Glacier loss on Kilimanjaro continues unabated

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The dramatic loss of Kilimanjaro's ice cover has attracted global attention. The three remaining ice fields on the plateau and the slopes are both shrinking laterally and rapidly thinning. Summit ice cover (areal extent) decreased ≈1% per year from 1912 to 1953 and ≈2.5% per year from 1989 to 2007. Of the ice cover present in 1912, 85% has disappeared and 26% of that present in 2000 is now gone. From 2000 to 2007 thinning (surface lowering) at the summits of the Northern and Southern Ice Fields was ≈1.9 and ≈5.1 m, respectively, which based on ice thicknesses at the summit drill sites in 2000 represents a thinning of ≈3.6% and ≈24%, respectively. Furtwängler Glacier thinned ≈50% at the drill site between 2000 and 2009. Ice volume changes (2000–2007) calculated for two ice fields reveal that nearly equivalent ice volumes are now being lost to thinning and lateral shrinking. The relative importance of different climatological drivers remains an area of active inquiry, yet several points bear consideration. Kilimanjaro's ice loss is contemporaneous with widespread glacier retreat in mid to low latitudes. The Northern Ice Field has persisted at least 11,700 years and survived a widespread drought ≈4,200 years ago that lasted ≈300 years. We present additional evidence that the combination of processes driving the current shrinking and thinning of Kilimanjaro's ice fields is unique within an 11,700-year perspective. If current climatological conditions are sustained, the ice fields atop Kilimanjaro and on its flanks will likely disappear within several decades.

climate change | climatology | glacier retreat | ice cores | paleoclimate

Despite their relatively small size the diminishing glaciers of Kilimanjaro (specifically on Kibo) are now recognized as symbols of changing climate in Africa. Since 1912 the ice cover on Kibo has been mapped intermittently, allowing the rate of ice retreat to be calculated periodically over the 95 years from 1912 to 2007. The maps for 1912 and 1953 were based on terrestrial photogrammetry, whereas maps produced for 1976 and 1989 were based on Landsat images (ref. 1 and references therein). The glaciers were mapped from aerial photographs taken in 2000 that revealed that the ice cover had diminished to 2.6 km^2 from 12.06 km^2 in 1912, a decrease of nearly 80% (2). Subsequent application of a better area calculation routine to the same measurements resulted in a 2000 area of 2.52 km^2 (Table S1).

In January and February of 2000 six ice cores were drilled on Kibo, three through the Northern Ice Field (NIF), two through the Southern Ice Field (SIF), and one through the Furtwängler Glacier (FWG). Analyses of these cores provided a proxy-based climate history extending back 11,700 years and revealed that the most recent 40 years (1960–2000) of accumulation were absent (had been removed) (2). Accumulation stakes were installed at each drill site and next to the vertical wall of the NIF in February 2000. Subsequently, 33, 4, and 13 additional stakes were installed on the NIF, FWG, and SIF, respectively, to better resolve the spatial patterns of horizontal-surface ablation. A subset of this stake network has been measured at 17 different intervals, most recently in January 2009. At nine sites, stakes provide a reference for NIF vertical-wall retreat, and Global Positioning System (GPS) surveys have been conducted annually around FWG since 2005 to track its margin retreat. In addition, all of the glaciers have been photographed repeatedly over the last decade.

Here, we report the changes in ice cover (areal extent) on Kilimanjaro from 2000 to 2007 by using a combination of aerial photographs and ground-based observations. We present our observations designed to evaluate thinning of the summit ice fields and volume changes for the NIF and FWG. The relative importance of the different processes responsible for the ice field shrinkage remains an area of active inquiry although multiple climatological factors are undoubtedly at work.

Results

Aerial photographs of the glaciers on Kibo were taken with mapping cameras on February 16, 2000, January 28, 2006, and October 15, 2007. Simple visual comparison of the 2000 and 2007 aerial photographs (Fig. 1) reveals dramatic changes. For example, since 2000 the hole near the center of the NIF has expanded so that it now opens to the west and will likely divide the NIF within a few years. Contemporaneously, FWG has shrunk and separated into two parts while the SIF has continued to dwindle.

