VARIATIONS OF MOUNT KENYA'S GLACIERS 1993–2004

With 2 figures, 4 tables and 1 supplement (II)

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Zusammenfassung: Veränderungen der Gletscher am Mount Kenya 1993–2004
In dem vorliegenden Aufsatz wird eine Karte der Gletscher am Mount Kenya im Maßstab 1:5.000 vorgestellt, die auf einer photogrammetrischen Auswertung von Luftaufnahmen vom 01. September 2004 beruht. Das stereo-photogrammetrische Modell wurde durch luftgestützte Triangulation und Bodenkontrollpunkte überprüft. In Verbindung mit der in gleicher Weise erstellten Kartierung vom September 1993 dokumentiert die Karte den drastischen Rückgang der Gletscher am Mount Kenya während der letzten elf Jahre.

Summary: A map is presented of Mount Kenya's glaciers at scale 1:5,000, based on photogrammetric evaluation of purpose-flown aerial photography of 01 September 2004. In conjunction with a corresponding map of September 1993, it documents the drastic recession of Mount Kenya's glaciers over the past eleven years.

1 Introduction

Tropical glaciers and their long-term variations deserve attention in the study of global climatic and environmental change (Intergovernmental Panel on Climate Change 2001, 127–130, 647–656; World Glacier Monitoring Service of IASH-ICSU-UNEP-UNESCO 1996, 1998). Historical continuity of observations is essential. In this regard, Mount Kenya (Fig. 1) and especially Lewis Glacier are unique within the tropical half of the Earth. Following the first expeditions to the peak region at the end of the 19th century, there are reports and photographs from visits in later decades (review in HASTENRATH 1984, 108–135), mappings of the Lewis Glacier in 1934 (TROLL a. WIEN 1949) and 1958 (CHARNLEY 1959), and of the entire peak region in 1963 (Forschungsunternehmen Nepal-Himalaya 1967). With this historical background, our glaciological studies on Mount Kenya began in the 1970's, included decades-long monitoring of precipitation, net balance and ice flow velocity on the Lewis, repeated mappings of that and all other glaciers, and exploration of the entire peak region (HASTENRATH 1984, 1991, 1996). The sequence of photogrammetric mappings, for the Lewis in 1974, 1978, 1982, 1985, 1986, 1990, and 1993, and for the entire mountain in 1947, 1987, and 1993, have been presented in this journal (CAUKWELL a. HASTENRATH 1977; HASTENRATH a. CAUKWELL 1979; CAUKWELL a. HASTENRATH 1982; HASTENRATH a. CAUKWELL 1987; HASTENRATH et al. 1989; HASTENRATH a. ROSTOM 1990; ROSTOM a. HASTENRATH 1994; HASTENRATH et al. 1995; ROSTOM a. HASTENRATH 1995). Our 1987 map (HASTENRATH a. CAUKWELL 1987) has also been published by the Survey of Kenya (1989). Another decade has passed since our 1993 mapping and, from an airborne survey in September 2004, here we present one last map at scale 1:5,000 of the remaining ice on Mount Kenya.

2 Ground control

Basic to aero-photogrammetric mapping is a network of control points surveyed and marked in the terrain. The IGY Mount Kenya Expedition (CHARNLEY 1959) established control points in a local coordinate system. In preparation for our 1987 mapping (HASTENRATH et al. 1989) we expanded this network, with a closure around the mountain. We marked the points in the terrain by painting white crosses ahead of the photo flight. Table 1 lists the coordinates of the points relevant here. All are plotted in the map, and the points identified in the photograph and used in the mapping are indicated by triangles. As the crosses, marking the ground control points, were white painted just before the 1987 flight mission, their images appeared very clearly on the central photograph No. 3490 of that flight. These images had been positively identified and marked on that diapositive, which formed the basis to transfer the position of the control points to the

Table 1: Coordinates of ground survey stations (m). Triangles indicate points used in mapping and circles points plotted but not used. Code identifies points plotted in map

