

Seventy-six years of mean mass balance rates derived from recent and re-evaluated ice volume measurements on tropical Lewis Glacier, Mount Kenya

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[1] Lewis Glacier on Mt Kenya has a unique history of detailed study, making it among the best documented tropical glaciers. Here we present (i) a new ice volume determination based on a bedrock DEM constructed from GPR data acquisition and (ii) the glacier's mean mass balance rates over the last 76 years derived from volume and area estimates based on seven historical maps and the newly determined bedrock topography. Total ice volume in 2010 was $1.90 \pm 0.30 \times 10^6 \text{ m}^3$ with a mean (maximum) ice depth of $18 \pm 3 \text{ m}$ ($45 \pm 3 \text{ m}$), which is one order of magnitude larger than previously published values. In 2010, the glacier had lost 90% (79%) of its 1934 glacier volume (area), with the highest rates of ice volume loss occurring around the turn of the century. Computed mean mass balance rates, covering the whole period of glaciological surveys of Lewis Glacier, provide the longest record of tropical glacier change and show that the mean mass balance rate varies consistently with global estimates, but the magnitude is always more negative than in other regions. **Citation:** Prinz, R., A. Fischer, L. Nicholson, and G. Kaser (2011), Seventy-six years of mean mass balance rates derived from recent and re-evaluated ice volume measurements on tropical Lewis Glacier, Mount Kenya, *Geophys. Res. Lett.*, 38, L20502, doi:10.1029/2011GL049208.

1. Introduction

[2] The recession of tropical glaciers in East Africa is a prominent feature of ongoing environmental change [e.g., Hastenrath, 2005b, 2008; Kaser *et al.*, 2010]. Though of limited socio-economical relevance in this part of the world [Kaser *et al.*, 2004; Mölg *et al.*, 2008], these glaciers have great potential to provide information about East African climate, its dynamics, and its evolution over decadal and century time scales, if their interaction with the atmosphere is understood, and their changes are documented or reconstructed [e.g., Osmaston, 1989; Hastenrath and Kruss, 1992; Kaser, 2001; Mölg *et al.*, 2009; Kaser *et al.*, 2010]. The East African glaciers capture a climate signal from atmospheric levels, between approximately 5 and 6 km a.s.l., where our knowledge of climate change is scarce and controversial [e.g., Karl *et al.*, 2006; Trenberth *et al.*, 2007]. Changes of tropical glaciers can thus be used to analyze changes in atmospheric conditions in the mid troposphere. Measuring

and reconstructing glacier changes quantitatively is the first prerequisite for this.

[3] Lewis Glacier ($0^{\circ}9'S$, $37^{\circ}18'E$) on Mt Kenya has been studied since the late 19th century, making it among the best documented of all tropical glaciers. Changes in the extent of Lewis Glacier over the Quaternary are recorded by down-valley moraines, and have been measured directly at irregular intervals in recent decades.

[4] In this paper we first present a brief summary of the extensive work carried out on Lewis Glacier since the late 1800s, then we address the specific aims of the paper which are to: (i) present a new ice volume determination based on a digital elevation model (DEM) from the bedrock constructed from ground penetrating radar (GPR) data acquisition, (ii) present the glacier's mean mass balance rates over the last 76 years derived from volume and area estimates based on historical maps and the newly determined bedrock topography and (iii) discuss the new volume measurement in the light of previously reported incorrect numbers.

2. Previous Research on Lewis Glacier

[5] First expeditions to the peak region of Mt Kenya in the late 19th and early 20th century produced sketches and photographs of the glacier at that time [e.g., Gregory, 1894; Mackinder, 1900; Dutton, 1929]. In 1934 and in 1957/58 the first scientific field campaigns were carried out, undertaking measurements of ice surface velocity and mapping the glacier surface [Troll and Wien, 1949; Charnley, 1959]. The latter expedition, initiated in the framework of the International Geophysical Year (IGY), established several ground control points on the mountain, which define a local coordinate system, used in all subsequent surveys. Schneider [1964] mapped the glacier and its surroundings in 1963, and Patzelt *et al.* [1984] did the same in 1983. Hastenrath and colleagues produced maps of the glacier outline and surface from terrestrial surveys and airborne photogrammetry for the years 1947, 1974, 1978, 1982, 1985, 1986, 1987, 1990, 1993 and 2004 (see reviews by Hastenrath [2005b] and Rostom and Hastenrath [2007]). The latest glacier map was produced by the authors of this study using differential global positioning system (DGPS) surveying in 2010. Additionally, area and topography of the glacier surface at different stages since the end of the Little Ice Age have been reconstructed from moraines [Patzelt *et al.*, 1984]. As part of a wider compilation, results of studies on Quaternary glacial history and palaeoclimatology on Mt Kenya were published by Mahaney [1989].

