at 0°21’N, 29°53’E and was formed during the most recent Omurubaho Glaciation (Osmaston et al., 1998), 6890±100 years B.P (Livingstone, 1966). The altitude of the lake is about 3990 mamsl and most of its catchment area is covered by alpine vegetation. The lake is shallow, with a maximum depth of 9m. Lake Bujuku is situated at 0°22’N, 29°54’E at about 3920 mamsl. The lake formed following the Omurubaho Glaciation about 2960±60 years B.P. Damming of the lake appears to have occurred as a result of landslides from the slopes of Mount Baker (Fig. 14). The lake has a maximum depth of 13 m. Lake Mahoma, located at an altitude of 2690 mamsl has the lowest elevation of the three. It is situated at 0°21’N, 29°58’E, and forms a headwater catchment of the River Mubuku. The lake formed during the waning phase of the Lake Mahoma Glaciation and is characterised by large converging lateral moraines extending up to three miles long and 150 m high. Carbon dating from this lake implies an age of 15 to 20 thousand years. No lower altitude glacial lake appears to exist in equatorial Africa. Vegetation around the lake is dominated by *Arundinaria* forest but there are also many scattered heather trees. The lake has a maximum depth of 25 m. The water is described as deeply stained, with bubbles of gas rising continually to its surface (Livingstone, 1962). The lake is stratified and only the upper 10 m contains more than 1 ppm of oxygen.

![Figure 32. Map of the location of Lakes Mahoma, Bujuku and Kitandara in the Rwenzori Mountains (reproduced from Livingstone, 1966).](image)
6.3 Methodology

6.3.1 Sediment-core collection and extraction
Sediment cores were taken from a representative part of the deep-water area of each lake from an inflatable boat using a gravity corer (Glew, 1991). Bathymetric surveys of each lake were conducted using an echosounder and hand-held GPS. All cores were extruded on site at 0.25 cm intervals (in the upper 10 cm), 0.5 cm (10 cm to the base of the core). Due to time limitations at the site, core MAHO1 from Lake Mahoma was extruded in 1 cm from 20 – 45 cm. All sediment samples were placed in Whirlpak bags to avoid contamination during transfer and to prevent loss of water prior to lithostratigraphic analysis.

6.3.2 Lithostratigraphy
Lithostratigraphic measurements were undertaken using standard techniques. Dry weight (DW) was measured by drying sub-samples in a furnace at 105°C for at least 12 hours. The same sediment was then placed in the furnace at 550°C for 2 hours to give the percentage loss of ignition (LOI) as an estimate for organic matter content. Sediment wet density (WD) was measured using 2 cm³ capacity brass phials.

6.3.3 Sediment-core dating
Sediment cores KITA3 and MAHO3 were dated by Dr. Handong Yang, University College London by analysing for $^{210}$Pb, $^{226}$Ra, $^{137}$Cs and $^{241}$Am by direct gamma assay in the Bloomsbury Environment Institute Facility using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. $^{210}$Pb was determined via its gamma emissions at 46.5 keV, and $^{226}$Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope $^{214}$Pb following three weeks storage in sealed containers to allow radioactive equilibration. Cesium-137 and $^{241}$Am were measured by their emissions at 662 keV and 59.5 keV respectively. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample. BUJU3 was dated by Dr. Andy Cundy, University of Sussex. Core sub-samples were counted for at least 8 hours on a Canberra well-type ultra-low background HPGe gamma ray spectrometer to determine the activities of $^{137}$Cs, $^{210}$Pb and other gamma emitters.

6.3.4 X-ray fluorescence (XRF)
X-ray fluorescence (XRF) analyses were carried out in Department of Geography, University of Liverpool. The Metorex Xmet920 X-ray fluorescence spectrometer uses $^{55}$Fe and $^{109}$Cd isotope X-ray sources and is run by the software DECONV. Reference Buffalo River sediment (NIST2704), stream sediment (GBW7309) and pond sediment (NIE2) were used to evaluate the
accuracy of the measurements. The technique produces reasonable accuracy for Si, K, Ca, Ti, Fe, Rb and Zr and was chosen because it is able to analyse over 70 samples per day. It is also a rapid and non-destructive method. It provides background geochemical data and acts as an exploratory tool prior to more detailed and time consuming trace element analyses.