Koordinaten der Bodenbeobachtungsstationen (m). Dreiecke bezeichnen die bei der Kartierung benutzten und Kreise die für die Kartierung nicht verwendeten Punkte. Der Code identifiziert in der Karte eingetragene Punkte

	name	code	+ Y(N)	+ X(E)	height
o	Melhuish Cross	MC	1637.9	2743.9	4878.1
Δ	Thompson Cross	TC	2037.8	3165.5	4958.1
Δ	Two Tarn Cross	TTC	1521.2	1518.7	4519.1
o	Molar Saddle	MS	3234.9	2327.8	4615.8
Δ	Kami Boulder	KB	3015.8	2961.9	4448.5
Δ	Gregory	G	2261.3	3303.1	4693.5
Δ	Hausburg	H	2979.3	1708.8	4359.9
o	Arthur's Seat	AS	2404.8	1555.6	4665.6
Δ	L2	L2	1450.4	3210.6	4797.2
o	L3	L3	1791.8	2884.0	4792.7
o	Lenana	LE	1847.9	3622.1	4985.0
o	Melhuish	ME	1630.6	2742.2	4876.5
Δ	S3	S3	1206.3	2745.5	4600.6
o	Two Tarn	TT	1524.0	1524.0	4519.6
Δ	Tyndall	TY	1771.1	1751.0	4551.3
o	S8	S8	1794.4	2086.0	4477.5

present 2004 photographs using Wild PUG 4 point transfer device. However, it was not possible to transfer all the control points due to difficulties in constructing the three-dimensional model in the locality of some points from the 1987 and the 2004 photographs. Eight points were positively identified and accurately transferred to the new 2004 photographs. Table 1 lists these points which served as basic control for the mapping and they are shown in the map and table 1 by triangles.

3 Air photography

The great difficulties in obtaining aerial photography suitable for mapping have been detailed before (Hastenrath et al. 1989; Rostom a. Hastenrath 1994). These are related to altitude and local relief, dead ground or blind spots caused by the ridges and peaks, and the seasonality in snow cover. As in the earlier surveys, the average scale of photography was designed to be 1:10,000, or half that of the map.

The aerial photography was flown at 9:36–9:53 am on 01 September 2004 by Photomap International, at an average height of 1,483 m above the average terrain level of 4,800 m. The photographs were taken by a Wild 153 mm RC 10 camera and are at an approximate average scale of 1 : 10,000 with 80 percent forelap and 60 percent sidelap. As shown in figure 2, these runs were flown in parallel strips, consisting of the frames nos. 6409–6419, 6427–6450, and 6461–6471.

4 Aerial triangulation and stereographic plotting

After examining the resulting photographs, the following five stereopairs were selected for mapping the glaciers: from run 1 the nos. 6412 and 6413; from run 2 the nos. 6444 and 6440, 6440 and 6437, 6437 and 6433; and from run 3 the nos. 6464 and 6465. These adequately cover the required mountain area with no dead zones. The control points falling within these stereopairs were either not sufficient to perform absolute orientation, or not falling at the favorable locations. Hence the need to carry out aerial triangulation.

The same stereopairs selected for mapping were chosen for the aerial triangulation. In addition to the available eight control points, six image points were selected in the approximate standard locations on each stereopair and their common images on the other adjacent stereopairs were identified. Sketch diagrams were plotted for each of these points to safeguard against misidentification. Altogether 16 points were selected in the network.

Aerial triangulation was conducted by independent models. The models were constructed by relative orientation of the stereopairs using Wild B8 modified by Quasco system for digital output. The coordinates of the perspective centers, the aerial triangulation points, and the control points in the model system were recorded and formed the input data for the computations. The approximate ground coordinates of the aerial triangulation points and the perspective centres were obtained by interpolating their locations from existing maps. The computations and adjustment were carried out with the help of AEROSYS programme. The average root-mean-square error (RMSE) on the control points was 0.79 m, 1.46 m, 0.97 m in easting, northing, and height, respectively, with a maximum residual of 3.6 m in the northing of point L2.

The stereocompilation was performed on the Wild B8 with Quasco and Kork supporting system to produce a digital map for the mountain at scale 1:5,000 with contour interval 10 m on the glaciers and 20 m on rocks outside the glaciers. The RMSE of the residuals of the interior orientation did not exceed 0.001 mm for any of the models. The RMSE of the relative orientation varied between 0.001 and 0.002 mm. The average RMSE of the absolute orientation of the five models was 0.83 m, 1.10 m, and 0.65 m in easting, northing, and height, respectively.