[6] Between 1974 and 1978 several field campaigns used a combination of seismology, gravimetry and ice-dynamic modeling to determine the thickness of Lewis Glacier [Bhatt *et al.*, 1980], which will be discussed in section 5. Volume

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Table 1. Key Information on the Maps of Lewis Glacier Which Provide the Basis of the Analyses Presented Here^a

Survey Date	Scale	Contour Interval	Survey Method	Map Coverage	Reference
24.04.-05.05.1934	1:13333	10 m	TP, TS	Lewis Glacier	<i>Troll and Wien</i> [1949]
21.02.1947	1:5000	20 m	AP	Mt Kenya	<i>Rostom and Hastenrath</i> [1995]
19.-25.01.1963	1:10000	20 m	TP	Mt Kenya	<i>Schneider</i> [1964]
20.02.1974	1:2500	10 m	AP, TS	Lewis Glacier	<i>Caukwell and Hastenrath</i> [1977]
25.-26.02.1983	1:5000	10 m	TP	Lewis Glacier basin	<i>Patzelt et al.</i> [1984]
09.09.1993	1:2500	10 m	AP	Lewis Glacier	<i>Hastenrath et al.</i> [1995]
01.09.2004	1:5000	10 m (20 m on non-glacierized terrain)	AP	Mt Kenya	<i>Rostom and Hastenrath</i> [2007]
02.-03.03.2010	in digital format, adjustable	in digital format, adjustable	DGPS	Lewis Glacier	this study

^aThe 2010 map is not yet available in a cartographic print out style. TP: terrestrial photogrammetry, AP: airborne photogrammetry, TS: theodolite survey, DGPS: differential global positioning system.

changes were estimated using two approaches: a geodetic approach using maps for different periods between 1947 and 2004 [e.g., *Hastenrath and Caukwell*, 1979; *Hastenrath and Rostom*, 1990; *Hastenrath et al.*, 1995; *Rostom and Hastenrath*, 1995; *Rostom and Hastenrath*, 2007] and surface mass balance measurements. The latter were carried out from March 1978 to March 1996 using a network of ablation stakes and snow pits [*Hastenrath*, 1984, 2005a]. Data of variations of Lewis Glacier area, length and annual surface mass balance were reported to the database of the World Glacier Monitoring Service. Complementary and concurrent runoff and precipitation data of various temporal resolutions are given by *Hastenrath* [1984, 2005a].

[7] Short-term measurements (two weeks in April 1960 and three weeks during January and March 1978) of glacier surface energy balance components and thoughtful assumptions allowed for early formulations of the relation between the surface energy and the surface mass balance of Lewis Glacier [*Platt*, 1966; *Hastenrath*, 1984]. The principle driver of observed glacier shrinkage from the late 1800s to the early 1960s was identified as increased solar radiation, constrained by local ice surface geometry and surrounding topography [*Kruss and Hastenrath*, 1987]. Since the early 1960s the primary driver appears to have changed to be an increase in specific humidity [*Hastenrath and Kruss*, 1992]. Ice-dynamic modeling suggested that a combination of temperature increase and precipitation decrease, along with changes in albedo and cloudiness, has also contributed to glacier shrinkage [*Hastenrath*, 1984, 1989]. Converting the energy surplus driving the glacier changes on Mt Kenya into temperature equivalent, a reduction of mean air temperature by 0.7°C could bring the surface mass balance to equilibrium [*Hastenrath*, 2010].

3. Data and Methods

3.1. Maps Used in This Study

[8] Out of a considerable number of maps of Lewis Glacier we have chosen for further analyses those which (i) are tied to the IGY ground control points of 1958, (ii) include the surrounding bedrock, and (iii) offer a near-decadal frequency of glacier variation; namely 1934, 1947, 1963, 1974, 1983, 1993, 2004 and 2010. Although the 1934 and 1947 maps do not meet (i), we included them in the analyses by visually identifying ground control points and height notations, which gave us confidence in a reasonable accuracy. The 1958 glacier map was not included, mainly because there is concern about the “generous interpolation” between the survey points and about some portions of the

surface map not being consistent with the subsequent surveys of exposed bedrock [*Patzelt et al.*, 1984]. Table 1 shows the features of the maps used and Figure 1 gives an overview of the derived areal ice extents.

