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Kilimanjaro Glaciers: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates

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[1] Recent and long term variations in ice extent on Kilimanjaro are investigated in the context of 20th century climate change in East Africa. Quickbird satellite data show that the areal extent of glaciers on Kilimanjaro is 2.51 km^2 in February 2003. To assess glacier retreat on Kilimanjaro two glacier systems are identified: (1) plateau ($\geq$5700 m) and (2) slope (<5700 m). Vertical wall retreat that governs the retreat of plateau glaciers is irreversible, and changes in 20th century climate have not altered their continuous demise. Rapid retreat of slope glaciers at the beginning of the 20th century implies a strong departure from steady state conditions during this time. This strong imbalance can only be explained by a sudden shift in climate, which is not observed in the early 20th century. Results suggest glaciers on Kilimanjaro are merely remnants of a past climate rather than sensitive indicators of 20th century climate change.
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1. Introduction

[2] Glaciers in tropical regions have retreated drastically since the mid and second half of the 19th century [*Kaser and Osmaston*, 2002], with glaciers on Africa's highest mountain, Kilimanjaro, being no exception to this trend [*Hastenrath and Greischar*, 1997]. Kilimanjaro (meaning 'shining mountain'), a huge stratovolcano (ca. 80 by 50 km at its base) located in tropical East Africa at the Kenya-Tanzania border (3° 04′ S, 37° 21′ E), formed in association with the Eastern Rift Valley about one million years ago [*Osmaston*, 1989]. It consists of three peaks: Shira (4005 m), Mawenzi (5140 m), and Kibo (5895 m), the latter being the only peak to still retain glaciers and be faintly volcanically active (fumarole activity [e.g., *Spink*, 1944; *Kaser et al.*, 2004]). Moraine evidence on Kilimanjaro suggests four major glaciations in the Pleistocene took place, both during and between phases of volcanic activity, followed by some lesser Holocene readvances and retreats [*Downie and Wilkinson*, 1972; *Hastenrath*, 1984; *Osmaston*, 1989; *Thompson et al.*, 2002]. Although absolute dating is poor, the maximum extent of moraines on Kibo and Mawenzi suggest that during the height of the last glaciation in the Pleistocene a large ice cap extending down to about 3200 m, covering an area of at least 150 km^2, blanketed Kilimanjaro [*Osmaston*, 1989].

[3] The precise age of existing glaciers on Kilimanjaro is uncertain, as is the exact time their present disintegration commenced, though reconstruction of the climatic history of East Africa indicates that decades immediately preceding 1880 coincided with a probable glacier maximum [*Hastenrath*, 2001]. When Hans Meyer made the first observations of glaciers on Kilimanjaro in the late 1880s and 1890s the break up of ice bodies had just begun [*Meyer*, 1900]. The areal extent of the glaciers just prior to this has been estimated to be about 20 km^2 [*Osmaston*, 1989]. Drastic shrinkage of the remaining glaciers continued throughout the 20th century, with total ice cover reduced to about 2.6 km^2 in 2000, as determined by *Thompson et al.* [2002] from aerial photographs. A thorough review of early observations on Kilimanjaro is given by *Hastenrath* [1984, p. 63–92].

[4] The retreat of glaciers on Kilimanjaro has in recent years attracted broad attention, with their disappearance sometimes linked to tropical warming [e.g. *Alverson et al.*, 2001]. However, glacier mass balance is the product of changes in more than one meteorological parameter, depending mainly on a combination of air temperature, solar radiation and precipitation [*Oerlemans*, 2005]. Annual precipitation in East Africa and the Kilimanjaro region has a bimodal distribution that reflects the seasonal zonal oscillation of the intertropical convergence zone, with 70–80% of annual precipitation occurring in March to May and October to December [*Coutts*, 1969]. This seasonality in rainfall makes glaciers on Kilimanjaro, like other tropical glaciers, particularly sensitive to changes in air humidity and cloudiness [*Kaser*, 1999]. In contrast, seasonal variations in air temperature are smaller than diurnal variations in air temperature at all altitudes in the Kilimanjaro region [*Mölg and Hardy*, 2004]. Unlike other glaciers in East Africa, the remaining ice bodies on the summit plateau of Kilimanjaro are also above the mean freezing level [*Kaser et al.*, 2004; *Hastenrath*, 2006]. The uncertainty about changes in air temperature in the tropical troposphere [e.g. *Thorne et al.*, 2005], and the known importance of moisture related variables on tropical glacier mass balance [*Kaser*, 1999], make it difficult to suggest that air temperature changes alone are responsible for glacier recession on Kilimanjaro.