An ice cover map was produced by using the 2007 photos and combined with four previous maps by Hastenrath and Greischar (1) and our map for 2000 to provide a 95-year observational record since 1912 (Fig. 2). Maps were produced for all three sets of our photographs but only those for 2000 and 2007 are shown here (see Fig. S1 for 2006). Contours were generated from digital elevation models of the ice and the surrounding terrain, and maps with outlines of the ice bodies were produced (see *Materials and Methods*). The areas of the individual ice bodies were computed and aggregated into discrete domains (Fig. S2 and Table S1) as defined by Hastenrath and Greischar (1). The 2000 and 2007 results for the four domains (A, D, E, and F) and the total area are given in Table 1, and the areas of all of the individual ice bodies in 2000, 2006, and 2007 are given in Table S1. The areal extent of Kilimanjaro's ice cover has decreased ≈85% from 12.06 km^2 in 1912 to 1.85 km^2 in 2007. Linear extrapolation of ice extent to the time axis [1912 to 2007, R^2 = 0.98; Fig. 2 *Inset*] suggests that the glaciers will disappear from the summit of Kibo in 2022. In view of the likely (but unknown) errors in the determinations of the ice area at each epoch, a straight-line fit to all available values seems justified. However, an argument can be made for a "better" fit to the data by fitting two straight lines to account for the apparent change in rate of area decrease beginning in 1976. Slightly better correlation coefficients are obtained (R^2 = 0.998 for 1912 to 1976 and 0.994 for 1976 to 2007) and the predicted disappearance of the ice occurs in 2033. In either case there is a strong likelihood that the ice fields will disappear within a decade or two if current conditions persist.

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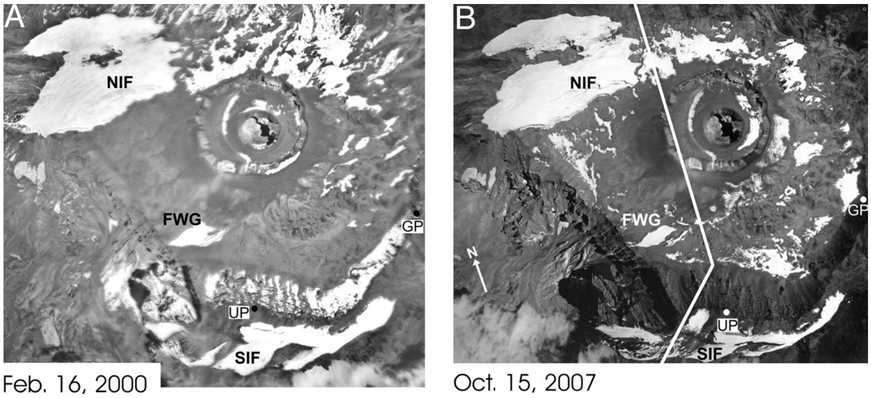

Fig. 1. Aerial photographs of the ice fields atop Kilimanjaro on February 16, 2000 (*A*) and October 15, 2007 (*B*). Note that two photos are required to cover the area in 2007 as emphasized by the white gap. Both images come from unrectified photos in which tilt and relief displacements have not been removed, thus possibly giving false impressions of the relative sizes of features. Both glaciers and snow cover appear in these images and cannot be distinguished at this reduced scale (≈1:100,000).

Table 1 also reveals that 26.4% of the mountain's 2000 ice cover was lost over the 7.7-year interval from Feb 2000 to Oct 2007. The annual rate of ice cover loss has increased over time (Table 2) from ≈1.1% yr^{-1} (1912–1953) to ≈1.4% yr^{-1} (1953–1989) and to values exceeding 2.4% yr^{-1} (1989–2007). Focusing on the remaining ice fields (84% of total ice area on Kibo) and the period with best aerial photo coverage (2000–2007) reveals that the ice areas primarily on the plateau (domains A + F) and southern slopes (domains D + E) have decreased at rates of ≈3.2% and ≈3.8% yr^{-1}, respectively (Table 1). An independent determination of the ice covered area in 2003 as 2.51 km^2 (3) differs slightly from ours, but does not affect any conclusions drawn here (see Table S2, Figs. S3 and S4, and *SI Text*).