6.3.5 Atomic Absorption Spectrometry (AAS)

Samples were prepared for Atomic Absorption Spectrometry (AAS) using a standard nitric acid digestion. AAS analysis was carried out in the Department of Geography, University of Liverpool using a Unicam 939 AAS instrument to measure Cd, Co, Cu, Ni, Pb and Zn. Hg analysis was undertaken by cold vapour atomic absorption spectrometry (CV-AAS) by Dr. Handong Yang using the same instrument.

6.3.6 SCP analysis

Sediment samples were prepared for SCP analysis using the standard approach described by Rose (1994). This involves a sequential mineral acid digestion to remove unwanted fractions of the sediment resulting in a suspension of mainly carbonaceous material in water. A known sub-sample of this suspension is then evaporated onto a cover-slip and mounted on a microscope slide. The number of SCPs are then counted using a light microscope at x400 magnification. The concentration of SCPs can then be expressed in units of ‘number of SCPs per gram dry mass of sediment (g⁻¹ DM⁻¹).

6.3.7 Interpretative techniques

Unlike SCPs, trace metals in sediment cores have both natural and anthropogenic sources. It is therefore necessary to apply techniques to metals data to assess the amount of element contributed by human activities. A number of methods have been used in various studies (Norton and Kahl, 1991; Kamman and Engstrom, 2002; Roulet et al., 2002; Pacyna, 1998; Bruland et al., 1974; Bilali et al., 2002) and most of them are based on enrichment factors or ratios of the element of interest to a ‘natural element’. Due to differences in geochemistry, different elements may be needed to act as passive tracers at the sites (Yang and Rose, 2005). The method devised by Hilton et al. (1985) is the most appropriate. Using this method, the trace-metal concentration is regressed against a major cation. Assuming that the trace element is associated with natural contributions, the scatter plot should be linear. However, if there is an additional enhancement due to anthropogenic pollution a change in slope gives an indication of the change in source.
6.4 Results

6.4.1 Percentage loss on ignition, dry weight and wet density

Figure 33 shows the percentage loss-on-ignition (LOI), dry weight and wet density in the analysed cores. The percentage LOI gives a crude measure of the organic content of the sediment. The percentage organic matter for KITA2 and BUJU1 shows a general decreasing trend as depth increases, with the former having a slightly higher organic content. MAHO1 is the most organic-rich sediment core and its percentage LOI fluctuates around 80% throughout the profile. Its lowest organic content of 71% at 41 cm is higher than the highest organic content for the other two lakes. In general, percentage LOI values often show an inverse relationship with percentage dry weight. This phenomenon is more obvious for BUJU1 but less so for KITA2 and MAHO1.

Figure 33. Loss on ignition (LOI), dry weight and wet density profiles for each analysed sediment core (BUJU3, KITA3, MAHO1).
6.4.2 Age - depth profiles of sediment cores

Details of the dating of BUJU3 core are presented in Chapter 5 (Section 5.4). A constant rate of supply model for $^{210}$Pb (Appleby 2001) is applied to KITA3 whereas a constant initial concentration (CIC) model (Appleby 2001) is applied to MAHO1. Dating results are unusual for KITA3, as the estimated 1963 level by $^{137}$Cs is higher than the level dated by $^{210}$Pb. This can be caused by the loss of surface sediments during sampling or by a small degree of sediment mixing. However, the similarity of the LOI profiles of KITA3 and the other KITA cores suggests that the possibility of loss of the top sediment is low. It is also unusual that the dry mass density in the uppermost sediments is the highest. $^{137}$Cs dates suggest the post-1963 sedimentation rate to be 0.011 g cm$^{-2}$ a$^{-1}$ which agrees reasonably well with the rate of 0.0114 ± 0.0025 g cm$^{-2}$ a$^{-1}$ for the entire core as calculated using CRS model for $^{210}$Pb.