[5] To re-evaluate possible causes of glacier retreat on Kilimanjaro we present a new detailed map of the remaining ice bodies on Kilimanjaro using high spatial resolution images from the Quickbird satellite taken in February

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2003. We compare this new classification to long term variations in ice extent on Kilimanjaro, with a focus on the rate of area change of different ice entities. To assess retreat of glaciers in the context of 20th century changes in air temperature, atmospheric moisture and precipitation in East Africa we focus on the response of two glacial systems on Kilimanjaro, which can be separated conveniently by elevation: (1) plateau (≥5700 m) and (2) slope (<5700 m) glaciers.

2. Data and Methods

[6] The areal extent of all glaciers and ice remnants on Kilimanjaro were obtained using two 0.60 m spatial resolution images taken at 14.6° from nadir on 1 February 2003 (07:56:40 UTC) by the sun-synchronous (98° inclination) Quickbird satellite (DigitalGlobe Inc.). The two cloud free satellite scenes, taken on the same orbital path, cover a total area of about 143 km^2 over the Kilimanjaro region. A georeferenced image of Kilimanjaro, with a total area of 16 km^2 and pixel size of 0.36 m^2, was used for the ice classification. Though the spatial resolution of the Quickbird imagery allowed us to manually mask transient snow we also used aerial photography that we obtained during a flight over Kilimanjaro on 21 July 2005 to validate this approach. There was very little transient snow cover on Kilimanjaro when the high-resolution photographs were taken using both digital and Hasselblad (ground resolution 10 cm) cameras. This allowed us to compare our photographs of all remaining ice bodies to the Quickbird imagery to carefully delineate the boundary between transient snow and glacial ice.

[7] Once satisfied with our snow mask an unsupervised classification was run, an iterative procedure that (1) calculated class means evenly distributed in the data space and (2) iteratively clustered the remaining pixels using minimum distance techniques [*Tou and Gonzalez*, 1974]. The planimetric area of each identified ice body was determined by counting the number of pixels it occupied in the data space. The classified ice regions were draped over a digital elevation model (DEM) used by *Thompson et al.* [2002] based on Global Positioning System (GPS) locations to obtain height information of each ice body. The GPS derived DEM was compared to but favoured over Shuttle Radar Topography Mission (STRM-3) data [*Rabus et al.*, 2003] because the GPS data reproduced elevations in the summit region more accurately. We accounted for two sources of error in our ice classification: (1) spatial (pixel) resolution and (2) miss-classification of ice, which together were estimated to be 0.02 km^2.

[8] To assess glacier recession in the context of 20th-century climate two data sets of gridded observations were used: (1) Climate Research Unit (CRU) TS 2.1 data [*Mitchell and Jones*, 2005] of monthly land surface air temperature and precipitation between 1901–2000 for East Africa (East Africa: 25°E–40°E; 10°N–15°S [*Mölg et al.*, 2006]) and (2) daily NCEP-NCAR reanalysis pressure level air temperature and specific humidity data [*Kalnay et al.*, 1996] for the grid location that contains Kilimanjaro (centered at 2.5 °S, 37.5 °E) between 1948–2005.

3. Results and Discussion

[9] The extent of all glaciers and ice bodies on Kilimanjaro on 1 February 2003 is shown in Figure 1, with the nomenclature for all ice entities given in Table 1. The total ice extent is 2.51 km^2 with the largest ice body the Northern Ice Field (Table 1; 18, 19, 20) (1.061 km^2). The Southern Ice Field glaciers (Table 1; 4, 5, 6, 7, 8, and 10 - a total area of 1.025 km^2) are the second largest remaining ice entities on Kilimanjaro, and extend to lower elevations than the Northern and Eastern Ice Fields. The asymmetry of low reaching glaciers on Kilimanjaro in the south-western sector of the mountain, a pattern that persisted throughout the 20th century, is most likely caused by enhanced cloudiness in the afternoon due to convective activity that shields the glaciers from shortwave radiation [*Hastenrath and Greischar*, 1997].