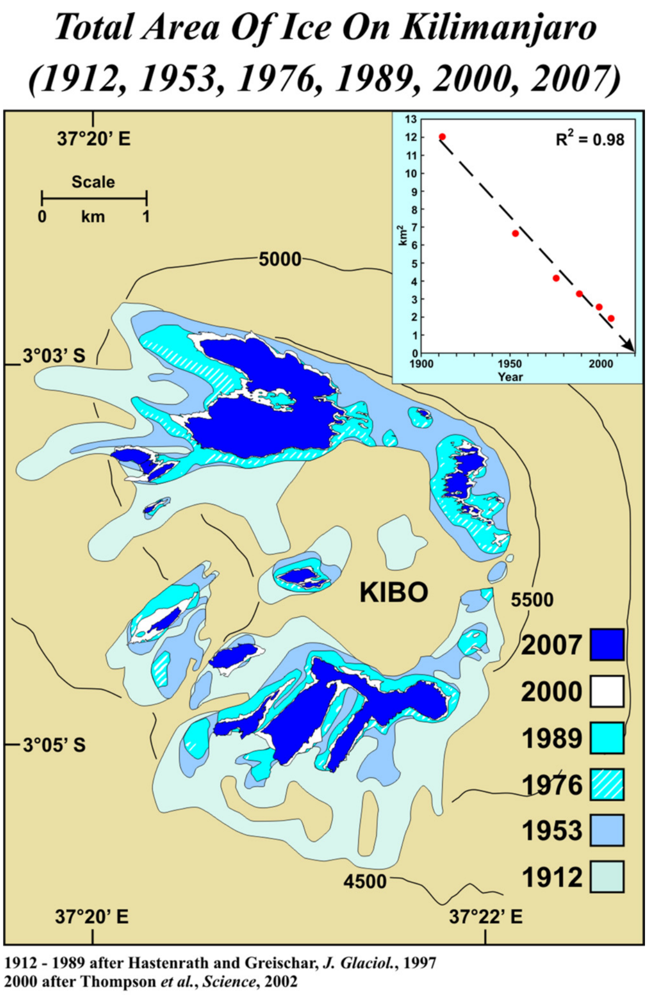

Fig. 2. Outlines of the Kibo (Kilimanjaro) ice fields 1912, 1953, 1976, and 1989 (1), 2000 (2) and updated with Ohio State University aerial photographs taken October 15, 2007. (*Inset*) Areal extent (km^2) versus time with a linear fit (R^2 = 0.98).

Shrinking of the NIF (≈2.3% yr^{-1}) has been further documented by measuring margin retreat on the air photos between 2000 and 2007 and the distance-to-ice from a small network of stakes placed next to its vertical wall on the crater side in 2000. The air photos reveal considerable spatial variability in the extent of margin retreat, yet display a consistent pattern. The mean of 405 points yields an average retreat of 3.4 $m \cdot yr^{-1}$, with least retreat on the thick, vertical south face (1.4 $m \cdot yr^{-1}$) and greatest retreat on the steeply sloping, west-facing tongue above the Little Penck (LP) Glacier (5.8 $m \cdot yr^{-1}$). GPS and other measurements corroborate these determinations. For a thick section along a 90-m stretch of the southern margin of the NIF, the photogrammetrically measured retreat averaged 0.81 $m \cdot yr^{-1}$. Discrete measurements from stakes positioned along the same section give an average retreat of 0.8 $m \cdot yr^{-1}$ over the same period (2000–2007). This excellent agreement of results using two entirely different approaches and completely independent measurements provides strong confidence that the measurements along the entire NIF perimeter are reliable.

Thinning of Kibo's glaciers has received less attention, because elevation changes are more difficult to confidently resolve from the air photos. Fortunately, a network of 50 accumulation stakes, manually measured and frequently redrilled into the ice, reveals dramatic changes with important spatial variability. For the period coinciding with the two air photo coverages (2000 and 2007), thinning at the summits of the NIF and SIF has amounted to a minimum of 1.9 and 5.1 m, respectively. To put this thinning in perspective, ice cores to bedrock at the summit in 2000 were ≈50 m long at the NIF and ≈21 m at the SIF.

The observed surface lowering is now partially the result of surface melting, a recent phenomenon as confirmed by observations of the ice cores drilled to bedrock in 2000. The upper 65 cm of the 49-m NIF core 3 is the only portion containing elongated bubbles, channels, and open voids characteristic of extensive melting (Fig. 3*A*) and refreezing; these features are not observed in the lower sections of any cores (Fig. 3*B*). This finding is significant, because it confirms the absence of surface melting