Figure 34 shows that the age-depth profiles for the Bujuku cores are relatively linear suggesting little change in sediment accumulation rate through time. The KITA and MAHO profiles suggest an increase in sediment accumulation rate in more recent times. The earliest dates obtained for KITA3, BUJU3 and MAHO3 are 1849, 1865 and 1836 respectively. BUJU1 is a shorter core and can only be dated back as far as 1927.

6.4.3 Sediment-core trace-element profiles

Within a sediment core, the distribution of heavy metals such as Cd, Co, Cu, Pb, Zn and Ni often exhibits correlations with the amount of organic matter or coincidental elements such as Ti, Al, Fe and Mn. With the addition of anthropogenic derived heavy metals deposited in lake systems, such correlations may breakdown. The comparison can, therefore, help to differentiate natural from anthropogenic contributions and geochemical processes.

6.4.3.1 Lower Kitandara Lake

Cadmium is the only trace metal that shows an increase towards the surface of the core (Fig. 35). With the exception of the uppermost sample, Ni concentration decreases towards the surface whereas Zn, Cu, Co and Pb show no obvious trends. Cu and Zn display similar trends, with corresponding peaks and troughs. A distinctive peak appears at 10cm on the Pb profile. Apart from Cd, the trace metals shows opposite trends to that of LOI.
Figure 34. The age-depth profile of sediments cores.
Figure 35. Depth (age) profiles of trace metal concentrations at Lower Kitandara Lake (KITA2).

6.4.3.2 Lake Bujuku

Like KITA2, the BUJU1 Cd profile differs from other trace-metal profiles (Fig. 36). Copper, like LOI, shows a slight increase towards the top of the core, whereas Co, Ni, Zn and Pb concentrations fluctuate. Zn and Pb concentrations show some similarity in their trends. An exceptional decline in Pb concentrations occurs at 18 cm and does not correspond with any trace metals. The trace metal profiles do not appear to correspond to the trends in geochemical data.
6.4.3.3 Lake Mahoma

Trace-metal concentrations in Figure 37 show unexpected patterns. Extremely high concentrations of Cu, Ni and Pb are detected in the shallowest (most recent) sample. The Ni concentration in this uppermost sample is ten times higher than the rest of the core (137 μg·g⁻¹) and has been removed from Figure 37 in order to represent temporal trends clearly. For Ni, Zn and Pb, high concentrations are observed but not at similar depths (ages). They do not appear to be comparable with peaks in the geochemical data. There is an increase in the concentration of Co, Ni, Pb and most obviously Cu, towards the most recent (shallow) sediments from a depth of approximately 16 cm.

Figure 36. Depth (age) profiles of trace metal concentrations at Lake Bujuku (BUJU1).
Figure 37. Depth (age) profiles of trace metal concentrations at Lake Mahoma (MAHO1).

6.4.4 SCPs

The concentrations of SCPs in the sediment cores were extremely low. Black, ‘disc-like’, particles were, however, detected throughout BUJU1. Unlike usual SCPs, these particles appear to be flat, have similar sizes and concentrations at each depth. This kind of particle has been found previously in sediments from Lakes Wandakara and Kasenda in Uganda but at present, it has not been possible to identify their nature and origin.
6.5 Discussion and analysis

6.5.1 Application of Hilton’s model

Hilton’s model (see 6.3.7) was applied to the trace-metal data in order to identify anthropogenic sources of metals in the three sediment cores. Figure 38 shows the relationship between trace metals with other elements as well as percentage LOI.

6.5.1.1 Lower Kitandara Lake

The model shows that for KITA2, Co, Cu, Ni and Zn all have high negative correlations with LOI. These elements do not appear to be controlled by the amount of organic matter in the sediment. Cu and Ni both show high correlation with K, Fe and Mn. This suggests a high affinity of Cu and Ni for mineral material containing these three elements. In many soils, the oxides and hydroxides of Fe and Mn play the most significant role in the distribution and behaviour of trace elements. The hydroxides occur in soils as a coating on soil particles, as filling in cracks and veins, and as concretions of nodules. They also have high sorption capacity for trace metals (Kabata-Pendas and Sadurski, 2004). Fe and Mn oxides co-precipitate and adsorb cations including Co, Cu, Mn, Mo, Ni, V and Zn (Alloway, 1995). In this core, Co is likely to be associated with minerals rich in Mn and Fe as it shows a high correlation with these elements.

