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MODERN GLACIER RETREAT ON KILIMANJARO AS EVIDENCE OF CLIMATE CHANGE: OBSERVATIONS AND FACTS

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ABSTRACT

In recent years, Kilimanjaro and its vanishing glaciers have become an 'icon' of global warming, attracting broad interest. In this paper, a synopsis of (a) field observations made by the authors and (b) climatic data as reported in the literature (proxy and long-term instrumental data) is presented to develop a new concept for investigating the retreat of Kilimanjaro's glaciers, based on the physical understanding of glacier–climate interactions. The concept considers the peculiarities of the mountain and implies that climatological processes other than air temperature control the ice recession in a direct manner. A drastic drop in atmospheric moisture at the end of the 19th century and the ensuing drier climatic conditions are likely forcing glacier retreat on Kilimanjaro. Future investigations using the concept as a governing hypothesis will require research at different climatological scales. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: tropical glaciers; Kilimanjaro; climatic change; data synopsis; glaciological field observations; research concept

1. INTRODUCTION

In the thermally homogeneous atmosphere of the tropics, the interaction between glaciers and climate represents a particularly sensitive process (Kaser *et al*., 1996; Kaser, 2001; Wagnon *et al*., 2001). Thus, tropical glaciers provide important proxy data in climate change research (Houghton *et al*., 2001; Oerlemans, 2001) and have become items of broad interest. Following the spatial delimitations proposed by Kaser *et al*. (1996), tropical glaciers still exist in Irian Jaya (New Guinea), in the South American Andes, and in East Africa. After the modern-time maximum extent around the mid and second half of the 19th century, they have all suffered drastic ice wastage (Kaser, 1999). On a global scale, air temperature is considered to be the most important factor reflecting glacier retreat, but this has not been demonstrated for tropical glaciers (Houghton *et al*., 2001). Rather, a complex combination of changes in air temperature, air humidity, precipitation, cloudiness, and incoming shortwave radiation is considered to govern the fluctuations of tropical glaciers (see Kaser (1999) for a summary of reasons). Scarcely noticed until today, changes in air humidity and atmospheric moisture content (e.g. Soden and Schroeder, 2000) seem to play an underestimated key role in tropical high-mountain climate (Broecker, 1997), since seasonality in the climate of the tropics is solely due to the annual cycle of atmospheric moisture concentration (Hastenrath, 1991), which is also the case at high altitudes (Hardy *et al*., 1998). Changes in moisture concentration induce changes in other variables controlling glacier mass balance (Kaser *et al*., in press), except in mean air temperature.

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2. MODERN CLIMATE AND GLACIER BEHAVIOUR IN EAST AFRICA

For the three East African glacierized massifs (Rwenzori, Mount Kenya, and Kilimanjaro), glacier retreat was comprehensively reported by Hastenrath (1984). Specific details for Mount Kenya are provided by Kruss and Hastenrath (1987), Hastenrath *et al.* (1989), and Hastenrath (1995); for the Rwenzori by Kaser and Noggler (1991, 1996), Kaser and Osmaston (2002), and Mölg *et al.* (2003a); and for Kilimanjaro by Hastenrath and Greischar (1997) and Thompson *et al.* (2002). Figure 1 illustrates the strong recession trend of all glaciers in equatorial East Africa since the end of the 19th century. The dominant reasons for this strong recession in modern times are reduced precipitation (Kruss, 1983; Hastenrath, 1984; Kruss and Hastenrath, 1987; Kaser and Noggler, 1996) and increased availability of shortwave radiation due to decreases in cloudiness (Kruss and Hastenrath, 1987; Mölg *et al.*, 2003a).

