NOTES AND RECORDS

VARIATIONS OF THE LEWIS GLACIER, MOUNT KENYA, 2004–2012

Rainer Prinz, Lindsey Nicholson and Georg Kaser

Summary: We present a new map of the Lewis Glacier, Mt Kenya (0°9' S, 37°18' E), which was determined with a differential global positioning system survey and ice thickness measurements from ground penetrating radar that was carried out in 2010. The Lewis Glacier is among the best monitored tropical glaciers and this new map provides a continuation of glaciological monitoring at this site. Glacier area for 2010 is $0.107 \pm 0.001 \times 10^6$ m² which is a 23% decrease since 2004. The formerly adjoining Gregory Glacier no longer exists. Surface mass balance measurements for the years 2010/11 and 2011/12 (-1.54 m water equivalent (w.e.) and -1.03 m w.e., respectively) are as negative as the minima measured between 1978 and 1996, and show a strong dependence on duration and depth of snow cover, which impact accumulation as mass input and ablation via the surface albedo.

Zusammenfassung: Wir stellen hier eine neue Karte des Lewis Gletschers am Mt. Kenya (0°9' S, 37°18' E) vor, dessen Topographie mit differentiellem globalen Positionierungssystem und dessen Eisdicke mittels Bodenradar im Jahre 2010 aufgenommen wurde. Der Lewis Gletscher zählt zu den am besten untersuchten Gletschern der Tropen und diese Karte dient als Grundlage für weitere glaziologische Untersuchungen. Die Fläche des Gletschers betrug im Jahre 2010 $0.107 \pm 0.001 \times 10^6$ m² – um 23% weniger als 2004. Der Gregory Gletscher, der ehemals mit dem Lewis Gletscher verbunden war, ist seitdem zur Gänze verschwunden. Die Massenbilanzen für die Jahre 2010/11 und 2011/12 (-1.54 m Wasseräquivalent (w.e.) beziehungsweise -1.03 m w.e.) sind ähnlich negativ wie die im Zeitraum 1978–1996 gemessenen Minima und sind stark von Dauer und Höhe der Schneedecke abhängig, die die Masse der Akkumulation bestimmt, aber auch die Ablation über die Albedo beeinflusst.

Keywords: Geosciences, Kenya, glacier mass balance, tropics

1 Introduction

Variations of low latitude glaciers are valuable indicators of environmental changes at tropical mid troposphere elevations (e.g., Hastenrath and Kruss 1992; Mölg et al. 2009; Vuille et al. 2008; Winkler et al. 2010a, 2010b) where, due to lack of observational data, our knowledge of climate change is scarce and controversial (Karl et al. 2006; Paeth 2004; Trenberth et al. 2007). In particular, the Lewis Glacier (0°9' S, 37°18' E) merits attention as it is among the best documented of all tropical glaciers, with almost 80 years of frequent observations of glacier length, area and volume changes (Hastenrath 1984, 2005a; Prinz et al. 2011). Unfortunately, after 18 years (1978–1996) of continuous surface mass balance observations, measurements were halted and the last mapping of the glacier was accomplished in

2004. To preserve a degree of continuity of observations of the Lewis Glacier, we revived the monitoring program in 2009, as a part of a project involving a multi-scale approach to quantify glacier change and the climate-glacier relationship of the Lewis Glacier, Mt Kenya, triggered by the World Glacier Monitoring Service and funded by the Austrian Science Fund. Measuring current glacier extent is the first prerequisite for mass balance determination and assessment of glacier areal change over time.

To continue Stefan Hastenrath's reports of glacier variations on Mt Kenya to this journal (Caukwell and Hastenrath 1977; Hastenrath and Caukwell 1979, 1987; Hastenrath and Rostom 1990; Hastenrath 2005b; Hastenrath et al. 1989, 1995; Rostom and Hastenrath 1994, 1995, 2007), we present (i) a new map of the Lewis Glacier from our 2010 survey in conjunction with (ii) the surface

mass balances for the years 2010/11 and 2011/12 (March–March respectively), which are discussed using data from an automatic weather station installed at the glacier.