Zn and Pb have a weak correlation with all geochemical elements as well as LOI. However, the Zn profile shares many similarities with those of Co, Cu and Ni suggesting that Zn derives from the same source. The Pb profile is similar but the low correlation likely stems from anomalously high concentrations observed at depths of between 7 and 12 cm. The origin of high Pb concentrations remains uncertain but is unlikely to be a result of contamination due to the stable rising and falling limb. Muwanga (1997) suggested that Pb dissolves at pH values below 4.5 and above 6. If it was a result of diagenesis or change in pH causing the mobility of the Pb, such changes should be seen in other elements. Cd is the only metal that shows an increase towards the surface. Although the model shows a low correlation with LOI, a Cd/LOI ratio gives a very consistent value, suggesting that the occurrence of this trace element is closely related to the presence of organic matter, and therefore the increase is likely to be due to a natural geological contribution.

6.5.1.2 Lake Bujuku

The application of Hilton’s model to BUJU1 shows that Cu shows a high positive correlation with percentage LOI, suggesting the increase is due to the contribution of organic matter. Cu in solid phase is often adsorbed by soil components in the following order: organics > Fe/Mn oxides > clays (Baker,
Figure 38. Element concentration correlations and Pearson’s correlation coefficient (r).
It has been documented that up to 98% of total Cu is associated with the organic fraction in soils (Flemming and Trevors, 1989). The lack of a correlation with mineral parameters in this case can be attributed to the greater natural contribution of organic matter to their adsorption by sediments. Cd also produces a high overall correlation with the percentage of LOI. At greater sediment depths (13 to 26 cm), a negative correlation occurs. This is due to the extremely low concentrations at that depth. No significant correlation between other trace metals and geochemical data or LOI was obtained.

6.5.1.3 Lake Mahoma

Hilton’s model does not appear to apply to MAHO1 as no correlation can be identified between trace metals and other geochemical data or LOI. It is possible that the high organic content (mean of 79%) in the sediment means that a very low percentage of mineral is present to provide sufficient adsorption sites for the metals. At the same time, the organic fraction is high so adsorption sites are unlikely to reach saturation. The increase in Co, Cu, Ni and Pb is attributed to anthropogenic sources. Comparisons are hindered by the fact that dissolution and sorption may affect some geochemical elements but not all (Alloway, 1995).

6.5.2 Assessment of anthropogenic origin of trace metals

The assessment of background and anthropogenic impact of trace metals in sediment cores is essential but often difficult. The ‘background’ usually refers to the natural contribution. In this study, it is more appropriate to describe this as a ‘baseline’. Metal contamination in sediments can be traced back as far as the Bronze Age (2500BC) (Kabata-Pendias and Sadurski, 2004). The 150-year period covered by sediment core archives includes considerable atmospheric pollution. Baseline concentrations in the sediment cores are unlikely to be solely natural.