Climate variability in East Africa is reasonably well documented on millennial to century time scales (e.g. Bonnefille and Chalié, 1999; Shanahan and Zreda, 2000; Thompson *et al.*, 2002), but there is a lack of knowledge in time scales of centuries to decades. Fortunately, several proxy data indicate the general climate history of East Africa since *ca* 1850 reliably. These are historical accounts of lake levels and analyses of glacier variations (Hastenrath, 1984), wind and current observations in the Indian Ocean and their relationship to East African rainfall (Hastenrath, 2001), water balance models of lakes (Nicholson *et al.*, 2000; Nicholson and Yin, 2001), and palaeolimnological data (Verschuren *et al.*, 2000). According to these proxies, the climatic evolution of East Africa over the past 150 years ('modern climate') is characterized by a drastic dislocation around 1880, when lake levels dropped notably and glaciers started to recede from the latest maximum extent. The ensuing relatively dry climate was maintained throughout the 20th century, which is supported by instrumental records of annual precipitation that vary only slightly during the 20th century (e.g. Rodhe and Virji, 1976; Hay *et al.*, 2002). Comparatively, the couple of decades preceding 1880 were very humid: lakes stood high, mountain glaciation was extensive, and precipitation more abundant. In contrast to this 'switch' in moisture conditions, there is no evidence of an abrupt change in air temperature (Hastenrath, 2001). As the glaciers of Mount Kenya and in the Rwenzori Mountains seem to have responded clearly to this change in moisture by retreating drastically and in spatially differential patterns (Kruss and Hastenrath, 1987; Mölg

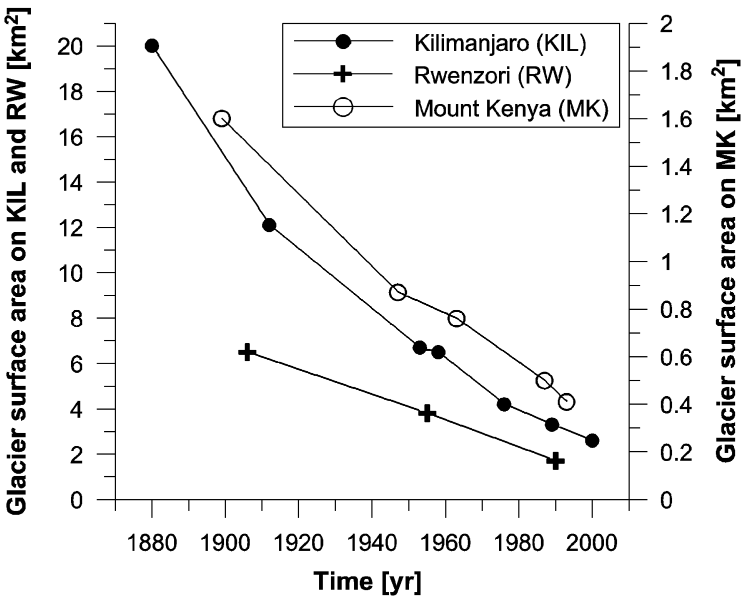


Figure 1. Time series of glacier surface areas on Kilimanjaro (data from Osmaston (1989), Hastenrath and Greischar (1997) and Thompson *et al.* (2002)), in the Rwenzori Range (data from Kaser and Osmaston (2002)), and on Mount Kenya (data from Hastenrath *et al.* (1989) and Hastenrath (1995)). Note the difference in vertical scales

et al., 2003a), a fundamental question arises: Did this sudden drop in atmospheric moisture also initiate the recession of the glaciers on Kilimanjaro and force it until the present day?

This question is vitally important and is addressed in this paper in order to develop a new research concept, since the recession of Kilimanjaro's glaciers is widely attributed to global warming only, i.e. understood as a direct consequence solely of increased air temperature (e.g. Irion, 2002; Thompson *et al*., 2002). This is an overly simplistic view and does not consider the following. (i) Temperature increases in the tropics on the surface and in the troposphere have been little in recent decades compared with the global trend (Gaffen *et al*., 2000; Hartmann, 2002). (ii) In the East African highlands, there is no trend in air temperature records that nearly span the whole 20th century (85 years; Hay *et al*., 2002). (iii) Glacier–climate interaction in the tropics shows peculiar characteristics compared with the mid- and high-latitudes (Kaser *et al*., 1996; Kaser, 2001), as they are located in a particular climate, which was outlined in Section 1. Several energy- and mass-balance investigations on tropical glaciers (e.g. Wagnon *et al*., 2001; Francou *et al*., 2003) reveal that these glaciers are most sensitive to shifts in hygric seasonality and changes in related parameters (e.g. precipitation, surface albedo). (iv) The enormous size and height of the mountain represents an exceptional phenomenon amongst glacierized mountains in the tropics, reducing the effect of air temperature on ice recession decisively (Kaser and Osmaston, 2002). (v) Early researchers have already suggested that changes in precipitation might be driving the retreat of Kilimanjaro's glaciers, based on direct field observations (e.g. Jäger, 1931; Geilinger, 1936).