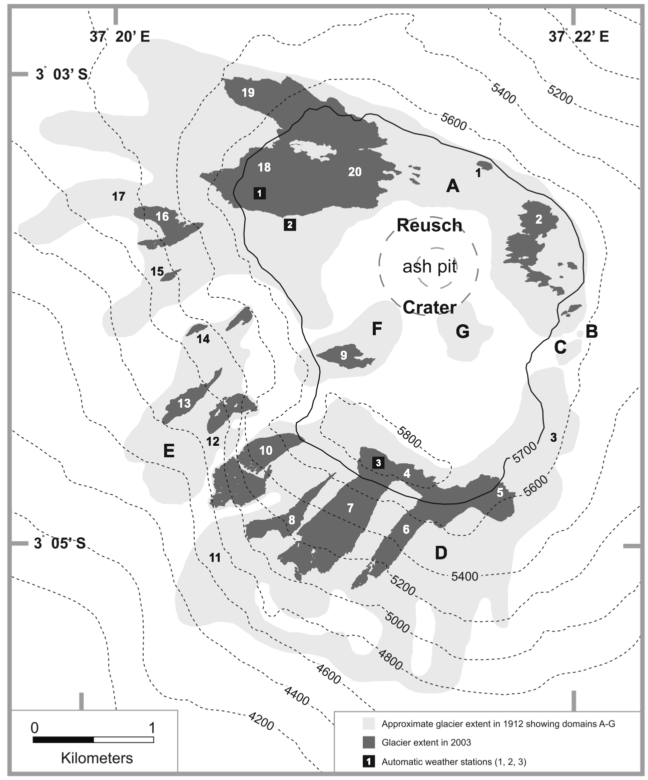

Figure 1. Glacier extent on Kilimanjaro in 1912 after *Hastenrath and Greischar* [1997] and in February 2003 (map contours in meters, UTM zone 37° S projection). The numbers refer to glaciers and ice bodies defined in Table 1. Glacier regions defined as domains A–G are also shown. The black boxes with numbers refer to the three automatic weather stations on Kilimanjaro. The solid black line represents the 5700 m contour, which is used to separate ice entities into plateau and slope glaciers.

[10] The spatial resolution of our satellite imagery allowed us to identify ice bodies that were not included in the *Thompson et al.* [2002] classification. A body of ice beneath the headwall of the Diamond Glacier (Table 1; Glacier 10) has been classified as glacial as it persists after ablation of transient snow (validated by our aerial photography). The area of this lower ice lobe of the Diamond Glacier is 0.11 km^2. The Great Barranco (Figure 1; Glacier 12, or previously known as the Great Breach) was not identified by *Thompson et al.* [2002] but is still present and is similar in extent (0.056 km^2) to its neighbour, the

Table 1. Nomenclature of Ice Entities on Kilimanjaro[a]

Glacier or Ice Entity	Number	Domain
Eastern Ice Field	1	A
Eastern Ice Field	2	A
Ratzel Glacier	3	D
Southern Ice Field	4	D
Rebmann Glacier	5	D
Decken	6	D
Kersten	7	D
Heim	8	D
Furtwangler	9	F
Diamond	10	D
Balleto	11	D
Great Barranco (Great Breach)	12	E
Little Barranco (Little Breach)	13	E
Arrow	14	E
Uhlig	15	A
Little Penck	16	A
Great Penck	17	A
Drygalski	18	A
Credner	19	A
Northern Ice Field	20	A

[a]Numbers are labeled on Figure 1, with domains used by *Hastenrath and Greischar* [1997] defined as A–G. Domains B, C and G are not listed as these ice entities did not get classified by name.