Application of the Hilton model to trace-metal profiles suggests that Lake Kitandara and Lake Bujuku, both located at higher latitudes, are relatively unpolluted. No obvious increase in metals due to anthropogenic influence can be identified. In contrast, the Lake Mahoma profiles (Fig. 37) reveal increased concentrations of Co, Cu, Ni and Pb in the most recent (shallow) sediments. Co and Pb show an increase from around 13 cm depth, which corresponds to a date between 1957 and 1962. Increased concentrations of Cu and Ni begin earlier in the 1940s (16 cm). For Co, Ni and Pb, the surface sediment is highly enriched. Calculation shows that the contaminated sediments of Co, Cu, Ni and Pb are 3.5, 1.4, 2.3 and 3.3 times higher than the baseline, respectively. The Pb and Co contamination levels remain relatively constant prior to the surface peak, whereas for Cu, the highest concentration level reaches 32 µg g\(^{-1}\) at 5 cm and corresponds to a period between 1985 and 1989. A massive drop in Ni concentration is recorded at 6 and 8 cm, representing periods in the 1970s and 1980s.
Mercury vapour (Hg\textsuperscript{0}) has a long atmospheric residence time and mercury contamination of lacustrine environments is ubiquitous (Engstrom and Swain, 1997). Hg analysis for the three Rwenzori lake sediment cores shows increasing concentrations for all profiles starting at different depths (Fig. 39a). In KITA2, Hg values fluctuate between 70 to 90 ng\cdot g\textsuperscript{-1} from the deep sediment to 18 cm, where the concentration increases and eventually exceeds 200 ng\cdot g\textsuperscript{-1} in the top few centimetres. Three major stages can be seen in the BUJU1 profile, (i) 18-22 cm, (ii) 8 to 17 cm, and (iii) 0 to 7 cm. Each of these stages shows a progressively higher Hg value than the previous one. MAHO1 shows a gradual increase from the base of the core (Fig 39a) until a very significant increase is observed at 22 cm depth to above 200 ng\cdot g\textsuperscript{-1} where it remains up to 10 cm when concentrations decline to the surface.

Hilton’s model suggests a high positive relationship between MAHO1 Hg and percentage LOI at 19 cm and below (Fig 33). This correlation is significantly lower above this depth. Using this relationship it is possible to identify the anthropogenically induced Hg concentration above this depth (Fig 39b). The Hg:LOI ratio for KITA2 is consistent below 17 cm, indicating Hg is contributed by organic matter at lower depths. The amount of Hg pollution is estimated by the linear relationship between background Hg and percentage LOI. The same method is used for BUJU1, where sediment between 17 and 26 cm provides a baseline.

Anthropogenically induced Hg contamination seems to have begun in the ca. 1860s in Lake Kitandara. It then reaches a peak in the 1920s, followed by a decline. The trend increases almost continuously since 1950s. In BUJU1, the pollution signal starts in ca. 1950s. No pollution above the background value is detected at 7.5 cm, but this is followed by a rapid increase towards the most recent sediments. MAHO1 Hg pollution signal started in ca. 1930s. A reduction occurs around 1971. A modern baseline ratio suggests an enrichment of Hg by 2.1, 2.2 and 1.5 for KITA2, BUJU1 and MAHO1 respectively. This is in reasonable agreement with the enrichment figure of 3 ± 1 (D. Engstrom, pers. commun.) for remote lakes in other areas of the world including Arctic Canada and Europe and New Zealand. The influence of Hg on this part of the Rwenzori Mountains is more widespread then other trace metals since it is detected in all three lakes. It is logical to suggest that the Hg originates from long-distance transport. It is unlikely to be local as contamination from other metals has not been detected in Lake Kitandara and Bujuku.
Figure 39. (a) Hg profiles; (b) anthropogenic Hg profiles; and (c) Correlation of background Hg and %LOI.
6.5.4 Trace metal flux profiles

Metal concentration profiles are strongly influenced by sedimentation rates. Concentrations of elemental constituents are accentuated under periods of reduced sedimentation, and vice versa (Kamman and Engstrom, 2002). Conversion of concentrations to flux rates normalises this covariance, and permits a better comparison between lakes. Figures 40 to 42 show the trace metal flux profiles.

Trace-metal fluxes for Lower Kitandara Lake (Fig. 40) show increasing deposition of Cu, Zn and Pb, and to a greater extent Cd and Hg. The change in Cu, Zn and Pb can be attributed to an increase in sedimentation rate. However, the enrichment factor of Cd and Hg in the upper layers is significantly higher than the sedimentation rate. Cd influx increases from 14 cm upwards. The influx Hg above this depth is 3.7 times higher than the baseline while the difference in sedimentation rate is less than 2. However, as seen earlier, this increase is very likely to be a result of an increase in organic matter. This agrees with the Hg:LOI ratio data and suggests a breakdown in the influence on Hg by LOI above 17 cm and supports the anthropogenic origin of Hg above that depth.