3. KILIMANJARO AND ITS GLACIERS

Since the scientific exploration of Kilimanjaro began in 1887, when Hans Meyer first ascended the mountain (not to the top this time, but to the crater rim), a central theme of published research has been the drastic recession of Kilimanjaro's glaciers (e.g. Meyer, 1891, 1900; Klute, 1920; Gillman, 1923; Jäger, 1931; Geilinger, 1936; Hunt, 1947; Spink, 1949; Humphries, 1959; Downie and Wilkinson, 1972; Hastenrath, 1984; Osmaston, 1989; Hastenrath and Greischar, 1997). Early reports describe the formation of notches, splitting up and disconnection of ice bodies, and measurements of glacier snout retreat on single glaciers, whereas later books and papers advance to reconstructing glacier surface areas.

Kilimanjaro, Africa's highest mountain, stands on the Kenya–Tanzania border, *ca* 370 km south of the equator and about the same distance from the Indian Ocean (3°04′S, 37°21′E). The huge stratovolcano (*ca* 80 by 50 km) consists of three single peaks: Shira (4005 m), Mawenzi (5140 m), and Kibo (5893 m), which is the only peak to retain glaciers (Figure 2). The summit region of Kibo has collapsed to form a caldera 1.9 km by 2.4 km in diameter. Within this lies the inner cone, enclosing a crater *ca* 800 m across (Reusch Crater) and harbouring a third cone with a central crater. The ice extent on Kibo is depicted in Figure 2. Total glacier surface area is currently 2.6 km^2, as determined by Thompson *et al*. (2002) from aerial photographs taken in February 2000. These remaining glaciers are the ragged fringe of an ice cap, which, it is believed, covered the entire summit of the mountain (Humphries, 1959). The summit glaciers typically have vertical walls mainly along their north and south margins (distribution: see Figure 2; photograph, see Figure 3(a) and (b)), and ice bodies show a strong east–west orientation. Since February 2000, an automated weather station (AWS) has been operating on the summit's Northern Icefield. An overview on measured variables and a synopsis of collected data are available at http://www.geo.umass.edu/climate/kibo. Detailed analysis of these data will be published elsewhere. In this article, only recordings directly pertinent to our overall concept are highlighted.

Large-scale circulation over equatorial East Africa is characterized by a double passage of the intertropical convergence zone (ITCZ) as it moves with the sun's zenith from one hemisphere to the other. As a consequence, northern Tanzania experiences a bimodal pattern of rains centred on March to May ('long rains') and October to December ('short rains'), separated by two drier seasons (Basalirwa *et al*., 1999). Some 70-80% of precipitation occurs when the ITCZ moves across the Kilimanjaro region (Coutts, 1969). Data recorded at the AWS (February 2000–February 2002) reflect this general character of climate well. Monthly mean air temperatures vary only slightly around the annual mean of −7.1 °C ('thermal homogeneity'), and *ca* 75% of snow falls during the two rainy seasons. The immense and isolated mountain rises far into the