Little Barranco glacier (0.055 km^2). We also identified a small body of ice above, and most likely a remnant of, the Arrow Glacier (Figure 1) that was not included in the *Thompson et al.* [2002] classification. The total area of these ice bodies is 0.182 km^2, over double the observed difference in the areal extent of the two classifications. Not included in our or other classifications is debris-covered ice. However, residual debris-covered ice has been observed during field visits in the former Great Penck (3° 03.4′ S, 37° 19.9 E; 4815 m), Arrow Glacier [*Kaser et al.*, 2004] and lower Great Barranco moraines, and most likely exists in other western regions of the mountain.

[11] Turning now to long-term variations in ice extent Table 2 shows the drastic retreat of ice cover on Kilimanjaro between 1912 and 2003, with only 21% of the 1912 ice cover remaining in 2003. Not included in Table 2 is the *Thompson et al.* [2002] classification from 2000 because of the discussed differences (see above) in the definition of remaining ice bodies. Over the period 1912–2003 domains A, D and E disintegrated into smaller entities (Figure 1 and Table 1), while domains B and F disappeared completely before the middle part of the 20th century. Domain C, located in the south-eastern part of the plateau region, disappeared before 1976. The highest recession rates occurred in the first part of the 20th century (Table 2), with the most recent retreat rates (1989–2003) smaller than in any other interval (56.8×10^3 m^2 a^{-1}). Domain A, which was characterized by a continuous ice cover connecting the Northern and Eastern Ice Fields, but now dominated mostly by the Northern Ice Field, retreated at a nearly constant rate between 1912 and 2003 (Table 2). The same is not true for domain D (Southern Ice Field glaciers). Drastic retreat of these glaciers occurred in the first part of the 20th century, and has since that time decreased. An interpretation of the processes that control these different retreat rates, in the context of 20th century climate change, is proposed in the following paragraphs.

[12] Rates of glacier area retreat are not only controlled by changes in climate but by shape, slope, thickness and bed shape of the glacier, as well as the type of ablation process (melt versus sublimation). We propose that to unravel a climate signal from glaciers on Kilimanjaro it is necessary to cluster them into two broad systems based on their physical characteristics. A practical way to do this is to separate all ice entities using the 5700 m contour (Figure 1), which is roughly the height of the outer crater rim: (1) plateau (≥5700 m) and (2) slope (<5700 m) glaciers. Using this definition, plateau glaciers can be characterized as tabular shaped ice bodies that rest firmly on flat surfaces, with distinctive vertical walls, ranging in height between 10 and 30 m, mainly on their north and south margins. Retreat of all plateau ice bodies has been continuous and almost linear since 1912 (Figure 2). In contrast, the slope glaciers, found on steeper surfaces below the outer crater rim, do not have vertical walls at their margins and have some downslope movement. Slope glaciers have not retreated at a constant rate (Figure 2); rather rapid recession between 1912–1953 has been followed by decreasing retreat. Slope glaciers account for 52% of all remaining

Table 2. Extension of the *Hastenrath and Greischar* [1997] Total Surface Area and Rates of Area Change of Domains A–G on Kilimanjaro to 2003

	A	B	C	D	E	F	G	Total
1. Areas (10^3 m^2)								
1912	5676	3	27	5011	811	372	158	12058
1953	3829	0	16	2156	493	181	0	6675
1976	2440	0	0	1409	209	113	0	4171
1989	1900	0	0	1168	147	90	0	3305
2003	1304	0	0	1025	132	49	0	2510
2. Rates of area change (10^3 m^2 a^{-1})								
1912–1953	45.0	0.1	0.3	69.6	7.8	4.7	3.9	131.3
1953–1976	60.4	0	0.7	32.5	12.3	3.0	0	108.9
1976–1989	41.5	0	0	18.5	4.8	1.8	0	66.6
1989–2003	42.6	0	0	10.2	1.1	2.9	0	56.8

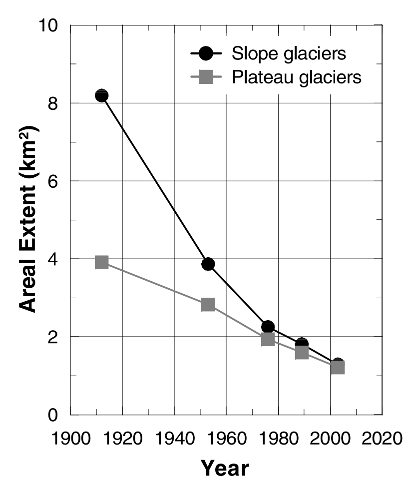

Figure 2. The area change of glaciers and ice bodies on Kilimanjaro separated by the 5700 m contour line between 1912–2003. The plateau (≥5700 m) and slope (<5700 m) ice bodies and glaciers are shown as grey squares and black circles, respectively.

