The Shrinking Glaciers of Kilimanjaro: Can Global Warming Be Blamed?

The Kibo ice cap, a "poster child" of global climate change, is being starved of snowfall and depleted by solar radiation

Philip W. Mote and Georg Kaser

The shrinking glacier is an iconic image of global climate change. Rising temperatures may reshape vegetation, but such changes are visually subtle on the landscape; by contrast, a vast glacier retreated to a fraction of its former grandeur presents stunning evidence of how climate shapes the face of the planet. Viewers of the film *An Inconvenient Truth* are startled by paired before-and-after photos of vanishing glaciers around the world. If those were not enough, the scars left behind by the retreat of these mountain-grinding giants testify to their impotence in the face of something as insubstantial as warmer air.

But the commonly heard—and generally correct—statement that glaciers are disappearing because of warming glosses over the physical processes responsible for their disappearance. Indeed, warming fails spectacularly to explain the behavior of the glaciers and plateau ice on Africa's Kilimanjaro massif, just 3 degrees south of the equator, and to a lesser extent other tropical glaciers. The disappearing ice cap of the "shining mountain," which gets a starring role in the movie, is not an appropriate poster child for global climate change. Rather, extensive field work on tropical glaciers over the past 20 years by one of us (Kaser) reveals a more nuanced and interesting story. Kilimanjaro, a trio of volcanic cones that penetrate high into the cold upper troposphere, has gained and lost ice through processes that bear only indirect connections, if any, to recent trends in global climate.

Glacial Change

The fact that glaciers exist in the tropics at all takes some explaining. Atmospheric temperatures drop about 6.5 degrees Celsius per kilometer of altitude, so the air atop a 5,000-meter mountain can be 32.5 degrees colder than the air at sea level; thus, even in the tropics, high-mountain temperatures are generally below freezing. The climber ascending such a mountain passes first through lush tropical vegetation that gradually gives way to low shrubs, then grasses and finally a zone that is nearly devoid of vegetation because water is not available in liquid form. Tropical mountaintop temperatures vary only a little from season to season, since the sun is high in the sky at midday throughout the year. With temperatures this low, snow accumulates in ice layers and glaciers on Kilimanjaro, Mount Kenya and the Rwenzori range in East Africa, on Irian Jaya in Indonesia and especially in the Andean cordillera in South America, where 99.7 percent of the ice in tropical glaciers is found.