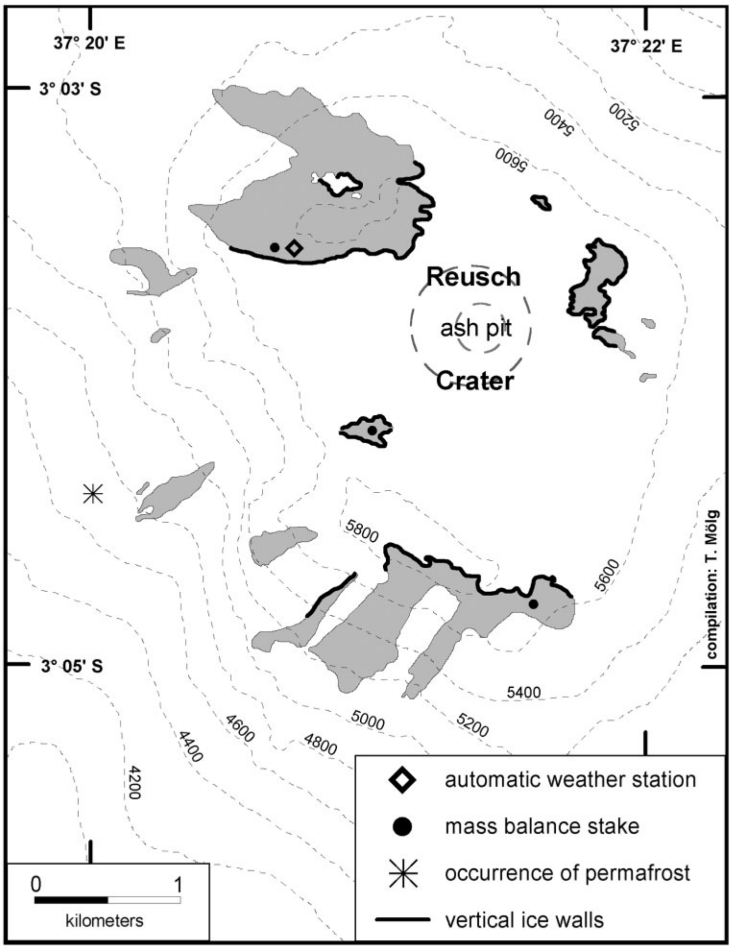


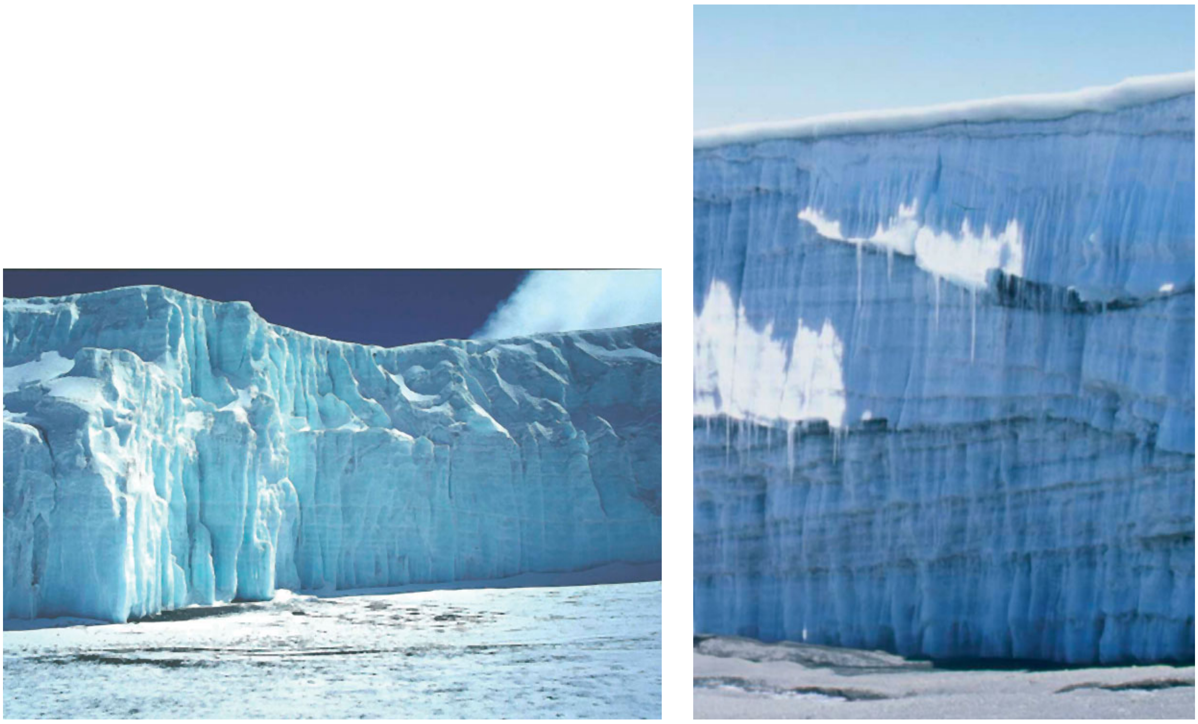
Figure 2. Distribution of the glaciers on Kibo in 2000 after Thompson *et al*. (2002), locations of the AWS and mass balance stakes, and occurrence of permafrost and vertical walls which were determined stereoscopically from the same aerial photographs as used by Thompson *et al*. (2002) (contours in metres, equidistance 200 m, UTM zone 37 S projection). Map compiled by Thomas Mölg, October 2002