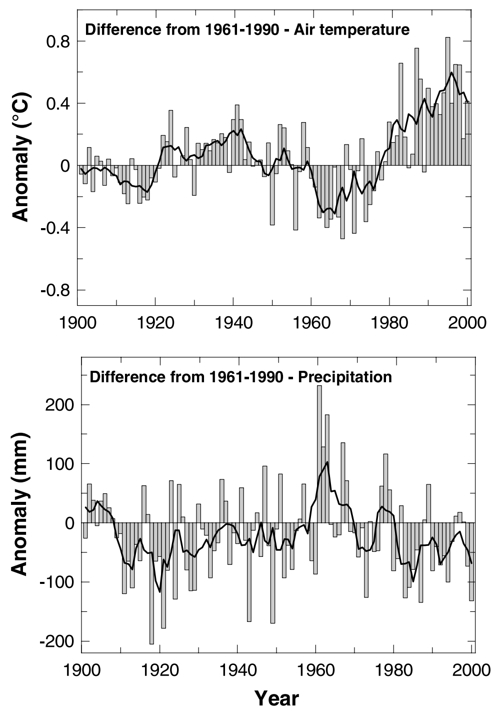

Figure 3. Annual anomalies of (top) land surface air temperature and (bottom) precipitation in East Africa (East Africa: 25°E–40°E; 10°N–15°S [*Mölg et al.*, 2006]), 1901 to 2000, relative to 1961 to 1990 using Climate Research Unit (CRU) TS 2.1 data [*Mitchell and Jones*, 2005]. The black solid lines are 5-point running means.

ice covered areas today, a proportion that has decreased by 16% since 1912.

[13] To place the different rates of retreat of the two glacier systems into the context of 20th century climate it is of interest to consider land surface (CRU) air temperatures and precipitation in East Africa (Figure 3). Surface air temperatures in East Africa between 1901 and 2000 show a statistically significant ($p < 0.01$) warming trend but the increase of 0.03 K decade^{-1} is about half of the global signal [*Jones and Moberg*, 2003]. Rates of temperature rise in East Africa since 1979 are 0.17 K decade^{-1} ($p < 0.01$), for a total warming of 0.35 K, which is equal to the global mean temperature rise. In contrast, no centennial-scale trend in precipitation is observed between 1901 and 2000 in East Africa (Figure 3).

[14] Annual anomalies of air temperature at 1000 hPa using NCEP-NCAR reanalysis data for the grid location that includes Kilimanjaro also show a statistically significant rise between 1979 and 2000 (after the introduction of satellite data into the reanalysis product [cf. *Kistler et al.*, 2001]), which is equal to the East Africa signal using the CRU data set (0.17 K decade^{-1}) (Figure 4). Significant warming trends ranging between 0.14 to 0.16 K decade^{-1} occur at all pressure levels between 1000 and 700 hPa in the NCEP-NCAR reanalysis 1948–2005 data (not shown). However, no temperature trends over the entire period (1948–2005) or between 1979 and 2000 are observed at 500 hPa, the approximate height of the glaciers on Kilimanjaro (Figure 4). A small but statistically significant decrease in specific humidity between 1948 and 2005, equal to 0.09 g kg^{-1} decade^{-1}, is observed at 500 hPa (Figure 4). There is no trend in specific humidity at 1000 hPa over the entire period but a large decrease of 0.75 g kg^{-1} decade^{-1} between 1979 and 2005 is observed ($p < 0.01$).