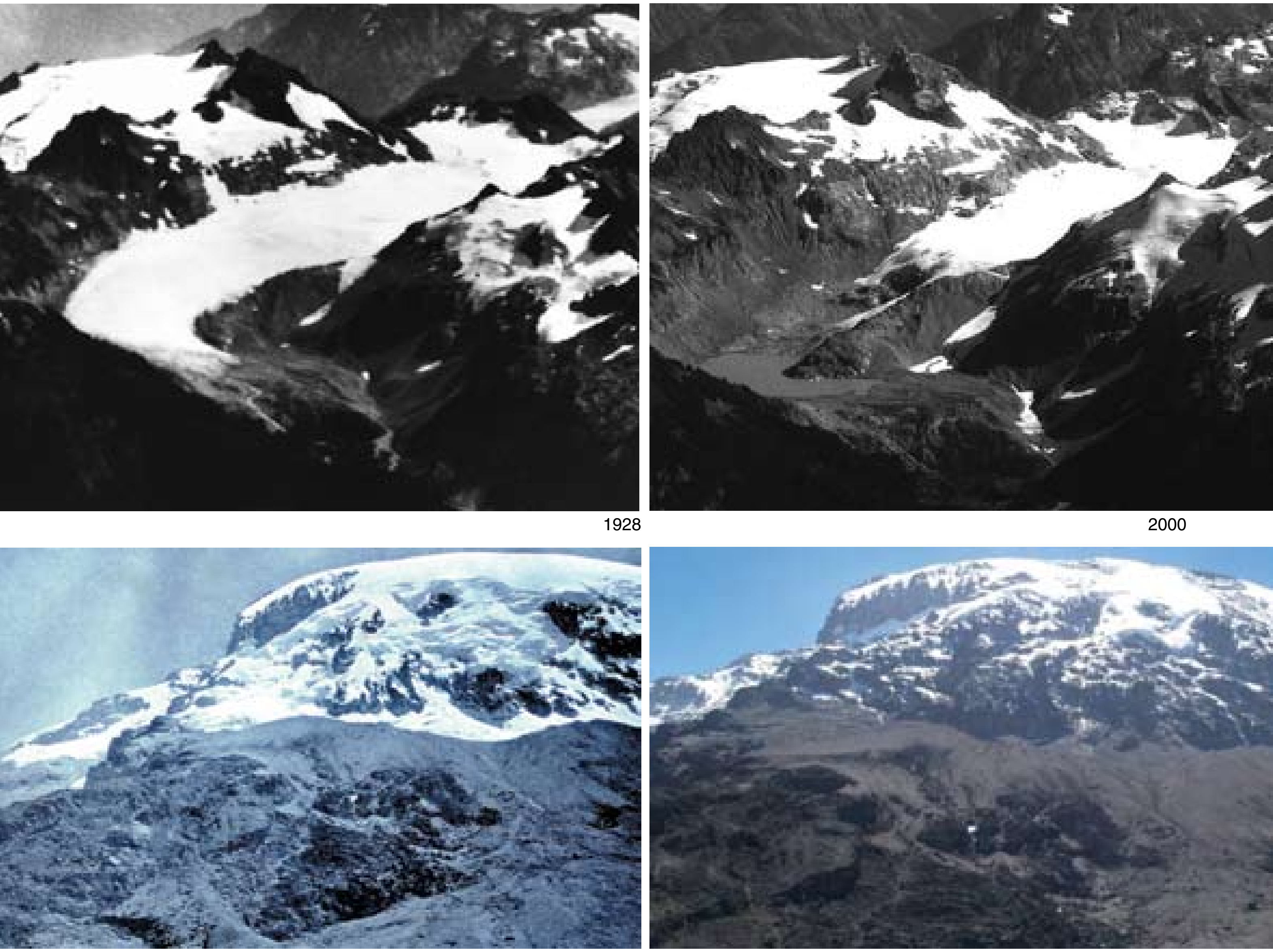
A simple, physically accurate way to understand the processes creating and controlling these and other glaciers is to think in terms of their *energy balance* and *mass balance*.

Mass balance is merely the difference between accumulation (mass added) and ablation (mass subtracted); in this case mass refers to water in its solid, liquid or vapor form. A glacier's mass is closely related to its volume, which can be calculated by multiplying its area by its average depth. When a glacier's volume changes, a change in length is usually the most obvious and well-documented evidence. Alaska's vanishing Muir Glacier, an extreme case, shrank more than 2 kilometers in length over the past half-century.

Glaciers never quite achieve "balance" but rather wobble like a novice tightrope walker. Sometimes a change in climate throws the glacier substantially out of balance, and its mass can take decades to reach a new equilibrium.

Added mass comes largely from the atmosphere, generally as snowfall but also as rainfall that freezes; in rare cases mass is added by *riming*, in which

Philip W. Mote is a research scientist at the University of Washington in the Climate Impacts Group, and an affiliate professor in the Department of Atmospheric Sciences. His research interests include Northwest climate and its effects on snowpack, stream flow and forest fires. A frequent public speaker, he has written about 60 scientific articles and edited a book on climate modeling published in 2000. He and Georg Kaser met when both served as lead authors for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Kaser, a glaciologist, is a professor at the University of Innsbruck in Austria. He has studied glaciers around the world, focusing on tropical glaciers, and has conducted field work on Kilimanjaro in Tanzania, Rwenzori in Uganda, the Cordillera Blanca in Peru and the European Alps. He is in the middle of a four-year term as president of the Commission for the Cryospheric Sciences of the International Union of Geodesy and Geophysics. He is coauthor of Tropical Glaciers, *published by Cambridge University Press in 2002. Address for Mote: CSES Climate Impacts Group, Box 354235, University of Washington, Seattle, WA 98195. Internet: philip@atmos.washington.edu*