The aerial triangulation and map compilation were done at Photomap. From the analysis of the residuals and the RMSE, it can be concluded that the present map meets comfortably the standard accuracy for its scale.

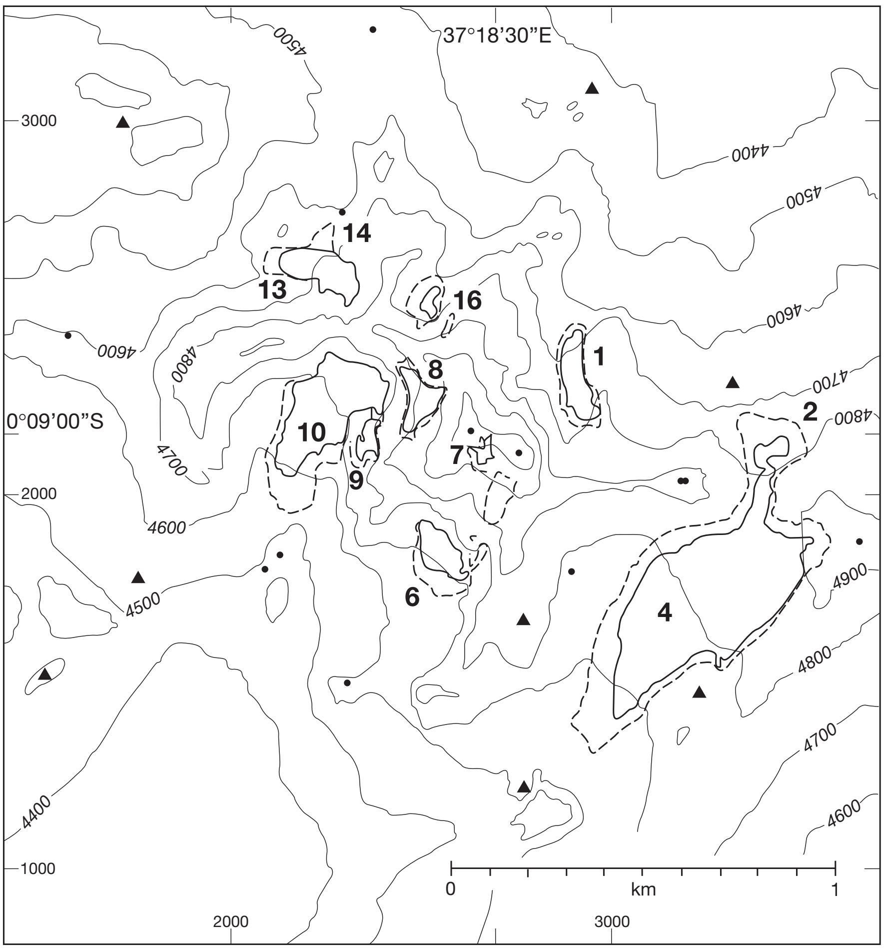

Fig. 1: Orientation map of the glaciers of Mount Kenya. September 1993 broken, September 2004 solid lines. Triangles denote topographic control points. Scale 1 : 20,000; contours at 200 m intervals. Large numbers denote glaciers listed in tables 2 and 3, as follows: 1 = Krapf, 2 = Gregory, 4 = Lewis, 6 = Darwin, 7 = Diamond, 8 = Forel, 9 = Heim, 10 = Tyndall, 13 = Cesar, 14 = Joseph, 16 = Northey

Orientierungskarte der Gletscher des Mount Kenya. September 1993 gestrichelte Linien, September 2004 durchgezogene Linien. Dreiecke bezeichnen topographische Kontrollpunkte. Maßstab 1:20.000. Höhenlinien im Abstand von 200 m; die großen Ziffern bezeichnen die in Tabelle 2 und 3 aufgelisteten Gletscher, s. o.