[15] Taken as a whole, these two data sets of gridded observations show that (1) a rise in air temperature at the land surface has occurred in East Africa during the 20th century, (2) no major change in precipitation has occurred in East Africa during the 20th century, although an early 1960s trend shift is evident and (3) the atmosphere has become drier but not warmer at the altitude of the glaciers between 1948–2005. The constant retreat of the plateau glaciers (Figure 2) gives no indication that fluctuations in 20th century climate have affected their demise. Rather, areal retreat of these tabular shaped ice bodies is governed primarily by solar radiation induced melting on their vertical walls [*Mölg et al.*, 2003]. Melting on the vertical walls occurs despite air temperatures at the altitude of the plateau glaciers remaining below 0 °C. Though it is still uncertain as to what physical processes lead to the formation of the vertical walls, once established, there is no pathway for the plateau glaciers other than to continuously retreat once their vertical margins are exposed to solar radiation.

[16] Though mass loss or gain on the mostly flat, upper parts of the plateau glaciers impact ice volume they are not responsible for the observed retreat. *Mölg and Hardy* [2004] used automatic weather station data from the northern ice field (Figure 1) to assess ablation, providing a full energy

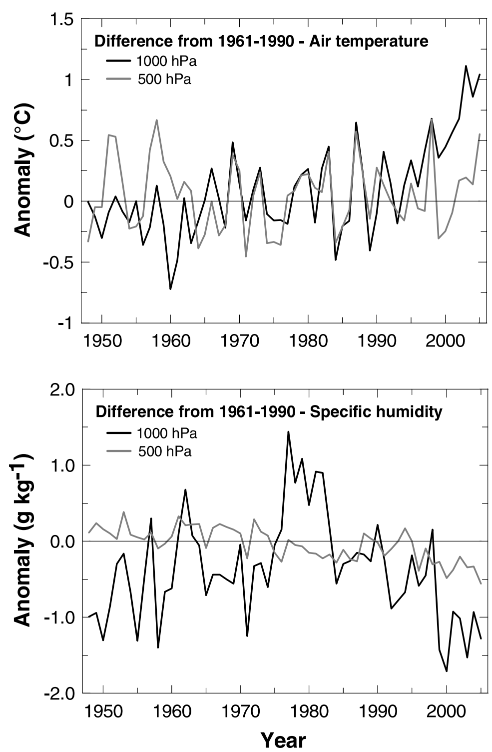

Figure 4. Annual anomalies for (top) air temperature and (bottom) specific humidity at 1000 (black line) and 500 (grey line) hPa, respectively, 1948–2005, relative to 1961 to 1990 using NCEP-NCAR reanalysis data [*Kalnay et al.*, 1996] for the grid location nearest to Kilimanjaro (2.5 °S, 37.5 °E). Averaging over a larger area representing East Africa does not alter the evident trends.

balance over two periods that in total spanned 19 months, to carefully show that variations in net shortwave radiation govern energy exchanges at this site. The marked difference in ablation between the two periods was controlled primarily by variations in surface albedo, which was most sensitive to precipitation amount and frequency. A sensitivity analysis by *Mölg and Hardy* [2004], which involved varying both temperature and precipitation, supported this conclusion. Importantly, sublimation accounts for nearly all observed ablation on the horizontal surfaces of the plateau glaciers, with melting only occurring for a few hours some days [*Mölg and Hardy*, 2004].

[17] The development of a large hole in the Northern Ice Field, first observed in 1989 [*Hastenrath and Greischar*, 1997] and clearly visible in Figure 1, has over the last two years opened to the west creating a large canyon feature reaching down to bedrock (as observed from our aerial photography and field investigations). Once a small bridge of ice on the eastern boundary of the canyon ablates the Northern Ice Field will become two separate ice entities. A similar split has also developed in the Furtwangler Glacier. With the exception of a small part of the western end of the Furtwangler Glacier its entire perimeter, including its new canyon like feature, has vertical walls that are all exposed to solar radiation at different times of the day and year. Exposure to more solar radiation on the newly formed vertical walls of both these ice entities can only enhance retreat rates. An increase in the Furtwangler retreat rate between 1989 and 2003 has already been observed (Table 2) and could be linked to the canyon development.