1928

2000

1912

2006

Figure 1. Glaciers around the world have been retreating in recent decades. The most-studied glacier in North America may be the South Cascade Glacier in Washington state, where photographs taken by U.S. government scientists in 1928 and 2000 provide visible evidence of the glacier's loss of half its mass *(top)*. Solid evidence implicates global warming in the retreat of South Cascade and other glaciers in temperate zones. There is scant evidence, however, of a direct connection between current global climate trends and the shrinking of the ice cap atop Kilimanjaro in tropical East Africa *(bottom)*, despite its new role as a climate-change poster child. However hot the dry plains below, temperatures atop the massif remain below freezing; observations suggest the ice faces are being scoured by solar radiation rather than heated by warm air. Today a river of meltwater flows from the toe of South Cascade, whereas on Kilimanjaro observations of runoff are scant. In the lower right photograph, scattered white fields are from a recent snowfall; only the larger, closed white fields are glaciers. (Photographs courtesy of the U.S. Geological Survey Glacier and Snow Program *(top)* and Georg Kaser *(bottom right)*. Bottom left photograph by Edward Oehler.)

wind carries water droplets that are so cold that they freeze on contact.

The most obvious subtractive process is the runoff of melted water from a glacier surface. Another process that reduces glacial mass is *sublimation*, that is, the conversion of ice directly to water vapor, which can take place at temperatures well below the melting point but which requires about eight times as much energy as melting. Sublimation occurs when the moisture in the air is less than the moisture delivered from the ice surface. It is the process responsible for "freezer burn," when improperly sealed food loses moisture.

Air, Ice and Equilibrium

Melting, sublimation and the warming of ice require energy. Energy in the high-mountain environment comes from a variety of energy fluxes that interact in complex ways. The Sun is the primary energy source, but its direct effect is limited to daytime; other limiting factors are shading and the ability of snow to reflect visible light. Energy can nevertheless reach the glacier through *sensible-heat flux*—the exchange of heat between a surface and the air in contact with it, in this case heat taken directly from the air in contact with the ice—and via infrared emission from the atmosphere and land surface. Energy can also leave glacier ice in several ways: sensible-heat flux from the glacier to cold air, infrared emission from snow and ice surfaces, and the "latent heat" required for water to undergo a phase