Table 1. Areal extents (m^2) for the individual ice fields

Item	Year 2000	Year 2007	% Change (2000–2007)	Annual % change (2000–2007)
Date of photo	2000.1	2007.8		
NIF, m^2	1,153,009	947,093	−17.86	−2.32
SIF, m^2	740,656	573,181	−22.61	−2.94
FWG, m^2	57,149	35,024	−38.71	−5.03
NIF + SIF + FWG, m^2	1,950,814	1,555,298	−20.27	−2.63
Domains A and F, m^2 (see Table S1)	1,511,074	1,186,740	−24.77	−3.22
Domains D and E, m^2 (see Table S1)	1,004,871	714,527	−28.99	−3.75
Total all ice bodies (Table S1 and Fig S2)	2,515,945	1,851,267	−26.42	−3.43
LP Glacier, m^2	101,129	60,416	−40.26	−5.23

Areal extents of the ice domains and glaciers are used to calculate the total percent change and annual percent change from 2000 to 2007. Data are included for LP Glacier (Fig. 5) and domains A and F (ice areas primarily on the plateau) and domains D and E (glaciers on the southern slopes) as shown in Fig. S2.

for the prior ≈11 millennia. Moreover, continued surface lowering on the NIF has now removed the ^{36}Cl horizon associated with the 1952 Ivy test that is routinely used as a time-stratigraphic marker in cores from glaciers worldwide. This layer, centered at 1.6-m depth in the 2000 NIF core 2, was critical for establishing the age at the top of the core (2).

It is important to note that very little of the surface meltwater percolates into these glaciers that consist of impermeable ice virtually to the surface as confirmed by the six cores drilled in 2000. Certainly water percolates into surface fractures but these are not extensive so the effect is minimal. Water does refreeze on flat surfaces. For example, core site 3 (NIF3) is quite flat, likely accounting for at least partial refreezing of any meltwater produced. Melting at NIF3 thus redistributes both mass and energy rather than being lost to ablation, but few other areas are as flat. Most of the meltwater produced on Kilimanjaro's glaciers runs downslope and is lost, from a mass-balance perspective.

The annual percentage of recent ice cover loss (2000–2007) is greatest for the FWG (5% yr^{-1}) as Fig. 4 suggests. The average retreat measured from the 2000 and 2007 boundaries at 74 points spaced 20 m apart along its whole perimeter is 1.8 $m \cdot yr^{-1}$, which is corroborated by the GPS survey around the perimeter from February 2005 to September 2008. FWG was already completely water saturated in 2000 as revealed during Ohio State University ice coring. Accumulation stakes maintained on FWG since February 2000 confirm that the glacier was 3.05 m thinner in October 2007. The best measurement of thinning on the FWG comes from a stake installed in the 2000 borehole. The stake consisted of a 4.67-m-long drill extension placed in the bottom of the 9.5-m borehole, resting on the surface beneath the ice, with an attached bamboo pole extending ≈2 m above the ice surface. In February 2009 the top of the drill extension was within 5 cm of the ice surface, indicating that between February 2000 and February 2009, the surface lowered ≈4.80 m. Thus, at the drill site the FWG has lost ≈50% of its 2000 ice thickness at a rate of ≈0.54 $m \cdot yr^{-1}$. Therefore, all available in situ observations confirm, across the mountain, that as the summit ice fields continue to shrink, they are also rapidly thinning.

Using the calculated change in area and the surface lowering measured from the stakes the ice volume loss from 2000 to 2007 for the NIF and FWG was calculated. The calculation required making assumptions based on logic and experience. The procedure used is described below and augmented by discussion in *SI Text* and sketches in Fig. S5. The input data and results are given in Table S3. Total volume loss is the sum of the loss caused by surface lowering and margin retreat. The surface lowering values from the stakes installed on each ice field were averaged and assumed to represent the mean lowering for the entire surface. This value was multiplied by the ice area in 2000 to obtain the volume loss caused by surface lowering (entity 1 in Fig. S5*A*). To calculate the volume loss by margin retreat each ice field was divided into segments with approximately equal ice cliff heights. There were 48 segments for the NIF and 23 segments for FWG. The ice area loss between 2000 and 2007 over that segment was calculated and multiplied by the corresponding ice cliff height to obtain volume loss for that segment. This approach entailed assuming that the ice cliff height in 2007 represents the ice height for the entire segment of area loss (entity 2 in Fig. S5*A*). The volume losses of all segments were summed to obtain the ice volume loss caused by area loss that was then added to the volume loss from surface lowering to attain the total volume loss.