As with our previous work (HASTENRATH et al. 1989; ROSTOM a. HASTENRATH 1994, 1995), the present map is in a local coordinate system based on the 1957–1958 IGY Mount Kenya expedition, and used also by Schneider in 1963 (Forschungsunternehmen Nepal-Himalaya 1967). A discrepancy between the geographical latitudes on the Survey of Kenya (1971) map and the Schneider 1963 map (Forschungsunternehmen Nepal-Himalaya 1967) has been discussed previously (HASTENRATH et al. 1989); no records appear to have been kept of the relation between the IGY and the Directorate of Colonial Surveys (DCS) coordinates, and without this the relationship between northings and latitude and eastings and longitude cannot be precisely known.

5 Glacier inventory for the September 1993 and September 2004 epochs

Our map is a further contribution to the inventory of tropical glaciers (Temporary Technical Secretariat for World Glacier Inventory of UNESCO-UNEP-IUGG-IASH-ICSI 1977) and affords an update on the 1993 inventory of the state of Mount Kenya's glaciers (ROSTOM a. HASTENRATH 1994) and an appraisal of the changes over this most recent eleven-year interval. Thus, tables 2 and 3 present characteristic parameters for the September 1993 and September 2004 epochs, as constructed from our maps. Table 2 repeats table 3 in our earlier report (ROSTOM a. HASTENRATH 1994).

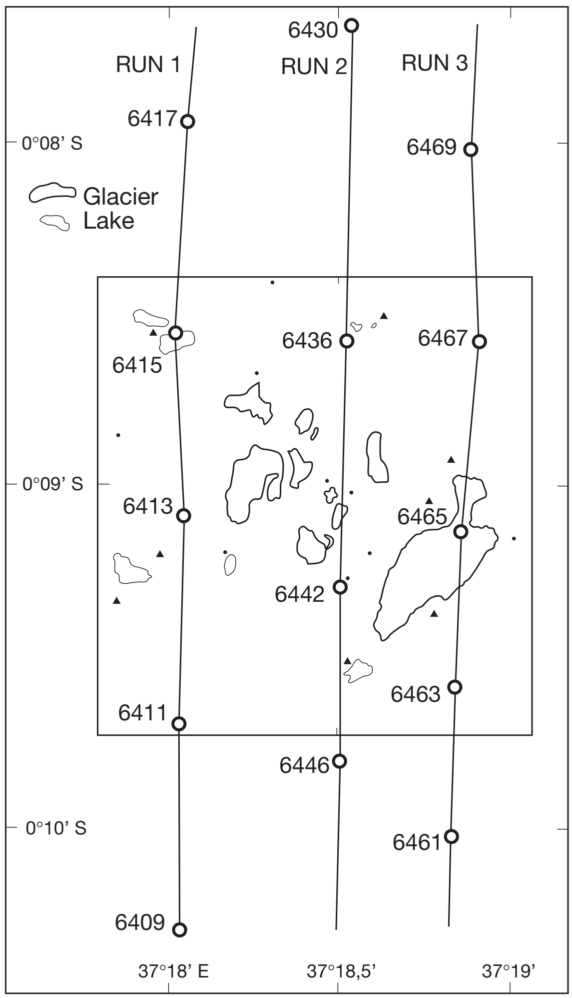

Fig. 2: Orientation map showing the flight lines of the aerial photography on 01 September 2004. Scale 1:40,000

Orientierungskarte mit den Flugstrecken der Bildflüge am 01. September 2004. Maßstab 1:40.000

Table 2: Characteristic parameters of Mount Kenya's glaciers, 1993
Charakteristische Kennziffern der Gletscher am Mount Kenya, 1993

No.	name	area [$10^3 m^2$]	length [m]	highest elevation [m]	lowest elevation [m]
1	Krapf	21	275	4802	4618
2	Gregory	35	335	4920	4722
4	Lewis	203	915	4960	4625
6	Darwin	23	185	4834	4647
7	Diamond	3	100	5150	4995
8	Forel	15	100	4980	4820
9	Heim	15	80	4860	4725
10	Tyndall	65	450	4790	4518
13	Cesar	18	275	4780	4620
14	Joseph	6	200	4750	4620
16	Northey	9	150	4820	4700
total		413			