2 Mapping the Lewis Glacier in 2010

2.1 Field survey

In two days (2nd and 3rd of March 2010) the glacier outline and surface topography were surveyed using differential global positioning system (DGPS) receivers (Trimble Pathfinder ProXT and ProXH with external Zephyr antennas). To allow co-registration and, thus, comparison to previous maps, ground control points surrounding the Lewis Glacier, installed during an expedition to Mt Kenya in the International Geophysical Year (IGY) of 1957 (Charnley 1959), were also surveyed (Tab. 1). These points define a local coordinate system that has been used in all subsequent mappings.

The base station was established at IGY ground control point L2 (see supplement map), and the ice extent was measured by collecting point locations every second while walking the rover instrument along the glacier 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 code and carrier phase post-processing, the ice surface and ice margin point locations were combined in a triangulated irregular network and interpolated to a digital elevation model (DEM) with 5 m grid point spacing.

The DGPS accuracy was <30 cm for 58.8% (<1 m for 93.5%) horizontally and <50 cm for 53.2% (<1 m for 86.9%) vertically of a total of >22000 measured positions (Prinz et al. 2011 and associated supplementary material). Contours were derived from the DEM and generalized for cartographic reasons using the ArcGis 9.3 smooth line algorithm based on the Bezier interpolation. In addition, the supplement map shows ice thickness from ground penetrating radar measurements, described in detail by Prinz et al. (2011). The map we present here is a reference surface to be used for on-going glaciological studies of the Lewis Glacier.

2.2 Length, area and volume changes 2004–2010

To compare the 2010 map to the previous map from 2004 (Rostom and Hastenrath 2007), two issues had to be considered. Firstly, it was necessary to bring both maps into the same coordinate system. Therefore, the 2004 map was transferred from its local coordinate system to the Universal Transverse Mercator coordinate system, using the DGPS positions of the IGY ground control points surrounding the Lewis Glacier as a reference. The root mean squared error of the georeferencing procedure is <2 m. Differences in altitude between DGPS and the IGY ground control points and height notations in the 2004 map are within 2 m on average (Prinz et al. 2011 and associated supplementary material). Secondly, the ice divide between the Lewis and Gregory Glaciers (on the col between Point Lenana and Point Thomson) was defined from the 2004 map. Due to fog and snow cover during the 2010 survey, it was difficult to determine if the Gregory Glacier still existed. In March 2011 we observed that the Gregory Glacier has disappeared and only

Tab. 1: The IGY survey points in different coordinate systems. Heights are defined as meters above mean sea level

IGY Point	Code	Hastenrath (2005)			UTM (WGS84) Zone 37 M			geographic coordinates	
		X	Y	Z	X	Y	Z	Latitude	Longitude
L2	L2	3210.6	1450.4	4797.2	312374.9	9982440.3	4796.4	0° 9' 31.675" S	37° 18' 50.758" E
L3	L3	2884.0	1791.8	4792.7	312048.3	9982783.8	4795.2	0° 9' 20.492" S	37° 18' 40.196" E
Lenana	LE	3622.1	1847.9	4985.0	312786.6	9982839.3	4987.7	0° 9' 18.686" S	37° 19' 04.071" E
S3	S3	2745.5	1206.3	4600.6	311909.3	9982196.7	4605.0	0° 9' 39.605" S	37° 18' 35.700" E
Thomson Cross	TC	3165.5	2037.8	4958.1	312331.7	9983028.8	4959.7	0° 9' 12.517" S	37° 18' 49.360" E
Top Hut	TH	3177.5	1361.4	4809.4	312342.0	9982350.5	4809.9	0° 9' 34.598" S	37° 18' 49.694" E
accuracy		± 0.5 m	± 0.5 m	± 0.3 m	± 0.1 m	± 0.1 m	± 0.3 m	± 0.003"	± 0.003"
			Charnley (1959)				Prinz et al. (2011)		

debris covered ice remnants of unknown thickness remain (PRINZ et al. 2011). However, a small portion (2×10^3 m²) of the Lewis Glacier still points towards the former flow direction of the Gregory Glacier. For mass balance studies of the Lewis Glacier, this portion is considered part of the total surface area ($0.107 \pm 0.001 \times 10^6$ m²; although its contribution to the area is within the range of the total area accuracy), but for consistency with how the glacier was delineated in previous mappings, it is subtracted from the reported total surface area ($0.105 \pm 0.001 \times 10^6$ m²) and glacier volume.