Although valid for calculating total volume loss, this approach overestimates loss by thinning and underestimates loss by shrinking (Fig. S5*A*). To correct for this problem, the volume loss along the top of the ice wall must be calculated as this part of the ice field has both thinned and retreated since 2000 (entity 3 in Fig. S5*B*). Half

Table 2. Total ice cover (km^2) for the seven maps (Table S1) allows calculation of the percent and annual percentage change in ice cover for each observational period (i.e., calculated relative to the previous map) along with the percentage of total ice cover lost from 1912 to 2007

Map year	Area, km^2	No. years	% Area change per observation period	Annual rate of % area change per observation period (% yr^{-1})	% Area change since 1912
2007.8	1.851	1.7	−4.1	−2.4	−84.65
2006.1	1.930	6.0	−23.3	−3.9	
2000.1	2.516	10.2	−23.9	−2.3	
1989.9	3.305	13.8	−20.8	−1.5	
1976.1	4.171	22.5	−37.5	−1.7	
1953.6	6.675	41.0	−44.6	−1.1	
1912.6	12.058				

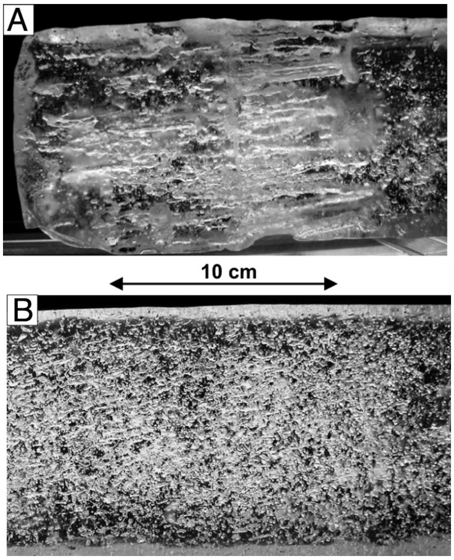

Fig. 3. Photographs of two sections from the Kilimanjaro NIF core 3. (*A*) Appearance of the top 0.65 m that contained elongated bubbles, channels, and voids characteristic of melting and refreezing. (*B*) The remainder of the 49-m core to bedrock appears as glacial ''bubbly'' ice shown here, confirming the absence of features associated with melting and refreezing.

of this volume is added to the loss by margin retreat, and half is subtracted from the loss by thinning. The results indicate that since 2000 overall ice volume losses caused by surface lowering and margin retreat have been nearly of the same magnitude, which is unlikely to have been the case in past decades. Thinning accounts for 49% and 43% of the ice volume loss on the NIF and FWG, respectively. Although measurements for the SIF were deemed insufficient or too unreliable for this calculation, our observations suggest a similar situation there.

Repeat photographs (Fig. 5) of LP, a slope glacier, illustrate that the glaciers off the plateau are also rapidly disappearing. Stereoscopic measurement of LP in 2000 (101,129 m^2) and 2007 (60,416 m^2; see Table 1) shows that LP has lost 40% of its areal extent since 2000. Clearly, LP is not close to equilibrium, as has been reported (4, 5).

Discussion

It has been suggested (refs. 3 and 6 and references therein) that drier conditions (reduced humidity) in East Africa during the 20th century (after several wetter decades before 1880) have reduced precipitation and cloud cover and thereby increased both incoming solar radiation (insolation) and net solar radiation (caused by less snow). An energy balance study (7) concluded that mass loss from the upper (horizontal) surfaces of the ice fields has been dominated by sublimation although there is physical evidence of melting as well (e.g., Fig. 3). In contrast, radiation balance modeling indicates that insolation-driven melting removes mass from the vertical ice walls and is primarily responsible for their retreat (8).

Attributing the ice fields' shrinkage to specific drivers is hampered by the scarcity of ground-based meteorological observations in this region of East Africa, while satellite-borne observations span only three to four decades. In situ observations by an automatic weather station on Kilimanjaro's NIF begin in 2000 (2, 7). The limited satellite observations have yet to confirm any unambiguous trend toward drier atmospheric conditions (1979–1995) and the lack of radiosonde observations over less-developed countries has limited the accuracy of tropical water vapor trends (9).