[18] Unlike the plateau glaciers, whose demise appear unavoidable given their present geometry, the size and location of slope glaciers make us believe that they should have a much shorter adjustment time to changes in climate (e.g. about 4 years in the Cordillera Blanca, Peru [*Kaser et al.*, 2003]). The rapid recession in the first part of the 20th century clearly shows that slope glaciers were drastically out of equilibrium, which we take as evidence that they were responding to a large, prior shift in climate at this time. A slow change in climate would have allowed the slope glaciers to adjust continuously and would never have caused such a strong departure from steady state conditions (Figure 2). We believe that the strong imbalance at the beginning of the 20th century can only be explained by a sudden shift in climate shortly before the strong retreat rates began. If the shift had occurred much earlier, the slope glacier imbalance would not have been as large as it was at the beginning of the 20th century.

[19] Whereas the areal extent of tropical glaciers elsewhere have fluctuated in response to changes in 20th century climate [e.g. *Kaser*, 1999], there is no hint in Figure 2 that slope glaciers on Kilimanjaro have behaved in the same way. No footprint of multidecadal changes in areal extent of slope glaciers to fluctuations in 20th century climate is observed but their ongoing demise does suggest they are still out of equilibrium. After responding to a sudden shift in climate at the end of the late 19th century, the ongoing imbalance of the slope glaciers is most likely linked to a constant trend in climate over the past 100 years. Though no long term trend in air temperature at the height of the glaciers has been observed (Figure 4), changes in specific humidity could account for the ongoing, but decreasing 20th century retreat. Less moisture in the atmosphere over Kilimanjaro is most likely linked to a decrease in cloudiness (enhanced solar radiation) and precipitation (lower albedo). The sensitivity of the slope glaciers (and vertical walls of the plateau glaciers) will soon be better understood as data from newly installed automatic weather stations (AWS) become available (Figure 1; AWS 2–3).

4. Conclusions

[20] All ice bodies on Kilimanjaro have retreated drastically between 1912–2003. Despite air temperatures always being below freezing, areal retreat of plateau glaciers is governed mostly by solar radiation induced melt on vertical walls that characterize their north and south margins [*Mölg et al.*, 2003]. Though the processes responsible for the formation of the vertical walls is still not well understood, once established, the vertical wall retreat is irreversible, and no change in 20th century climate appears to have significantly altered their ongoing demise. However, the apparent and near disintegration of the Northern Ice Field and Furtwangler glaciers into two ice entities, respectively, can only accelerate present retreat rates of these two ice bodies.

[21] Though constant shrinkage of the plateau glaciers could have started as a result of a slow change in climate, through a process that allowed the glaciers to reach some threshold to produce vertical walls, evidence for a sudden change in climate prior to the 20th century appears to come from the slope glaciers. The rapid recession of slope glaciers in the first part of the 20th century clearly shows that they were drastically out of equilibrium. The strong imbalance at the beginning of the 20th century can only be explained by a sudden shift in climate shortly before the strong retreat rates began. If such a change in climate had occurred much earlier, the slope glacier imbalance would not have been as large. Slope glaciers are still out of equilibrium, and though 20th century changes in air temperature at the height of the glaciers do not appear responsible (Figure 4), we cannot rule out that changes in moisture (reduction in specific humidity) may be linked to their ongoing imbalance.

[22] Rather than changes in 20th century climate being responsible for their demise, glaciers on Kilimanjaro appear to be remnants of a past climate that was once able to sustain them. *Hastenrath* [2001, 2006] suggests an increase in net shortwave radiation, accompanied by a decrease in cloudiness and precipitation, initiated the retreat of the glaciers during the last two decades of the 19th century. This is supported by a recent finding that a higher frequency of climatically significant Indian Ocean Zonal Mode events in the 19th century (1820–1880) may have provided a mechanism to contribute to a wetter climate in East Africa, and thus stable glaciers [*Mölg et al.*, 2006]. To fully understand what climatic conditions enabled glaciers to accumulate and grow prior to the onset of modern glacier recession on Kilimanjaro, more effort to reconstruct 19th century climate is necessary.

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