Table 2 lists data of glacier length, area and volume of 2004 and 2010. Over these six years, the glacier terminus retreated 79 m upslope. The total central flowline length change is greater than the terminus retreat because of loss of ice area in the uppermost part of the glacier.

3   Surface mass balance 2010–2012

The surface mass balance was measured with the direct glaciological approach using a floating date time system (COGLEY et al. 2011; HOINKES 1970), although the sampling dates were within 5 days of each other. Ablation was measured using surface height change against bamboo ablation stakes drilled into the ice with a mechanical auger, and accumulation was determined from snow depth measurements made by probing the snow layer in conjunction with density measurements from snow pits. To identify specific patterns of surface height change over the glacier area, 26 ablation stakes were distributed over the surface of the Lewis Glacier on the 25th of September, 2009. This is a fairly high coverage of 260 stakes/km² and once areas of similar patterns are discovered, the number of ablation stakes can be reduced accordingly. On the upper part of the glacier, ablation stake density is less because blocks falling from slopes of Point Lenana pose a hazard to the stakes and to measurement of them. Each bamboo stake measures 2–4 m in length and was read and usually replaced twice a year. Accumulation measurements were sparse since there is no pronounced accumulation season and ablation occurs year round. The glacier was snow covered three times during our field visits (March 2010: 5–20 cm, September 2010: 15–50 cm and September 2011: 15–50 cm) with a bulk snow density of 430 kg/m³, averaged over all our snow density measurements. Ice density was assumed to be 900 kg/m³.

Tab.2: Changes of length, area and volume of the Lewis Glacier 2004–2010 (PRINZ et al. 2011)

	Length*	Area		Volume	
	m	10^6 m²	$\pm 10^6$ m²	10^6 m³	$\pm 10^6$ m³
2004	746	0.136	0.007	2.37	0.49
2010	613	0.105	0.001	1.90	0.30
Difference	-133	-0.031	0.007	-0.47	0.57

* Length of the approximated central flow line; position of the glacier front: -79 m

For consistency with HASTENRATH (2005a), the mass balance year on Mt Kenya begins on the 1st of March and can be subdivided in two wet seasons (March–May, MAM and October–December, OND), separated by two dry seasons (June–September, JJAS and January–February, JF). However, as observed in meteorological measurements from the glacier surface, wet seasons may fail and dry seasons may contribute significantly to the total annual precipitation.

The annual surface mass balances 2010–2012 of the Lewis Glacier are shown in table 3. Areas of same volume change were manually interpolated between ablation stake records, digitized and calculated as area-weighted averages for 50 m altitudinal zones. Most (least) negative values were recorded at the glacier tongue (at the central upper part). In both years, the glacier experienced mass loss over the entire surface, thus the equilibrium line altitudes are undefined (Fig. 1 and Fig. 2). This was also the case for ten years of the historical record from 1978–1996 (HASTENRATH 2005a), indicating that the hypothetical equilibrium line altitude has frequently been higher than the upper limit of the glacier over recent decades.

4   Discussion

Spatial patterns of the surface mass balance (Fig. 1) are generally controlled by local geometry and its interaction with the radiative energy balance of the glacier surface (KRUSS and HASTENRATH 1987). High mass loss that was observed in the 2011/12 mass balance year on the northernmost edge of the glacier (the former part of Gregory Glacier; on the col between Point Lenana and Point Thomson), where the north-easterly aspect favours ablation in the usually clear sky morning hours, substantiates this finding. However two features, in which other meteorological influences strongly modulate the radiative energy

Tab.3: The surface mass balances of the Lewis Glacier 2010–2012 for 50 m altitudinal zones

Altitudinal Zone	Area [10³ m²]	Volume Change [10³ m³]		Surface Mass Balance [m w.e.]	
		2010/11	2011/12	2010/11	2011/12
4675	9,1	-19,6	-18,9	-2,15	-2,07
4725	21,8	-42,6	-38,3	-1,95	-1,75
4775	19,7	-32,7	-19,9	-1,66	-1,01
4825	43,2	-54,2	-25,7	-1,26	-0,59
4875	13,7	-16,8	-7,9	-1,23	-0,58
total	107,5	-165,9	-110,6	-1,54	-1,03

balance, were observed: (i) Large dissimilarities in measured surface mass balance over short distances between neighbouring ablation stakes indicate large differences in surface conditions on a very small scale without year-to-year consistency, complicating the spatial interpolation of surface mass balance patterns. (ii) Contrasting mass loss patterns on the lower part of the glacier in the two years of observation cannot be explained qualitatively and were not reported in the historical surface mass balance record (HASTENRATH 2005a), perhaps due to a lower ablation stake density. These issues must be further investigated and quantified using an energy balance approach.