For Lake Bujuku, the profiles reveal a decrease in flux towards the surface. This is due to the decrease in sedimentation rate towards the uppermost sediments and can again be explained by the amount of organic matter present. The flux of trace metals in Lake Mahoma increases particularly in the shallowest (most recent) sediments from 7 cm. To a certain extent, this can also be attributed to a rapid increase in sedimentation rate. However, for Co, Cu, Ni, Pb and Hg, the proportional increase is too big to be solely attributable to the change in sedimentation rate. The upper sediment enrichments are 7 times higher than the bottom sediment for Co and Hg, and 3, 9 and 8 times higher for Cu, Ni and Pb respectively. This supports the hypothesis that the metals are probably anthropogenically enhanced in these upper layers.

6.5.5 Trace-metals concentrations in moss

The use of certain terrestrial moss species to monitor the deposition of metals is now well established in Europe and elsewhere. Briefly, these mosses obtain everything they require from atmospheric deposition and so do not uptake any nutrients or minerals through a root system which is used only to secure the plant to its substrate. As a consequence, the metal content of the moss tissue reflects the metal deposited onto the moss and its analysis provides the opportunity to study the transfer of trace metals from the atmosphere virtually independent of the underlying mineral material or organic matter.
Figure 40. Depth (age) profiles of trace-metal fluxes for Lower Lake Kitandara.
Figure 41. Depth (age) profiles of trace-metal fluxes for Lake Bujuku.
Figure 42. Depth (age) profiles of trace-metal fluxes for Lake Mahoma.
Two moss species are typically used for this in Europe, *Hylocomium splendens* and *Pleurozium schreberi*, based on their widespread distribution. Fortuitously, *Hylocomium splendens* was found near Lake Bujuku and opportunistically sampled. Species identification was confirmed by experts at the Natural History Museum, London. The Bujuku moss sample analysis resulted in metal concentrations shown in Table 4. Hg and Cu are relatively low, similar to values found in relatively unpolluted areas of Great Britain. Hg concentration is comparable to that of Lochnagar, a remote mountain lake in Scotland. Pb, Zn and Cd are in the middle of the range for British sites. This further supports that the area around Lake Bujuku is relatively free from atmospheric pollution.

**Table 4.** Elemental concentrations in moss sampled near Lake Bujuku.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration (ng g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hg</td>
<td>30</td>
</tr>
<tr>
<td>Cu</td>
<td>2.4</td>
</tr>
<tr>
<td>Pb</td>
<td>4.3</td>
</tr>
<tr>
<td>Zn</td>
<td>37</td>
</tr>
<tr>
<td>Cd</td>
<td>0.46</td>
</tr>
</tbody>
</table>

### 6.5.6 Possible sources of trace metals

Extremely low concentrations of SCPs detected in the sediment of the Rwenzori lakes may occur for two reasons. First, the source that produced trace metals detected in Lake Mahoma does not involve the combustion of fossil fuels. Electricity in Uganda is generated almost entirely by hydroelectric means and most of this is generated from a single hydroelectric station at Owen Falls. Another possibility is that the source of metal contamination is at a distance sufficient to preclude the transport of SCPs to the sites. This suggestion is consistent with the conclusion that increased Hg in the most recent (shallow) sediments arise from global sources.

Copper was discovered in the Rwenzori Mountains in 1906 and since then an extensive exploration programme regarding the potential for mining has been undertaken (Muwanga, 1997). Therefore, a possible source of Co, Cu, Pb and Ni detected in MAHO1 is local mining in the area. The production of copper in Kilembe, which is in close proximity to the study area (Figure 15) commenced in 1956 when the railway to Kasese was completed. Nearly 16 million tonnes of ore averaging 1.95% Cu had been mined by 1978 when production ceased. After processing, the material was sent to Jinja about 400 km away in Eastern Uganda for smelting (Figure 15a). The increase in Co and Pb seems to correspond with the period when the copper production commenced whereas the increase in Cu and Ni pre-dates this time and may stem from local, traditional smelting of copper. Considering the distance from the smelter, it is uncertain whether metal pollution detected in Lake Mahoma is a result of this smelting.