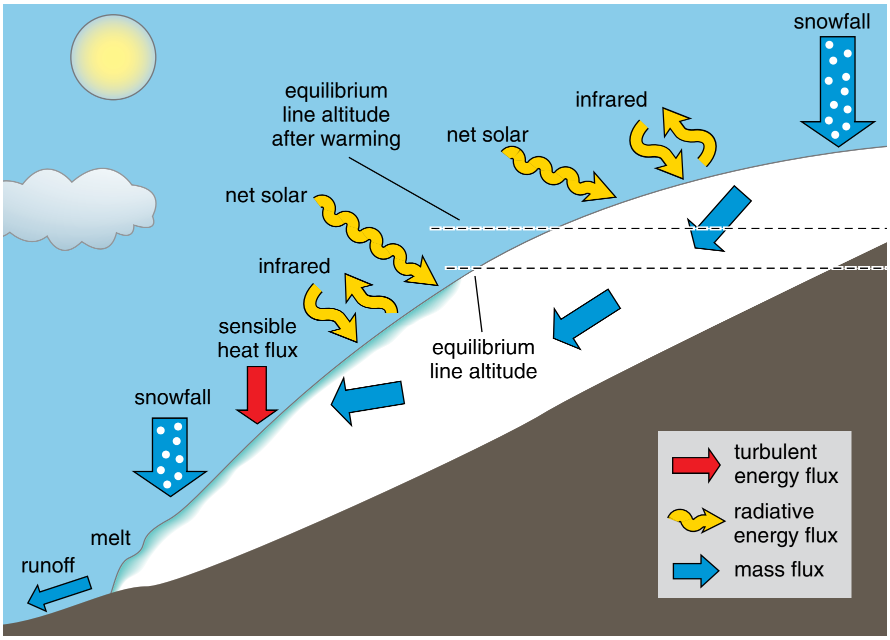


Figure 2. Most glaciers gain mass chiefly from snowfall and lose it primarily through the runoff of meltwater. A variety of factors can affect the mass balance of a glacier, and a glacier's location plays a major role in this balancing act. A typical midlatitude glacier (shown in the summertime in this cartoon) gains mass in its higher parts and loses it at the tongue. The glacier's equilibrium-line altitude is the point where these processes balance. Above this line, the glacier gains energy from solar radiation but loses it through infrared radiation toward the air. Below the line, sensible-heat transfer from warmer air into the glacier adds energy. With environmental warming, the equilibrium line moves up; inputs of sensible-heat flux and infrared radiation increase, with the result that melting is enhanced. Wind-driven water droplets, or rime, make small contributions to mass.

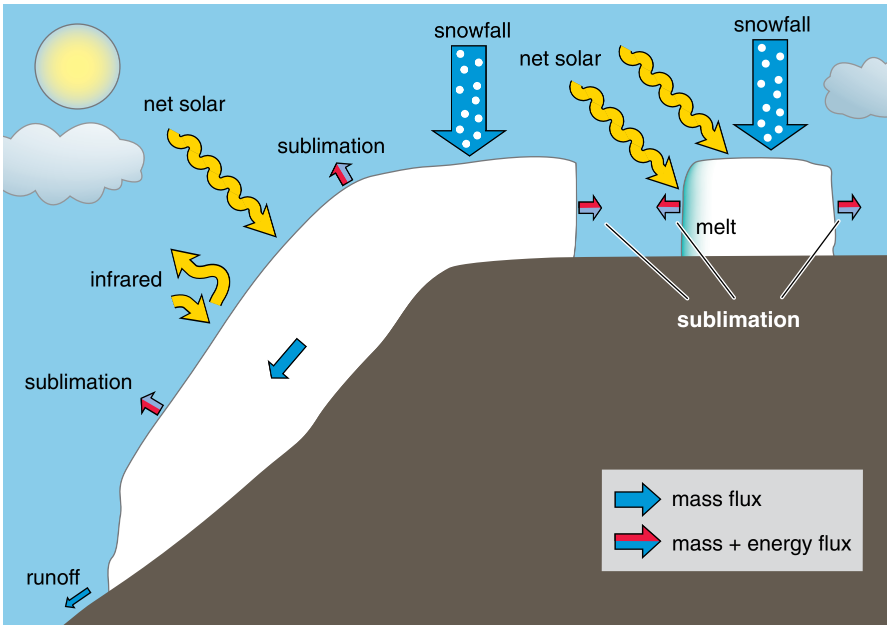


Figure 3. Kilimanjaro's location in a dry and cold tropical climate zone changes its mass-balance equation. In the tropics glaciers do not move between winter and summer, snowfall and melting; temperatures vary more from morning to afternoon than from season to season. The ice cap on Kilimanjaro consists of ice on the 5,700-meter-high flat summit, some with vertical edges, and several slope glaciers, mostly at altitudes where temperatures stay well below freezing and the major source of energy is solar radiation. Considerable infrared radiation is emitted from the glacier surface into the surrounding air, and the glaciers lose the most mass through sublimation—the direct conversion of ice to water vapor. Observers have seen only a trickle of meltwater.

change from solid to liquid (melting) or gas (sublimation).

Mountain glaciers accumulate snow at high altitudes, slide downhill—some at speeds approaching 2 meters a day—and melt at low altitudes in summertime. Some midlatitude glaciers reach sea level in part because of copious snowfall, exceeding the liquid equivalent of 3 meters per year.