tropical troposphere and penetrates the dry seasons' trade wind inversion, which shows a median base height above Nairobi of *ca* 3750 m and a typical thickness of 125–250 m (Hardy, unpublished analysis of CARDS data (e.g. Eskridge *et al*., 1995)). The elevation and shape of the mountain modify the local atmospheric circulation in many ways that remain poorly understood.

4. INTERPRETATION OF OBSERVATIONS AND FACTS

The evidence for a drop in atmospheric moisture around 1880, and the indication of only minor temperature changes over East Africa since then, supports the following compilation of observations and interpretations on Kibo's retreating glaciers. For this, Geilinger's (1936) approach of looking at separate glacier regimes — i.e. (i) the summit horizontal glacier surfaces, (ii) the summit vertical ice/firn walls, and (iii) the slope glaciers below the summit — is extended by a potential fourth regime of basal melting:

1. Today, as in the past, Kilimanjaro's glaciers are markedly characterized by features such as penitentes, cliffs (Figure 3(a) and (b)), and sharp edges, all resulting from strong differential ablation. These features



(a) (b)

Figure 3. (a) The ∼25 m high south-facing wall of the Northern Icefield in June 2001. Note the southeast-facing portions being in the morning sun, where dripping meltwater has removed the thin crater snow cover that fell 2 days prior. Photograph: G. Kaser. (b) The ∼20 m high northeast-facing wall of the Rebmann Glacier (Southern Icefield) in July 2002; an extreme example illustrating discontinuous accumulation. Humphries (1959) noted that '... in several instances there appears to have been marked erosion of the ice surface before further accumulations of snow'. Photograph: D. R. Hardy. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

illustrate the absolute predominance of incoming shortwave radiation and turbulent latent heat flux in providing the energy for ablation (Kraus, 1972). A considerably positive heat flux from either longwave radiation or sensible heat flux, if available, would round-off and destroy the observed features within a very short time, ranging from hours to days. On the other hand, if destroyed, the features could only be sculptured again under very particular circumstances and over a long time. Thus, the existence of these features indicates that the present summit glaciers are not experiencing ablation due to sensible heat (i.e. from positive air temperature). Additional support for this is provided by the Northern Icefield air temperature recorded from February 2000 to July 2002, which never exceeded −1.6 °C, and by the presence of permafrost at 4700 m below Arrow Glacier on the western slope (for location see Figure 2).

2. The vertical cliffs rising 20–50 m from the almost planar ash plateau (Figure 3(a) and (b)) seem to have suffered no marked lowering between *ca* 1880 and 1960. This can be assumed since researchers' height estimates are approximately the same in this period (40–60 m, depending on the specific site), starting with H. Meyer's reports from his ascents to the summit between 1889 and 1898 (Meyer, 1900) and continuing through the first half of the 20th century (Gillman, 1923; Spink, 1949) until the late 1950s (Humphries, 1959). Since then, negative mass balances seem to dominate. An average thinning of 17 m is reported over the period from 1962 to 2000, determined from stereoscopic aerial photographs (Thompson *et al*., 2002). Nevertheless, single years with mass balances close to equilibrium can occur, as measured at the AWS site between February 2001 and February 2002 (Thompson *et al*., 2002; Mölg and Hardy, 2004).
3. In contrast to the limited or indeterminate evidence for ice mass thinning, areal changes illustrated by Figure 1 show a continuous and drastic lateral retreat of the ice walls (Figure 3(a) and (b)), which are