The elevation dependence of the surface mass balance is primarily a result of albedo feedback. Snow accumulation varies little over the glacier surface and measured accumulation gradients show no systematic variation with elevation. However, field observations of ascending snowlines after relatively uniform snowfall events indicate that slightly higher ablation rates towards the terminus of the glacier result in more rapid and more frequent removal of snow cover from the ice surface which then, as it has a lower albedo than the upper zones that are still snow covered, is subject to further enhanced ablation rates. Although ablation often removes the snow from the entire glacier surface, exposing ice at all elevations, frequent snowfall events would result in a relatively thicker snowpack towards the top of the glacier as compared to the lower reaches, where snow is removed at a faster rate.

To allow a climatic interpretation of the surface height change at a higher temporal resolution, an automatic weather station was set up on the glacier at 4828 m and operated from September 2009 – March 2012. Amongst other meteorological variables, this station recorded half-hourly means of surface height, albedo and air temperature from measurements taken every minute. Figure 3 shows large albedo

variations in MAM 2010 indicating rapid melting of frequent shallow snow covers. Minimum albedo coincides with maximum air temperature, suggesting a water-saturated, melting ice surface until July. The sparse accumulation in OND was quickly removed in the following JF 2011 dry season, exposing bare ice to ablation processes. The mass balance year 2011/12 started with a short period of very low albedo followed by very light snowfalls, immediately increasing the albedo. Although no major accumulation event was recorded during the MAM 2011 wet season, which almost completely failed over East Africa (LYON and DEWITT 2012), the albedo remained high throughout March and April. This contrast in albedo conditions between MAM 2010 and MAM 2011 is likely related to how the potential melting rate is influenced by air temperature, which showed a marked thermal optimum in MAM 2010 that was absent the following year. Frequent abundant snowfall events from July to December 2011 partly compensated the MAM lack of accumulation. However, as in 2011, no accumulation was preserved during the JF 2012 dry season, resulting in negative mass balances over the entire glacier surface.