[9] In March 2010 the IGY ground control points, ice extent, and surface topography of Lewis Glacier were surveyed using DGPS. Measurements were made using Trimble Pathfinder ProXH and ProXT receivers with external Zephyr antennas. The base station was established at IGY ground control point L2 (see Figure 1), and the ice extent was measured by collecting point locations every second while walking the rover instrument along the glacier’s margin. Where obstacles or cliffs forced the surveyor to deviate from the glacier margin, the survey path was offset from the true glacier margin by a set horizontal distance (maximum 2 m) and the data were corrected manually for this offset after the differential post-processing step. The topography of the glacier surface was surveyed by traversing the glacier several times. After differential correction, the ice surface and ice margin point locations were combined in a triangulated irregular network and interpolated to a DEM with 5 m grid point spacing.

[10] The historical maps were transformed from their local coordinate system into the Universal Transverse Mercator (UTM) coordinate system, using DGPS positions of five of the IGY ground control points surrounding Lewis Glacier as a reference (Figure 1). From the contours, a DEM with 5 m grid point spacing for each map was interpolated using ESRI ArcGIS 9.3.1 tool topo2raster, which is based on the ANUDEM algorithm [*Hutchinson*, 1989].

3.2. Ice Thickness and Volume

[11] The ice thickness of Lewis Glacier was measured with GPR at 25 locations in March 2010. This GPR system has been used successfully on numerous glaciers in the Austrian Alps and is described in detail by *Span et al.* [2005] and *Fischer* [2009]. A miniature high-power impulse transmitter was combined with resistively loaded dipole antennas. The central frequency is 6.4 MHz corresponding to an antenna half length of 15 m. A Fluke 105B oscilloscope received and stored the data. The distance between transmitter and receiver antennas was 10 m. The velocity of the signal in the ice was taken to be 168 m/μs. Ice thickness was calculated from the measured time difference between the travel time of the signal through the air and the signal reflected from the glacier bed, and corrected for the slope, defined by the DGPS-derived DEM.

[12] Since the ice thickness was small compared to the distance from each measurement location to the glacier margins,

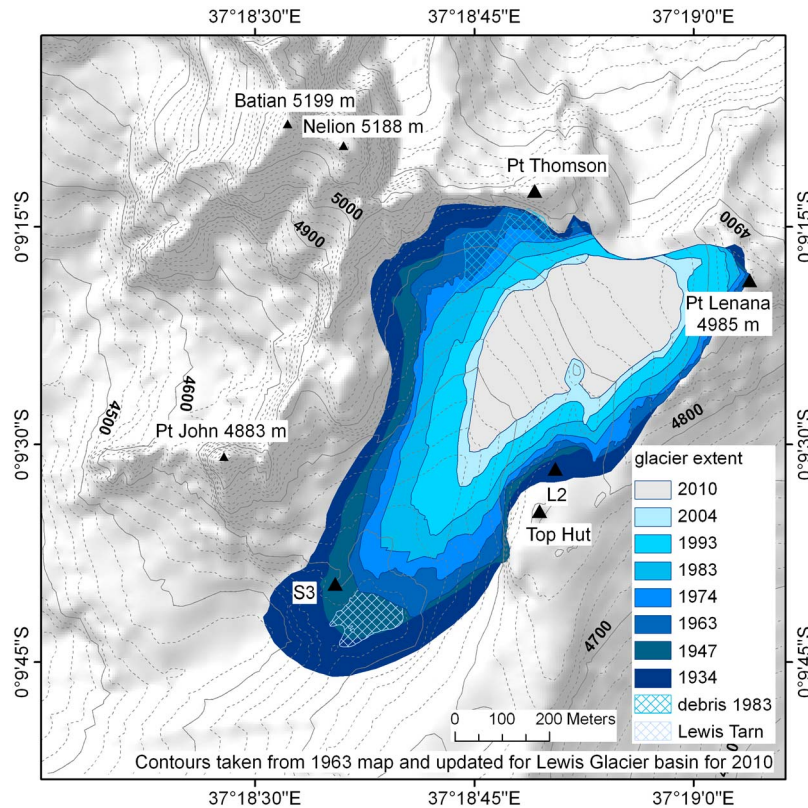


Figure 1. Lewis Glacier extents in 1934, 1947, 1963, 1974, 1983, 1993, 2004 and 2010. Bold triangles mark IGY ground control points set in 1957/58 and used during the 2010 survey.