primarily north- and south-facing. This implies (i) the occurrence of persistent negative mass balances on these cliffs, which greatly exceed ablation on the horizontal surfaces, and (ii) that ablation on the vertical walls is mainly tied to the seasonality of solar radiation. Accumulation can only be due to resublimation (direct transition of water from vapour to solid phase) and is considered to be very small, whereas small-scale circumstances may force a strong ablation including melting (which is eight times more efficient than sublimation at removing ice). During the dry seasons, the low incidence angle of the sun on relatively low-albedo ice provides enough energy at walls for substantial ablation, despite negative air temperatures; this is shown in Figure 4 by means of a simple, conceptual drawing. Lack of turbulent air flow along the vertical surfaces (owing to generally low wind speeds) minimizes sublimation and, thus, allows the surface to melt. The observation of strong melting on the illuminated walls (Figure 3(a)), and the appearance of huge hoar crystals a few centimetres away on the shady walls during the field visits in 2001 and 2002, supports this interpretation. The intensively dripping melt water immediately evaporated from the dark crater surface without leaving any sign of fluvial erosion behind. Small-scale moisture transport may lead to crystal growth on adjacent (shady) surfaces, but it cannot compensate for the predominance of melting on the illuminated walls. A similar microclimate is known to be established at vertical ice walls of Antarctic glaciers that are also located in a dry and cold climate. Lewis *et al*. (1999), for instance, performed a detailed energy balance study at the vertical cliff of such a glacier and showed that turbulent heat exchange is small due to low wind speeds — which leaves more energy for melting, the most effective energetic ablation mechanism.

4. The seasonal variation of solar incidence, due to the seasonal cycle of solar radiation geometry, causes substantial lateral ablation on the cliffs. A daily cycle of convective clouds is superimposed on this seasonality, and is most pronounced during the dry seasons, which is described in the classical model of Troll and Wien (1949). Thus, differential ablation is more apparent on the eastern ends of the cliffs than on the western ends, where afternoon clouds protect the ice from direct solar radiation.
5. The thickness of the ice on the summit plateau (Figure 3(a) and (b)) does not allow substantial deformation; therefore, no major mass transport from the nearly horizontal plateau into the slope glaciers can be expected. Thus, the slope glaciers can be seen as dynamically independent from the summit glaciers. This would also have been the case when the ice cap was intact, and for those slope glaciers currently still connected

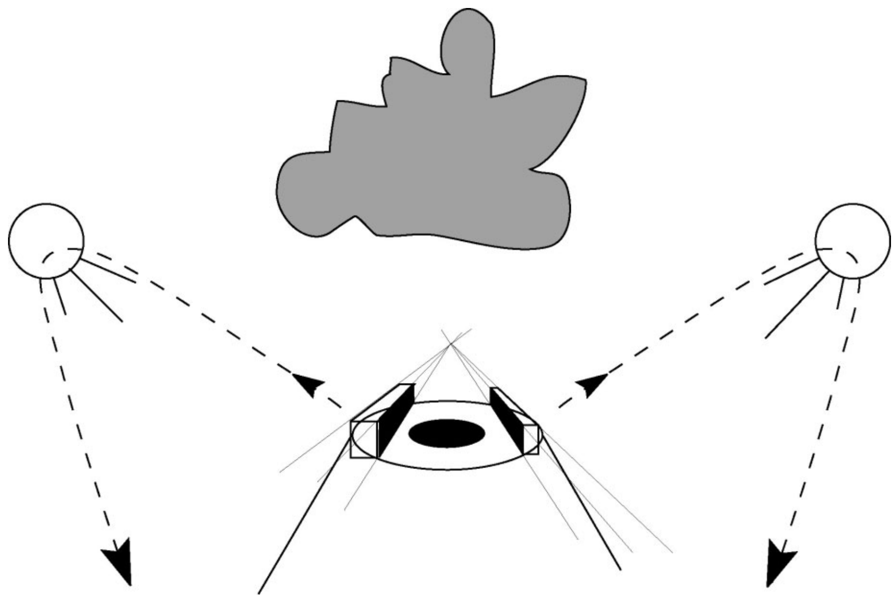


Figure 4. Concept of seasonal variations of the effective solar incidence on Kilimanjaro. During solsticial periods (dry seasons), the vertical cliffs are alternately exposed to substantial ablation (i.e. north-facing during boreal summer, south-facing during austral summer). Summit glacier bodies are protected from the direct sun during the equinoctial periods (rainy seasons) through clouds

with a plateau glacier (e.g. the northern slope glaciers with the Northern Icefield). Slope glaciers now disconnected from the plateau glaciers, such as those on the western slopes, are entirely independent.