Table 3: Characteristic parameters of Mount Kenya's glaciers, 2004
Charakteristische Kennziffern der Gletscher am Mount Kenya, 2004

No.	name	area [$10^3 m^2$]	length [m]	highest elevation [m]	lowest elevation [m]
1	Krapf	14	250	4802	4640
2	Gregory	12	270	4850	4740
4	Lewis	139	700	4895	4640
6	Darwin	12	90	4785	4655
7	Diamond	3	100	5150	4995
8	Forel	12	50	4920	4860
9	Heim	5	50	4780	4750
10	Tyndall	51	400	4790	4550
13	Cesar	16	200	4780	4640
14	Joseph	–	–	–	–
16	Northey	3	100	4820	4730
total		267			

Concerning the Diamond Glacier, the 2004 ice boundary traced in a recent map (Hastenrath 2005) is here rectified. Regarding the previously contiguous Heim/Tyndall and Cesar/Joseph glaciers, the following details of changes from 1993 to 2004 should be noted. The Heim separated from the Tyndall and a remnant area of some 6,000 m^2 formerly pertaining to the Heim is now ascribed to the Tyndall. Similarly, the Joseph disappeared, and a narrow strip of some 1,000 m^2 formerly pertaining to the Joseph is now ascribed to the Cesar. Comparison of the present tables 2 and 3 reveals substantial changes. These are discussed in the following section.

6 Length, area and volume changes during 1993–2004

The length and area changes of glaciers can be retrieved from topographic maps containing accurately traced ice boundaries. The estimation of volume change is more demanding, because this requires a high degree of internal consistency between successive mappings. Much care has been devoted to this concern, as detailed in sections 2, 3, and 4. Further precautions were taken in the evaluation of ice thickness changes. This was done digitally, with co-registering of control points and using a 2.5 m grid. Topography differences of 2004 minus 1993 were calculated not only for the glaciers but

Table 4: Decrease in length ΔL (m), area ΔA (10^2 m^2), thickness ΔZ (m), and volume ΔV (10^3 m^3) of Mount Kenya's glaciers during 1993–2004
Abnahme der Länge ΔL (m), Fläche ΔA (10^2 m^2), Mächtigkeit ΔZ (m) und des Volumens ΔV (10^3 m^3) der Gletscher am Mount Kenya 1993–2004

glacier No.	name	ΔL	ΔA	ΔZ	ΔV
1	Krapf	25	7	12.8	268
2	Gregory	65	23	14.9	410
4	Lewis	215	64	13.6	2761
6	Darwin	95	11	23.7	545
7	Diamond	0	0	4.7	14
8	Forel	50	3	3.3	50
9	Heim	50	10	15.5	233
10	Tyndall	50	14	13.1	852
13	Cesar	75	2	18.0	324
14	Joseph	200	6	17.4	104
16	Northey	50	6	20.7	186
all glaciers			146	13.9	5,747

also for a 50 m wide perimeter around the glaciers; on this basis glacier thickness changes were adjusted according to apparent discrepancies in rock topography.

The quantitative evaluation of changes over the recent eleven-year interval is summarized in table 4. The length of the glaciers decreased by as much as 215 m; the total area by 146 x 10^3 m^2, or more than a third of the 1993 extent; the ice thickness in average by about 14 m; and the total volume by 5,747 x 10^3 m^3.

7 Concluding remarks

The glaciers on the high mountains of the tropics are a very sensitive component of the environment and merit attention in the study of global change. Mount Kenya, right at the Equator, has a particularly long and continuous historical documentation of varying ice extent. Indeed, observations of expeditions since the end of the 19th century are followed by a sequence of photogrammetric mappings from the middle of the 19th century onward, amounting to quantitative information unparalleled in the entire tropics. These sources have been evaluated in context and results are reported elsewhere (HASTENRATH 2005). Within our lifetime we have witnessed a drastic and progressive shrinkage of ice on the mountain, and this has become very pronounced from the 1987 to the 1993 mapping. Another eleven years have passed, with further drastic ice retreat. At the end of decades-long work on this beautiful mountain, we have been fortunate to complete one last mapping of its vanishing glaciers.