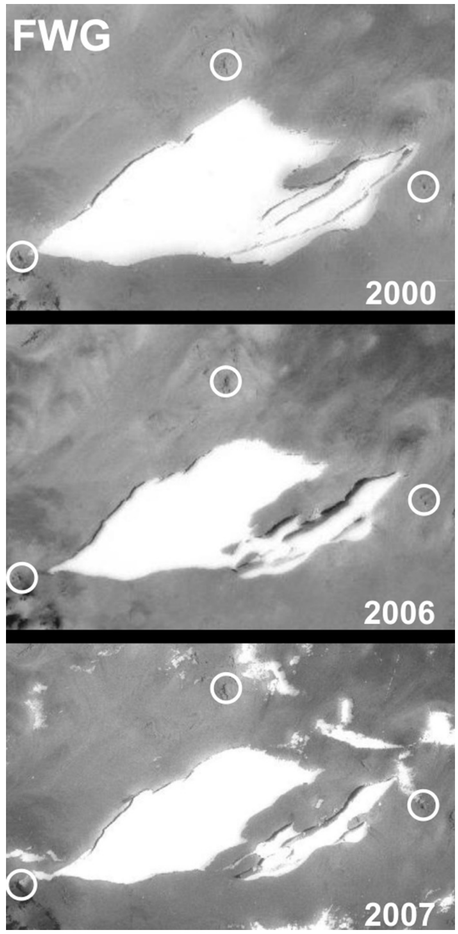

Fig. 4. Aerial photographs (2000, 2006, and 2007) of FWG illustrate its rapid disappearance. For orientation the same three surface features are circled.

Meteorological observations in the region are sparse, most records are short, and individual stations are necessarily biased by both local processes and regional conditions. Limited meteorological data in the region from 1939 to 1992 (10) exhibit large spatial differences although several robust trends were reported (e.g., increasing January minimum temperature). Figure 8 in ref. 10 reveals that the strongest upward trend is situated over the Kilimanjaro region, whereas locations along the coast and near large water bodies generally exhibit negative trends. On a larger scale, East Africa (10°N - 15°S; 25°E - 40°E) exhibits an overall warming trend (1901–2000) with large decadal variability and no overall precipitation trend, although the 1961–1970 precipitation maximum is present (figure 3 in ref. 3). A 25-year temperature and precipitation history recorded in the Amboseli Basin, a few kilometers from the northern base of Mount Kilimanjaro, reveals a warming trend in both maximum and minimum temperatures and large interannual variability in precipitation but no long-term trend (11). Altmann et al. (11) note that the weather and water availability at Amboseli are highly affected by conditions on the mountain. Over recent decades there has been a continual transformation of the landscape surrounding Kilimanjaro into agricultural land, thus, unraveling large-scale climate forcing from regional forcing caused in part by landscape changes is difficult.

Regardless of the relative importance of the multiple drivers responsible for the loss of Kilimanjaro's summit ice fields, these shrinking ice fields are not unique (12, 13). The remaining glaciers throughout Africa (14–16) will soon disappear, most glaciers in

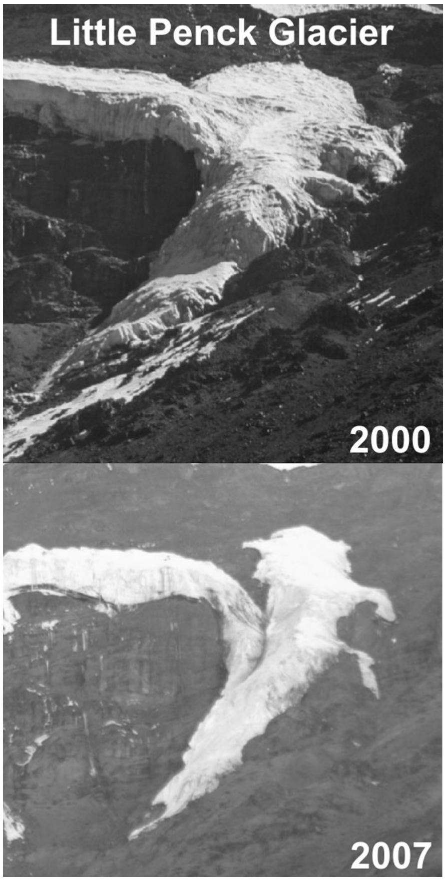

Fig. 5. Slope glaciers, such as LP Glacier (2000 and 2007), are also rapidly shrinking (photos by D.R.H.).

tropical South America are in rapid retreat (12, 17–19), the few remaining glaciers in Indonesia are rapidly disappearing (20), and on balance most Tibetan glaciers, including many in the Himalayas, are also retreating (21). Moreover, some of the highest glaciers in the Himalayas are now wasting from the surface downward (22) just like the ice fields on Kilimanjaro.