6. At 4700 m, close to Arrow Glacier camp on the western side of Kibo, a layer of permafrost covered by morainic sediments was found in June 2001 and July 2002 (for location see Figure 2). This ice is at least 0.5 m thick, the extent to which we investigated. The present terminus of Arrow Glacier lies at about 4800 m and, thus, is higher than the potential equilibrium line altitude indicated by the permafrost. This means that thermal readiness (Messerli, 1973) is present for a glacier extending to much lower elevations than today, if only precipitation was more abundant.
7. The glaciers on Kibo's western slope show a distinctly convex shape, e.g. Little Penck Glacier (Figure 5), Little and Great Barranco Glaciers, and Heim Glacier. This indicates that these glaciers are close to equilibrium (e.g. Paterson, 1994), under favourable thermal yet dry conditions. This finding may not hold for other slope glaciers that have not yet been examined.
8. On the eastern edge of the Northern Icefield, an unusual ablation feature was found during our fieldwork (Figure 6). An almost perfect, 3–4 m high arc was melted out of an ice mass situated above a circular, 5 m diameter hole in the crater surface, probably resulting from brief, localized fumarole activity. On a much larger spatial and temporal scale, fumarole activity inside the Reusch Crater, which has been documented since 1933 (e.g. Tilman, 1937; Spink, 1944; Hunt, 1947), may have melted a central opening in the original plateau ice cap; associated, vertical ice walls may have helped initiate the 20th century ice retreat. When researchers first reached the summit, Reusch Crater was already free of ice (Meyer, 1891, 1900).

5. SYNOPSIS OF INTERPRETATIONS AND FACTS: A HYPOTHESIS

A synopsis of (i) proxy data indicating changes in East African climate since *ca* 1850, (ii) 20th century instrumental data (air temperature and precipitation), and (iii) the observations and interpretations made during two periods of fieldwork (June 2001 and July 2002) strongly support the following scenario. Retreat from a maximum extent of Kilimanjaro's glaciers started shortly before Hans Meyer and Ludwig Purtscheller visited

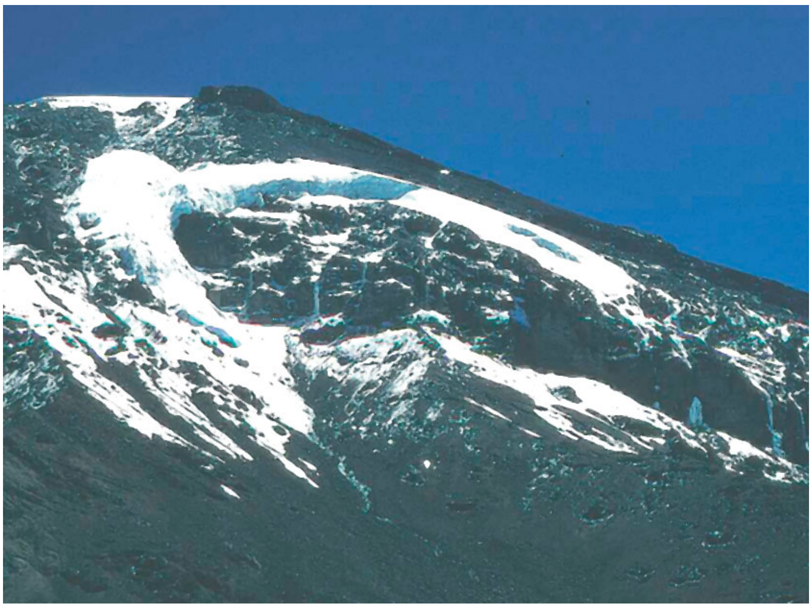


Figure 5. Little Penck Glacier and other slope glaciers are disconnected from those at the summit. The convex shape indicates the glacier is close to equilibrium. Photograph: G. Kaser, June 2001. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