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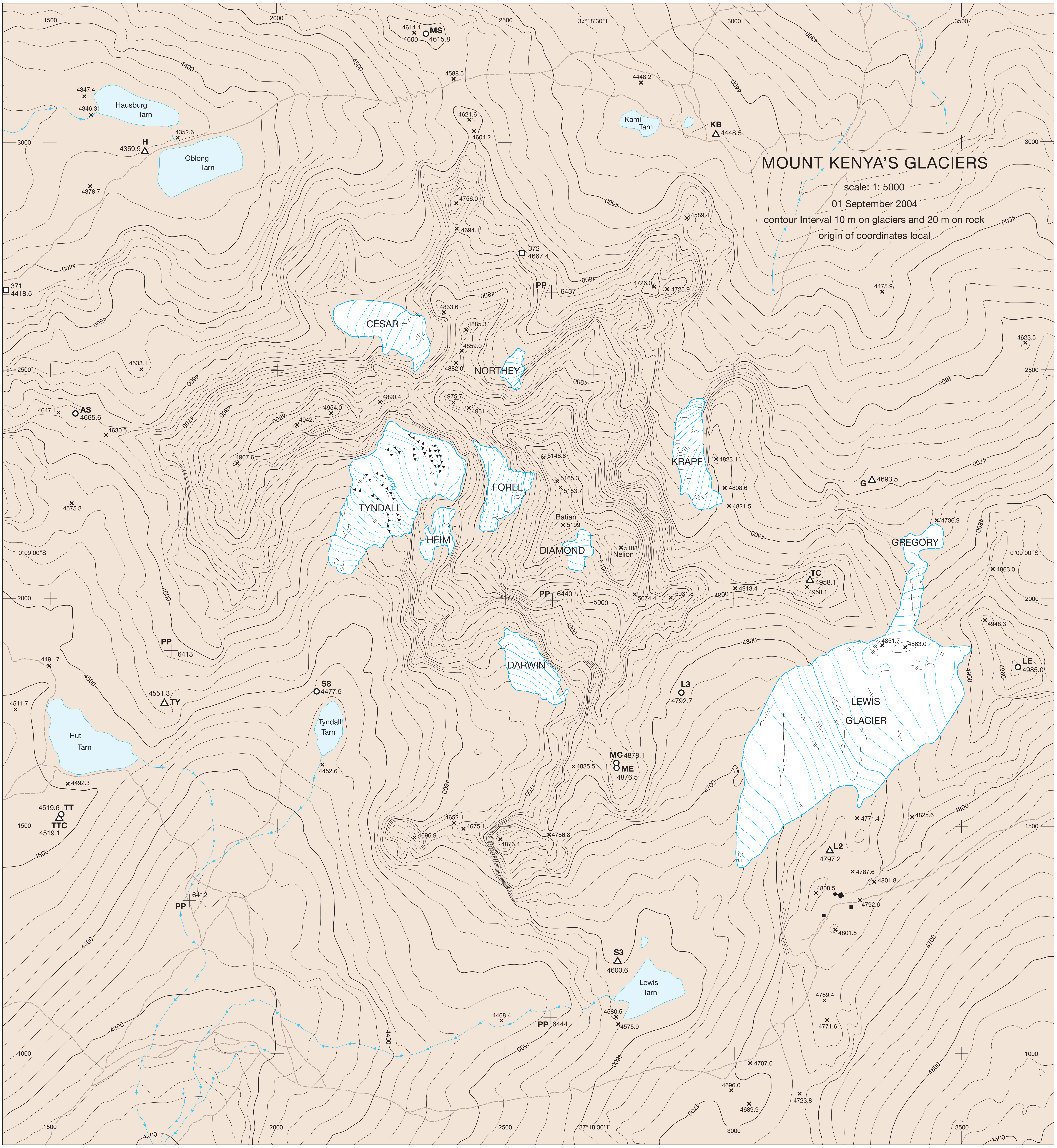

△ ground control points used in mapping

○ ground control points not used in mapping

× spotheight

+ principal point

glacier boundary

principal crevasses

ice cliff

lake, pond

stream

huts

footpath

0 100 200 300 400

meters