5   Conclusion and outlook

Glaciological monitoring of the Lewis Glacier, one of the few tropical reference glaciers, has been continued by surveying the glacier topography and measuring the annual surface mass balance. The 2010 survey updates records of length, area and volume changes in the same frame of reference as historical surveys, and thus forms the basis for continuing glaciological work on Mt Kenya. Glacier mass change at Lewis Glacier retains its negative trend as observed in both direct and geodetic measurements and the formerly connected Gregory Glacier has now disappeared entirely.
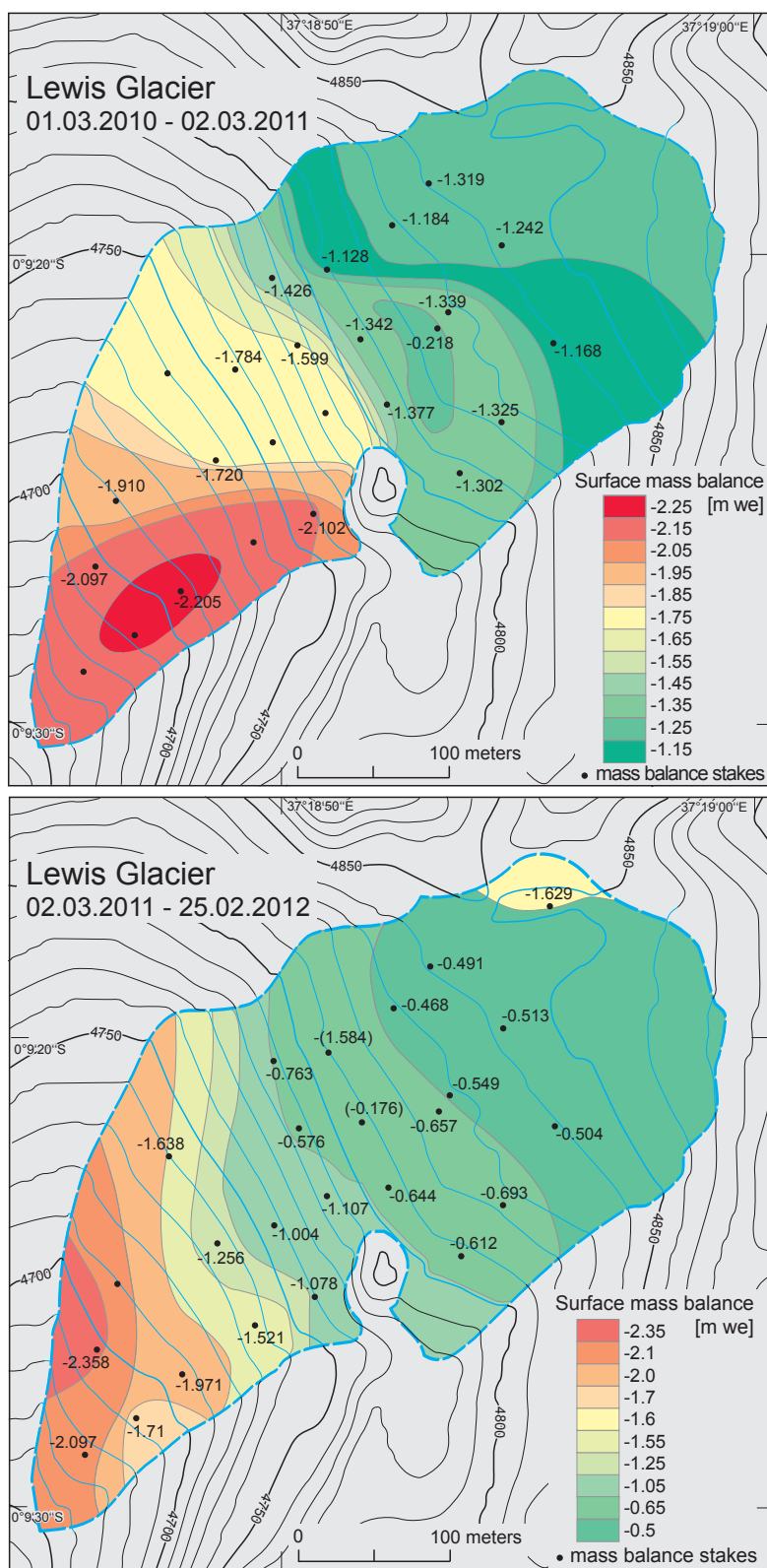
Fig. 1: Areal distribution of surface mass balances for the years 2010/11 (top) and 2011/12 (bottom). Note the different colour scaling. Values in brackets are questionable and not used for areal interpolation. Stake positions without numbers indicate missing data
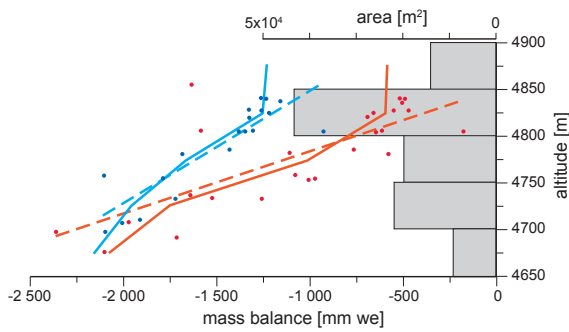
Fig. 2: Solid lines show the vertical surface mass balance profiles for the years 2010/11 (blue) and 2011/12 (red). Points depict the measured surface mass balance at individual ablation stakes, which are linearly interpolated by the dashed lines. Grey bars (reversed x-axis on top) indicate the area altitude distribution of the Lewis Glacier

The inter-annual variability in the surface mass balance of the Lewis Glacier is large and meteorological data measured above the glacier surface indicate that a combination of persistently higher air temperatures, in conjunction with little snow accumulation over the course of the year resulted in a more negative surface mass balance in 2010/11 than in 2011/12, during which daily mean air temperature remained predominantly below 0 °C and more snow was accumulated over a longer period. Hence, the stronger gradients of (i) ablation (0.8 compared to 1.5 m w.e./100 m for 2010/11 and 2011/12, respectively) and (ii) the vertical surface mass balance profile (Fig. 2) mainly resulted from more frequent or more persistent snow cover on the upper part of the glacier in the 2011/12 mass balance year. This sensitivity of the vertical surface mass balance profile of glaciers in the humid inner tropics to changes in net shortwave radiation (controlled by the surface albedo) and air temperature is conceptually explained in a modelling approach by KASER (2001).