Figure 6. Melting features attributed to isolated fumarole activities on the Kibo plateau. Photograph: G. Kaser, June 2001. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

the summit for the first time in 1889, caused by an abrupt climate change to markedly drier conditions around 1880. Intensified dry seasons accelerated ablation on the illuminated vertical walls left in the hole within Reusch Crater, probably a result of volcanic activity. The development of vertical features may also have started on the outer margins of the plateau glaciers before 1900, primarily as the formation of notches, as explicitly reported following field research in 1898 and 1912 (Meyer, 1900; Klute, 1920). A current example of such a notch development is the hole in the Northern Icefield (see Figure 2). Once started, the lateral retreat was unstoppable, maintained by solar radiation despite less negative mass balance conditions on horizontal glacier surfaces, and will come to an end only when the glaciers on the summit plateau have disappeared. This is most probable within the next few decades, if the trend revealed by Figure 1 continues. Positive air temperatures have not contributed to the recession process on the summit so far. The rather independent slope glaciers have retreated above the elevation of their thermal readiness, responding to dry conditions. If the present precipitation regime persists, then these glaciers will most probably survive in positions and extents that are not much different than today. This is supported by the spatial patterns of glacier extent shown in the Thompson *et al.* (2002) map, which indicate that slope glaciers retreated more from 1912 to 1953 than since then.

From a hydrological point of view, meltwater from Kibo's glaciers has been of little importance to the lowlands in modern times, contrasting with the statements of Gasse (2002) and Thompson *et al.* (2002). Most glacier ablation is due to sublimation, and where ice does melt it immediately evaporates into the atmosphere. Any intervals of runoff on the summit plateau are extremely brief and insignificant, and only very small rivers discharge from the slope glaciers. Rainfall reaches a maximum amount at about 2200–2500 m a.s.l. (Coutts, 1969; Røhr and Killingtveit, 2003), which primarily feeds the springs at low elevation on the mountain; one estimate attributes 96% of such water to a forest origin (Lambrechts *et al.*, 2002).

The scenario presented offers a concept that implies climatological processes other than increased air temperature govern glacier retreat on Kilimanjaro in a direct manner. However, it does not rule out that these processes may be linked to temperature variations in other tropical regions, e.g. in the Indian Ocean, where a large-scale connection between sea-surface temperature and East African rainfall amounts has been found in several studies (e.g. Latif *et al.*, 1999; Black *et al.*, 2003). Long-term changes in this specific large-scale mechanism are also likely to govern the long-term deficit of accumulation on Kilimanjaro glaciers and, thus, have to be considered particularly in future studies (see Section 6).

6. CONCLUSIONS AND DIRECTION FOR FUTURE RESEARCH

Under present climate conditions, glaciers on Kibo continue to retreat, and it appears likely that by mid-century the plateau glaciers will disappear from the mountain for the first time in over 11000 years. Still, there are several open questions to be answered in future investigations. How and when has the glaciation reached a maximum extent, of which today's remnants are the matter of both scientific and public concern? How did local convection on the mountain slopes and regional advection work, in order to allow sufficient moisture transport to the summit of Kibo for the formation of glaciers? How did the East African or even the large-scale vertical structure of the tropical troposphere differ? Has the Indian Ocean played a role different from today? How different was the atmospheric circulation over East Africa, and was this only a regional peculiarity? To find a way in this complex web of questions, future research must span different scales: from the microscale when detecting the processes at the glacier–atmosphere interface, to the mesoscale when simulating the circulation on the mountain slopes and over East Africa, and can even reach the global scale when providing information that can be considered in general circulation climate models. Such research is currently in progress as a collaborative effort between Innsbruck and Massachusetts universities, using the concept presented here as a working hypothesis.

Two studies within this collaborative project have been conducted in the meantime (Mölg *et al*., 2003b; Mölg and Hardy, 2004) and provide a first detailed support for the microscale part of the hypothesis derived in this article. Mölg *et al*. (2003b) illustrate that solar-radiation-driven melting controls vertical ice wall retreat, given the generally dry climate with a lack of accumulation on glaciers. Their results verify the concept for ice wall retreat depicted in Figure 4. Further, Mölg and Hardy (2004) show that mass loss on the summit horizontal glacier surfaces is mainly due to sublimation (i.e. turbulent latent heat flux) and is little affected by air temperature through the turbulent sensible heat flux — both aspects that support the interpretations made in the first item of Section 4. However, validation and verification of the entire hypothesis presented in this paper will require additional meteorological measurements and experiments, and mesoscale modelling of atmospheric dynamics over Kilimanjaro.

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