According to Baker and Senft (1995), major sources of pollution such as smelters, usually yield the highest concentrations in soils within 1 to 3 km of the stack with concentrations decreasing exponentially with distance. For the Cu-Ni complex in Sudbury (Canada), most of the emitted Cu is deposited within 32 km
but soils in areas closer than 7.5 km frequently contain well over 1000 mg kg\(^{-1}\). Copper smelters also release large quantities of As and Zn but no increase in Zn in MAHO1 was detected.

Atmospheric inputs of Cu to soils from both rain and dry deposition vary considerably according to the proximity of industrial emissions containing Cu and the type and quantity of wind-blown dust. Hence, the atmosphere is an important medium for the transmission of pollutant Cu to remote areas of the Earth and analysis of moss samples and polar ice cores reveal a substantial increase in airborne Cu at locations far from emission sources (Baker and Senft, 1995).

As the increase in Co, Cu, Pb and Ni continues to the present day and Cu production ended in 1978, metals in Lake Mahoma may derive from local mine deposits and tailings. According to Muwanga (1997), wastes produced by the mining operation were disposed of in Kilembe valley. These mine wastes have been exposed to strong tropical weathering which leads to the oxidation of residual sulphides resulting in mobilisation and migration of heavy metals into the surrounding terrestrial and aquatic environments. Elevated levels of Cu, Co, Ni and Zn are enriched in soils, water and stream sediments in the mine area and around the waste disposal sites. Cu toxicity is also detected in vegetation in the Rwenzori National Park (Edroma, 1974) associated with copper concentrate leakages along pipe lines. It is possible that the trace metals detected in Lake Mahoma are associated with physical processes during mining, when the metals are exposed and transported by aeolian processes into lake catchments. The fact that the pollution signal is not detected in the other two lakes may then be explained by their greater distance and higher altitude from the source. If this were the case, then the exposed tailings may continue to provide a source of metals to the lakes long after production has ceased and provide a mechanism for contamination into the future. Further research is required to better understand the most likely causes.
6.6 Conclusions

Among the three remote, high mountain lakes in the Rwenzori Mountains under study only Lake Mahoma, the lowest in altitude, displays signs of anthropogenic, atmospheric deposition of trace metals. The flux of SCPs to the lake is below detection limits so it has not been possible to conclude whether emission sources involve the combustion of fossil fuels. Enrichment of the sediment profiles in mercury is consistent with (1.5 to 2.2) with that of remote environments around the world (3 ± 1). The observed increase in atmospherically deposited Co and Pb at Lake Mahoma began between the mid-1950s and early-1960s and coincides with the production of copper in the Kilembe mine. However, initial contamination from anthropogenic Cu and Ni pre-dates this period. The sources of continued pollution are unclear but likely involve the re-mobilisation of trace metals in mine tailings in the Kilembe valley and atmospheric transport from remote (non-local) sources.
7 Overall project findings

The project has been considerable progress toward realising its scientific objectives. Each is discussed below.

7.1 magnitude of current glacial recession

Field mapping and analysis of Landsat imagery show that glacial cover on the three remaining glacierised summits (Mounts Stanley, Speke and Baker) has decreased from $2.01 \pm 0.11 \text{ km}^2$ in 1987 to $0.96 \pm 0.34 \text{ km}^2$ in 2003. These determinations confirm a continued, steady decline in the areal extent of glaciers in the Rwenzori Mountains of $\sim 0.7 \text{ km}^2$ per decade over the last century. Assuming present trends continue, glaciers in the Rwenzori Mountains are expected to disappear within the next two decades.

7.2 impact of glacial recession on alpine riverflow

Meltwater flows from glaciers in the Rwenzori Mountains do not contribute significantly ($> 0.5\%$) to alpine riverflow. This conclusion, based on stream fluxes measured during the dry season, is consistent with previous assertions by Temple (1967) and Osmaston (2006). The possibility that receding glaciers signal a decline in precipitation over the 20th century is supported neither by meteorological records from lowland stations in western Uganda nor regional hydrological records. Insufficient data exist to verify local reports in Uganda (Kasese District) of an increased frequency and magnitude of flood events at the base of the Rwenzori Mountains. Changes in land use and land pressures outside of the Rwenzori Mountains National Park (i.e., below 1700 mamsl) in the River Mubuku basin may explain, in part, the perceived increase in flood risk rather than significant changes in the hydrology of alpine riverflow.