Such widespread glacier mass loss, shrinkage, and retreat at high elevations (>5,000 m above sea level) in lower latitudes (30° N to 30° S), particularly in the thermally homogeneous tropics, suggests the likelihood of an underlying common driver on which more localized factors such as changes in land use, precipitation, cloudiness, and humidity are superimposed. The Quelccaya ice cap (Peru) has been monitored for more than three decades (12) and is rapidly retreating along its margins. However, the net annual mass accumulation on the summit, derived from the 2003 core and annual pit sampling, has not declined, suggesting other mechanisms are more important. Most obvious would be warmer air temperatures, which would result from the vertical amplification predicted by models that include anthropogenic forcing and are observed in the corrected vertical temperature profiles (22).

Evidence presented here documents that Kilimanjaro's remaining summit glaciers are rapidly thinning and laterally shrinking and that the slope glaciers are responding very similarly. Ice cores collected in 2000 provide several lines of evidence suggesting that drier and less cloudy conditions are unlikely to be sufficient to account for the observed ice loss. For example, Kilimanjaro's NIF has persisted for at least 11,700 years, and ≈4,200 years ago a widespread drought lasting ≈300 years was insufficient to remove the NIF, where the drought is recorded by a 30-mm-thick dust layer. Finally, the upper 65 cm of the NIF core 3 contains clear evidence of surface melting that does not appear elsewhere in the 49-m core containing the 11,700 year history. Hence, the climatological conditions currently driving the loss of Kilimanjaro's ice fields are clearly unique within an 11,700-year perspective. These observations suggest that warmer near-surface conditions observed in the region, coupled with observed vertical amplification of temperature in lower latitudes (23–25), are playing an important role. Regardless of the contributions of various drivers, the ice fields atop Kilimanjaro will not endure if current conditions are sustained and adaptive actions to minimize the potential impacts should be developed quickly.

Materials and Methods

The ice cover maps were produced from stereoscopic aerial photography taken specifically for that purpose at photo scales of ≈1:20,000 for 2000 and 2006 and ≈1:15,000 for 2007 (see *SI Text*). A conservative estimate of 15 μm for pointing precision on the photographs yields an expected measurement precision in the terrain of 0.2–0.3 m in plan and 0.3–0.4 m in elevation. Sixteen targeted ground control points (not shown) were set out for the 2000 mapping, but because of GPS receiver problems no satisfactory positions were obtained for any of the points. Thus, the 2000 mapping used two points, Gillman's Point (GP) and Uhuru Peak (UP), established in 1999 by the Geodetic Institute of the University of Karlsruhe (Karlsruhe, Germany) with centimeter accuracy by differential GPS measurements and seven points determined in 2001 by GPS measurements to several meter accuracy by members of the University of Massachusetts field team. For the 2006 mapping, the two existing points from the Karlsruhe survey (GP and UP) along with six other points on the summit plateau were targeted for use as ground control points (points are shown in Fig. S1). The six points were surveyed by differential GPS measurements with respect to the Karlsruhe GP point. These points were easily identified in the 2006 photos (Fig. S1) and their positions were recovered and used for the 2007 mapping (Fig. 1*B*) as well. To directly compare the graphical results with the mapping of Hastenrath and Greischar (1) the control point coordinates were transformed to the New 1960 Arc datum on which the existing Kilimanjaro topographic map is based (Surveys and Mapping Division, Tanzania, 1977), using the best available transformation parameters. The Universal Transverse Mercator map projection (zone 37 S) is used.

Delineation of the boundaries of the ice bodies was straightforward, particularly on the summit plateau. The line of contact of the ice with the terrain was taken as the boundary. Where it was not visible, the top edge of the ice was used. Positions of the points defining the boundaries are estimated to be good to approximately half a meter in this region. On the steep southern slopes stereo viewing is difficult in some places and considerably larger errors in position are likely, but cannot be readily quantified. On featureless snow and ice surfaces, where there is little texture, stereoscopic perception is poor, making elevation measurements difficult and in some places impossible. The surface rendering varies greatly with the lighting. Stereoscopic perception of the surface is best in 2000 and worst in 2006.