The impact and relative importance of variations of air temperature, precipitation and other atmospheric drivers on the glacier surface mass and energy balance will be investigated more fully in forthcoming mass and energy balance modelling work.
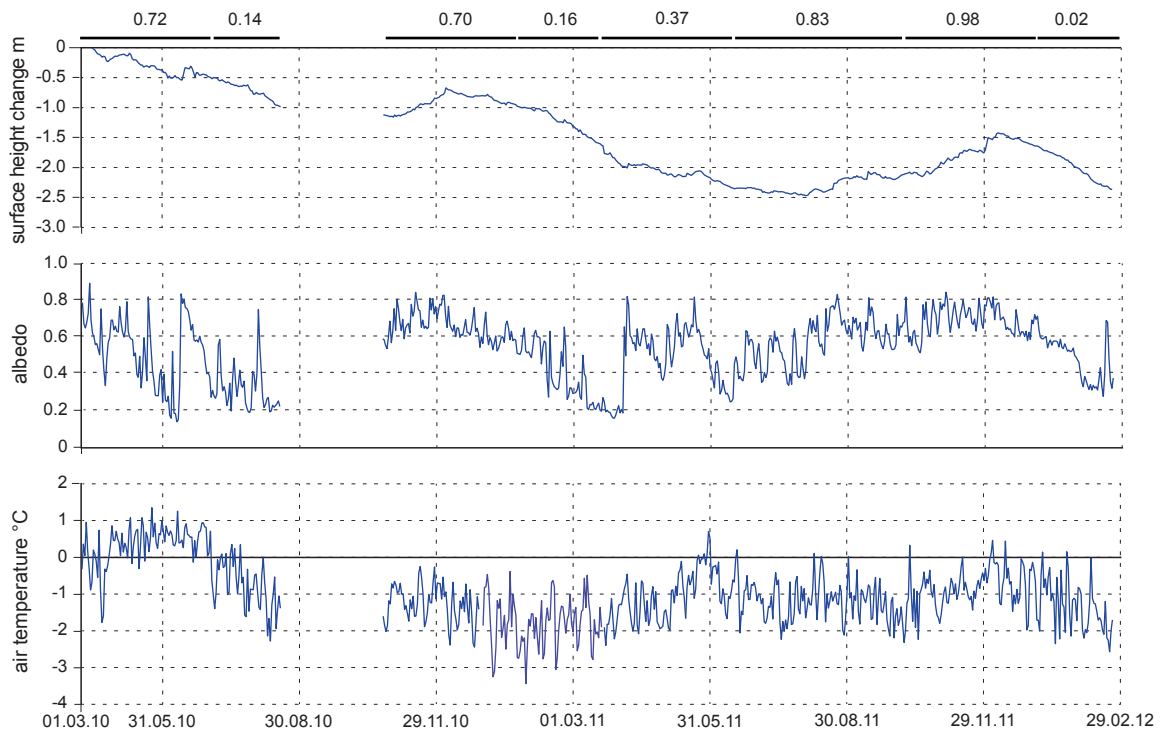

Fig. 3: Daily means of (top) surface height change measured from a Campbell SR50 sonic ranger; values above give seasonal sums of daily snowfall in meter; (middle) albedo as a ratio of daily totals of reflected solar radiation to daily amounts of global radiation (OERLEMANS and KNAP 1998) from a Kipp&Zonen CNR4 net radiometer and (bottom) air temperature from an unventilated Vaisala HMP45 probe at the automatic weather station at Lewis Glacier at 4828 m from 01.03.2010 to 23.02.2012 (data gap from 20.07.–27.09.2010)

Acknowledgements

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Lewis Glacier, Mount Kenya, 2010

Legend:

- Lewis Glacier 2010
- Lewis Glacier 2004
- ice thickness (m)
- contour 50 m
- contour 10 m
- ▲ automatic weather station
- • ablation stakes
- ⊕ IGY ground control points

0 ——— 100 meters

N

Glacier topography: DGPS survey 02./03. March 2010
Ice thickness: GPR survey 03. March 2010
Rock topography: Schneider 1963
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Austrian Hut 4795 m
TH