7.3 recent environmental change from observational datasets and sediment-core archives

Glacial recession is associated with increased air temperatures not only suggested by the spatially uniform nature of recent loss of glacial cover but also indicated by meteorological observations at the surface (station data, gridded climate datasets) and mid-troposphere (radiosonde measurements) in western Uganda. There are, however, insufficient data to represent the complex interactions of radiant energy and heat at the glacier’s surface and thus quantify the link between changes in climate variables and glacial mass in the Rwenzori
Mountains. Although increasing air temperature and reduced air humidity remain plausible and likely related hypotheses to explain recent glacial recession in the Rwenzori Mountains, there is currently greater evidence of trends of increasing air temperature than decreasing humidity to explain deglaciation in the Rwenzori Mountains. This conclusion does not preclude, however, the likelihood that changes in humidity and radiative fluxes associated with rising air temperatures, have also contributed to observed glacial recession.

Despite a steady reduction in the areal extent of glaciers, the sediment-core archive from Lake Bujuku indicates that the lake ecology and flora of Afroalpine areas of the Central Rwenzori Massif have not undergone dramatic changes over the last century and a half. This is most due to the highly adaptive nature of its dominating species (e.g., *Fragilaria sp*.). Changes in the diatom assemblage suggest, however, that a perturbation lasting over 25 years is superimposed upon the general trend of increasing lake productivity. These trends in diatom flora later begin to reverse in the last few years of the record. Overall, the responses indicate a recent decline in epiphytic habitats and concomitant increase in algal productivity.

Atmospherically deposited mercury, consistent with global trends and emissions, is detected in lake sediment within the Heath-moss Forest zone (3000 mamsl) and Afroalpine zone (4000 mamsl). Trace-metal contamination via atmospheric deposition from more localised sources is evident from the mid-1950s and coincides with onset of copper mining downslope at Kilembe (1700 mamsl). Some anthropogenic loading of Cu and Ni appears to pre-date operation of the Kilembe mine and may stem from localised, small-scale traditional copper smelting practices.
8 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. Four student dissertations at the B.Sc. and M.Sc. levels have also been completed as part of this research.

8.1 stakeholder meetings

Focused meetings were held to discuss the findings of research and solicit input from local stakeholders including Uganda Wildlife Authority, Rwenzori Mountaineering Service and Water Resources Management Department.

On 24 January 2005, discussions were held at a meeting room of the Rwenzori Mountaineering Service in Nyakalengija (Kasese) with the Uganda Wildlife Authority, RMS 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 rivierflow, and the impact of glacial recession on the traditional cultural beliefs of the BaKonzo.

On 17 July 2006, discussions were held with the Water Resources Management Department in Entebbe pertaining to (i) current glacial extent and the rate of glacial recession, (2) the factors, both local and regional, driving glacial recession, and (3) the impact of glacial recession and related climate change on alpine rivierflow.

8.2 scientific publications

Panizzo, V.N., Mackay, A.W., Ssemmanda, I., Taylor, R.G., Rose, N. and Leng, M., in review. Recent changes in aquatic productivity in a remote, tropical alpine lake in the Rwenzori Mountain National Park, Uganda, associated with glacier recession since the 1860s. *Journal of Paleolimnology*


### 8.3 conference presentations and speaking invitations


### 8.4 popular press


"African ice caps will soon disappear due to global warming” also appeared in European Commission DG Environment News Service, Science for Policy, Issue 25 (June 8, 2005)


8.5 student dissertations


* Awarded Best Undergraduate Dissertation Prize in hydrological science by the British Hydrological Society.
** Awarded Best Undergraduate Dissertation Prize in Quaternary science by the Quaternary Research Association.

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