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1. Hastenrath S, Greischar L (1997) Glacier recession on Kilimanjaro, East Africa, 1912–1989. *J Glaciol* 43:455–459.
2. Thompson LG, et al. (2002) Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* 298:589–593.
3. Cullen NJ, et al. (2006). Kilimanjaro Glaciers: Recent areal extent from satellite data and new interpretation of observed 20th-century retreat rates. *Geophys Res Lett*, 10.1029/2006GL027084.
4. Kaser G, Hardy DR, Mölg T, Bradley RS, Hyera TM (2004) Modern glacier retreat on Kilimanjaro as evidence of climate change: Observations and facts. *Int J Climatol* 24:329–339.
5. Mote PW, Kaser G (2007) The shrinking glaciers of Kilimanjaro: Can global warming be blamed? *Am Sci* 95:318–325.
6. Mölg T, Cullen NJ, Hardy DR, Winkler M, Kaser G (2009) Quantifying climate change in the tropical midtroposphere over East Africa from glacier shrinkage on Kilimanjaro. *J Climate* 22:4162–4182.

7. Mölg T, Hardy DR (2004) Ablation and associated energy balance on a horizontal glacier surface on Kilimanjaro. *J Geophys Res*, 10.1029/2003JD004338.
8. Mölg T, Hardy DR, Kaser G (2003) Solar-radiation maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *J Geophys Res*, 10.1029/2003JD003546.
9. Soden BJ, Schroeder SR (2000) Decadal variations in tropical water vapor: A comparison of observations and a model simulation. *J Climate* 13:13337–133341.
10. King'uyu SM, Ogallo LA, Anyamba EK (2000) Recent trends of minimum and maximum surface temperatures over Eastern Africa. *J Climate* 13:2876–2886.
11. Altmann J, Alberts SC, Altmann SA, Roy SB (2002) Dramatic change in the local climate patterns in the Amboseli basin, Kenya. *Afr J Ecol* 40:248–251.
12. Thompson LG, et al. (2006) Evidence of abrupt tropical climate change: Past and present. *Proc Natl Acad Sci USA* 103:10536–10543.
13. Kaser G, Cogley JG, Dyurgerov MB, Meier MF, Ohmura A (2006) Mass balance of glaciers and ice caps: Consensus estimates for 1961–2004. *Geophys Res Lett*, 10.1029/2006GL027511.
14. Kaser G, Noggler B (1996) Glacier fluctuations in the Ruwenzori Range (East Africa) during the 20th century: A preliminary report. *Z Gletscherkd Glazialgeol* 32:109–117.
15. Taylor RG, et al. (2006) Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature. *Geophys Res Lett*, 10.1029/2006GL025962.
16. Mölg T, Rott H, Kaser G, Fischer A, Cullen NJ (2006) Comment on ''Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature'' by Taylor RG, et al. *Geophys Res Lett*, 10.1029/2006GL027254.
17. Ramírez E, et al. (2001) Small glaciers disappearing in the tropical Andes: A case study in Bolivia: Glaciar Chacaltaya (16°S). *J Glaciol* 47:187–194.
18. Francou B, Vuille M, Wagnon P, Mendoza J, Sicart J-E (2003) Tropical climate change recorded by a glacier in the central Andes during the last decades of the 20th century: Chacaltaya, Bolivia, 16°S. *J Geophys Res*, 10.1029/2002JD002959.
19. Francou B, Ribstein P, Wagnon P, Ramirez E, Pouyaud B (2005) in *Global Change and Mountain Regions: An Overview of Current Knowledge*; eds Huber UM, Bugmann HKM, Reasoner MA (Springer, Dordrecht, The Netherlands), pp 197–204.
20. Klein AG, Kincaid JL (2006) Retreat of glaciers on Puncak Jaya, Irian Jaya, determined from 2000 and 2002 IKONOS satellite images. *J Glaciol* 52:65–79.
21. Yao T, Pu J, Lu A, Wang Y, Yu W (2007) Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau, China, and surrounding areas. *Arct Antarct Alp Res* 39:642–650.
22. Kehrwald NM, et al. (2008) Mass loss on Himalayan glacier endangers water resources. *Geophys Res Lett*, 10.1029/2008GL035556.
23. Santer BD, et al. (2008) Consistency of modelled and observed temperature trends in the tropical troposphere. *Int J Climatol* 28:703–1722.
24. Thorne PW, Parker DE, Christy JR, Mears CA (2005) Uncertainties in climate trends: Lessons from upper-air temperature records. *B Am Meteorol Soc*, 10.1175/BAMS-86-10-1437.
25. Bradley RS, Keimig FT, Diaz HF, Hardy DR (2009) Recent changes in freezing heights in the tropics with implications for the deglacierization of high mountain regions. *Geophys Res Lett*, doi:10.1029/2009GL037712.