the reflections from the surrounding rocks did not influence the reflected signal significantly. Therefore, a correction of this potential error was not necessary. The horizontal positions of the GPR measurement points were recorded with a handheld Garmin eTrex Vista Cx GPS with horizontal accuracy of 2–10 m; sufficient for the size of the GPR footprint. The altitudes of the positions recorded with the handheld GPS were taken from the DEM. At the time of the measurements, the surface of the glacier was covered by a few centimeters of fresh snow overlying glacier ice. As in previous field trips (2006–2009) no firn cover on the glacier was observed, thus the total glacier volume was considered as ice.

[13] From the DEM of the glacier surface and the ice thickness measured at 25 locations, the subglacial topography was derived by manually drawing contour lines of the bedrock elevation at 10 m intervals as described by Fischer [2009]. To cover the recently deglaciated area the bedrock contours were extended using digitized contours from the 1983 and 1993 maps, interpolated to the current glacier margin, to construct a bedrock DEM with 5 m grid point spacing using ESRI ArcGIS 9.3.1 tool topo2raster. Input accuracies and the resulting errors in the DEMs are tabulated in the auxiliary material.¹ Error margins were estimated using Gauss' propagation of errors.

4. Results

4.1. Ice Volume Estimate 2010

[14] The ice volume obtained for Lewis Glacier in 2010 is $1.90 \pm 0.30 \times 10^6 \text{ m}^3$, corresponding to a mean ice thickness

of $18 \pm 3 \text{ m}$ over an area of $0.105 \pm 0.001 \times 10^6 \text{ m}^2$. The deepest parts are located along the central flow line with the maximum ice thickness ($45 \pm 3 \text{ m}$) in a bedrock over-deepening close to the center of the glacier. Ice thickness distribution and profiles along and across the glacier are shown in the auxiliary material (Figures S1 and S2).

4.2. Ice Volume Change 1934–2010

[15] To allow an intercomparison of the ice volumes of Lewis Glacier from 1934–2010, two issues concerning the surface topography had to be considered. Firstly the location of the ice divide between Lewis and Gregory Glacier, which were formerly connected in their uppermost parts, was defined using the maps of 1963, 1983 and 2004, and in the absence of better information was held constant for all maps. Gregory Glacier disappeared between 2006 and 2011 and only debris covered ice remnants of unknown thickness are left. Secondly, due to the shrinkage of the glacier, debris-covered ice has developed in the rockfall zone below Point Thomson since the late 1960s. Except for the 1983 map, all maps used in this study exclude the debris-covered part of the glacier, so, for consistency, we excluded the debris covered portion ($14 \times 10^3 \text{ m}^2$, i.e., 5%) from the 1983 glacier area.

[16] Ice volumes for 1934, 1947, 1963, 1974, 1983, 1993, 2004 and 2010 were derived by subtracting the bedrock DEM from the surface DEM of each of these years. Table 2 lists the changes in ice volume and in glacier area showing that Lewis Glacier has lost $16.67 \pm 3.82 \times 10^6 \text{ m}^3$ (90%) of volume and $0.394 \pm 0.015 \times 10^6 \text{ m}^2$ (79%) of surface area between 1934 and 2010. The maximum surface lowering was

¹Auxiliary materials are available in the HTML. doi:10.1029/2011GL049208.

Table 2. Ice Volumes and Glacier Area for Each Mapping Date, Respective Changes During the Covered Intervals, and Derived Mean Mass Balance Rates for Lewis Glacier^a

Year	Ice Volume		Area		Period	Mean Mass Balance Rate	
	10 ⁶ m ³	±10 ⁶ m ³	10 ⁶ m ²	±10 ⁶ m ²		m w.e./a	±m w.e./a
1934	18.57	3.81	0.499	0.015			
1947	15.04	1.56	0.397	0.012	1934–1947	−0.54	0.63
1963	12.85	1.30	0.363	0.012	1947–1963	−0.31	0.29
1974	11.93	1.11	0.310	0.011	1963–1974	−0.22	0.40
1983	9.00	0.97	0.266	0.011	1974–1983	−0.99	0.51
1993	7.01	0.76	0.206	0.008	1983–1993	−0.70	0.43
2004	2.37	0.49	0.136	0.007	1993–2004	−2.22	0.44
2010	1.90	0.30	0.105	0.001	2004–2010	−0.63	0.77

^aThe large error ranges for the period 2004–2010 are explained by large uncertainties of the 2004 map compared to the small glacier.

97 ± 7 m close to the current glacier terminus. In the upper half of the glacier, surface lowering was between 30 ± 7 and 40 ± 7 m.

4.3. Mass Balance 1934–2010

[17] Using the geodetic approach, the mean mass balance rate \bar{M} (m w.e./a) between two mappings is

$$\bar{M} = \frac{\rho \Delta V}{\bar{S}} \frac{1}{\Delta t},$$

where ρ is the density of the ice or snow gained or lost, ΔV the volume change, \bar{S} the average glacier area and Δt the time difference in years between two observations. The firn layer thickness and its density (660 kg/m³) were estimated from a firn core drilled in 1978 [Thompson and Hastenrath, 1981], which shows characteristic features of tropical firn packs exposed to daily melting conditions: high fresh snow densities, shallow firn cover due to fast metamorphosis and many ice layers due to refreezing of percolating meltwater. Averaging the density according to the proportion of firn and ice gives a total glacier density of 870 kg/m³ between 1934 and 1993 and 900 kg/m³ between 1993 and 2010 (refer to the auxiliary material for further explanation). Figure 2 and Table 2 show ice volumes, areas, their changes and the respective mean mass balance rates for and in between each mapping date since 1934.

5. Discussion

[18] The only previously available bedrock estimate of Lewis Glacier is based on measurements of ice thickness and ice surface topography carried out between 1974 and 1978 [Bhatt et al., 1980]. Ice thickness was obtained from seismic, gravimetric and ice flow approaches and the respective results correspond mutually within “error tolerances of 5–10 m” in most cases [Bhatt et al., 1980]. However, in 2004 Hastenrath and Polzin [2004] found the ice surface had lowered by an amount that in places exceeded the ice thickness reported by Bhatt et al. [1980]. As a consequence, they adjusted the 1978 volume estimate from 6.20×10^6 m³ to 7.71×10^6 m³ [Hastenrath and Polzin, 2004]. The data acquisition and processing is not sufficiently documented in Bhatt et al. [1980] to allow identification of possible reasons for the underestimate. However, at least in the case of seismic ice thickness measurements,

problems have been reported repeatedly [Span et al., 2005; Fischer et al., 2007; Lambrecht and Kuhn, 2007].

[19] After adjusting the 1978 ice volume, Hastenrath and Polzin [2004] stated that the average thickness of the remaining ice of Lewis Glacier was 2.1 m in 2004. However, already in September 2009, 6 months before the GPR measurements, holes of 2–4 m depth were drilled for 26 ablation stakes evenly distributed over the glacier surface and none reached the bedrock, indicating that the mean ice thickness of 2.1 m reported for 2004 was likely to be too low. In fact, our ice volume estimates are significantly larger than those previously assessed, including the adjusted Hastenrath and Polzin [2004] numbers (Figure 2). In contrast, reported changes of ice volume derived from maps [Hastenrath and Caukwell, 1979; Patzelt et al., 1984; Hastenrath and Rostom, 1990; Hastenrath et al., 1995; Rostom and Hastenrath, 1995; Hastenrath and Polzin, 2004; Rostom and Hastenrath, 2007] correspond well with our results, suggesting that the discrepancy in total volume and mean ice thickness is not due to errors in the surface surveys but rather due to an incorrect bedrock determination in 1974–78.

[20] Between 1978 and 1996 Hastenrath measured surface mass balance on Lewis Glacier showing a mean rate of −0.87 m w.e./a [Hastenrath, 2005a]. Although not perfectly

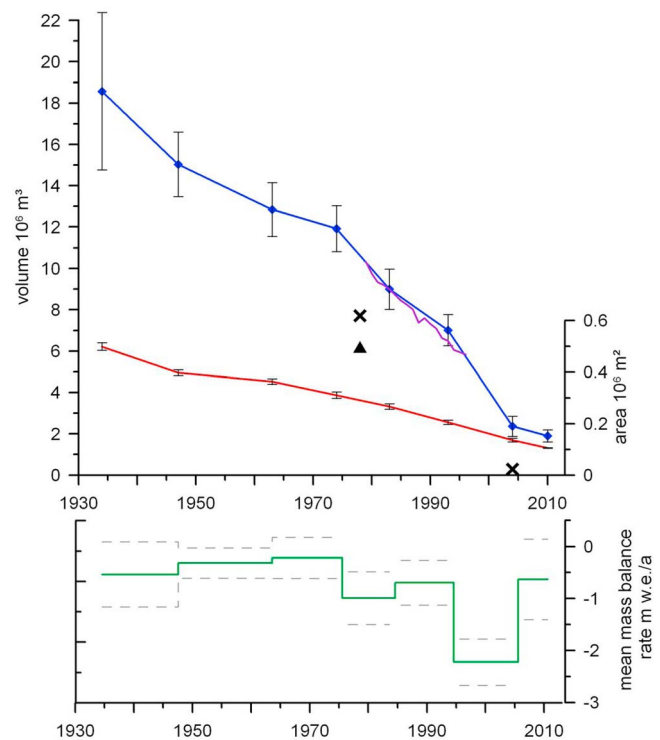


Figure 2. Changes in area, volume and mean mass balance rates of Lewis Glacier 1934–2010: change of Lewis Glacier’s ice volume (blue); Hastenrath’s surface mass balance measurements [Hastenrath, 2005a], using the 1983 volume as a reference (purple), area changes (red, right axis); 1978 ice volume estimate [Bhatt et al., 1980] (triangle); correction of the 1978 ice volume estimate [Hastenrath and Polzin, 2004] and their derived ice volume estimate for 2004 (crosses); mean mass balance rates for the respective periods (green step plot).

matched in time, the geodetically derived rates for the two periods 1974–1983 (-0.99 ± 0.51 m w.e./a) and 1983–1993 (-0.70 ± 0.43 m w.e./a) show values in the same range. For the period 1983–1993 it is possible to compare the two mass balance approaches concurrently. The timing of glacier maps does not coincide exactly with the March–March mass balance year, so the geodetic volume change was adjusted using Hastenrath's ablation stake records to account for the volume loss March 1993–September 1993. The March 1983–March 1993 ice volume change from the surface mass balance measurements (-2.50×10^6 m³) is within error of that obtained geodetically ($-1.89 \pm 1.23 \times 10^6$ m³); and -0.86 m w.e./a compared to -0.69 ± 0.43 m w.e./a for the mean mass balance rates. Local patterns of ice thickness change as derived from the 1983 and 1993 maps show a slight thickening around 4800 m in the orographic right part of the glacier, which was also evident in geodetic observations by Hastenrath and Rostom [1990]. However, as this portion of the glacier was poorly covered with ablation stakes during this period an underestimation of accumulation could explain the more negative values of the surface mass balance. During the following decade (1993–2004) thinning rates reached their most negative values ($\dot{M} = -2.22 \pm 0.44$ m w.e./a), indicating considerable changes in the meteorological conditions controlling the mass and energy balance of the glacier. The most recent values of \dot{M} (-0.63 ± 0.77 m w.e./a, 2004–2010) are comparable to those during 1983–1993 (-0.70 ± 0.43 m w.e./a). However, for the 12 month interval between September 2009 and September 2010 the average point surface mass balance measured at 26 mass balance stakes shows again a more rapid ice surface lowering of 1.40 m w.e. (single stake maximum/minimum lowering: 2.10 m w.e./0.74 m w.e.).

6. Conclusions and Outlook

[21] The analyses presented here provide a considerably improved assessment of ice volume changes of Lewis Glacier, Mt Kenya over the last eight decades. Previously published estimates of total ice volumes have been corrected and volume changes have been broadly confirmed. Long term mean mass balance rates in a near decadal resolution are presented for the first time covering the whole period of glaciological surveys on Lewis Glacier. This is the longest high quality record for a tropical glacier and a first prerequisite for quantifying potentially changing climatological conditions in the mid troposphere as suggested by Hastenrath and Kruss [1992]. Comparison of the mean mass balance rates on Lewis Glacier with those observed in other regions of the world shows that this tropical glacier has more negative rates throughout recent decades, but that changes over time are qualitatively consistent with globally observed patterns [Kaser *et al.*, 2006, Figure 2]. In order to further investigate the climate-glacier relationship in various temporal and spatial scales and to decipher the causes of glacier volume change an automatic weather station was installed on Lewis Glacier in September 2009.

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