Somewhere between the top and bottom of a glacier on a mountain slope, there is an elevation above which accumulation exceeds ablation and below which ablation exceeds accumulation. This is called the *equilibrium line altitude* or ELA. Rising air temperatures increase the sensible-heat flux from the air to the glacier surface and the infrared radiation absorbed by the glacier, so that melting is faster and is taking place over a larger portion of the glacier.

Thus rising temperatures also raise the equilibrium-line altitude. In latitudes with pronounced seasons, this expands the portion of the glacier that melts each summer and may even, in some cases, reduce the portion of the glacier that can retain mass accumulated in the winter. Virtually all glaciers in the world have receded substantially during the past 150 years, and some small ones have disappeared. Warming appears to be the primary culprit in these changes, and indeed glacial-length records have been used as a proxy for past temperatures, agreeing well with data from tree rings and other proxies.

In many respects, however, conditions are quite different for glaciers in the tropics, where temperature varies far more from morning to afternoon than from the coldest month to the warmest month. The most pronounced seasonal pattern in the tropics is the existence of one or two wet seasons, when glacial accumulation is greater and, owing to cloud cover, solar radiation is less.

Because there is almost no seasonal fluctuation in the ELA of tropical glaciers, a much smaller portion of the glacier lies below the ELA. That is, because the processes causing depletion of the glaciers operate almost every day of the year, they are effective over a much smaller area. This smaller area also means that the terminus or bottom edge of tropical glaciers tends to respond more quickly to changes in the mass balance.

An additional important distinction among tropical glaciers divides wet and dry regimes. In wet regimes, changes in air temperature are important in mass-balance calculations, but for dry regimes like East Africa, changes in atmospheric moisture are more important. Connections between such changes and global increases in greenhouse gases are more tenuous in tropical regimes. Year-to-year variability and longer-term trends in the seasonal distribution of moisture are influenced by the surface temperatures of the tropical oceans, which, in turn, are influenced by global climate. On many tropical glaciers, both the direct impact of global warming and the indirect one—changes in atmospheric moisture concentration—are responsible for the observed mass losses. The mere fact that ice is disappearing sheds no light on which mechanism is responsible. For most glaciers, detailed observations and measurements are missing, adding to the difficulty of distinguishing between the two agents.

The Shining Mountain

What about Kilimanjaro? Tropical glacier–climate relations are different, but among them Kilimanjaro's glacial regime is unique. Its ice consists of an ice cap (up to 40 meters thick) sitting on the relatively flat summit plateau of its tallest volcanic peak, Kibo, about 5,700 to 5,800 meters above sea level and, below this, several slope glaciers. The slope glaciers extend down to about 5,200 meters (one, in a shady gully, extends to 4,800 meters). The ice cap is too thin to be deformed, and the plateau is too flat to allow for gliding. The summit's flanks are plenty steep—with angles averaging 35 degrees—but the slope glaciers move little compared with midlatitude, temperate glaciers. The slope glaciers gain and lose mass along their inclined surfaces. The plateau ice, by contrast, has two faces that each interact quite differently with the atmosphere and therefore with climate: near-horizontal surfaces and near-vertical cliffs, the latter forming the edges of the plateau ice.

What factors may explain the decline in Kilimanjaro's ice? Global warming is an obvious suspect, as it has been clearly implicated in glacial declines elsewhere, on the basis of both detailed mass-balance studies (for the few glaciers with such studies) and correlations between glacial length and air temperature (for many other glaciers). Rising air temperatures change the surface energy balance by enhancing sensible-heat transfer from atmosphere to ice, by increasing downward infrared radiation and finally by raising the ELA and hence expanding the area over which loss can occur. The first and only paper asserting that the glacier shrinkage on Kibo was associated with rising air temperatures was published in 2000 by Lonnie G. Thompson of Ohio State University and co-authors.

Another possible culprit is a decrease in accumulation combined with an increase in sublimation, both possibly driven by a change in the frequency and quantity of cloudiness and snow-

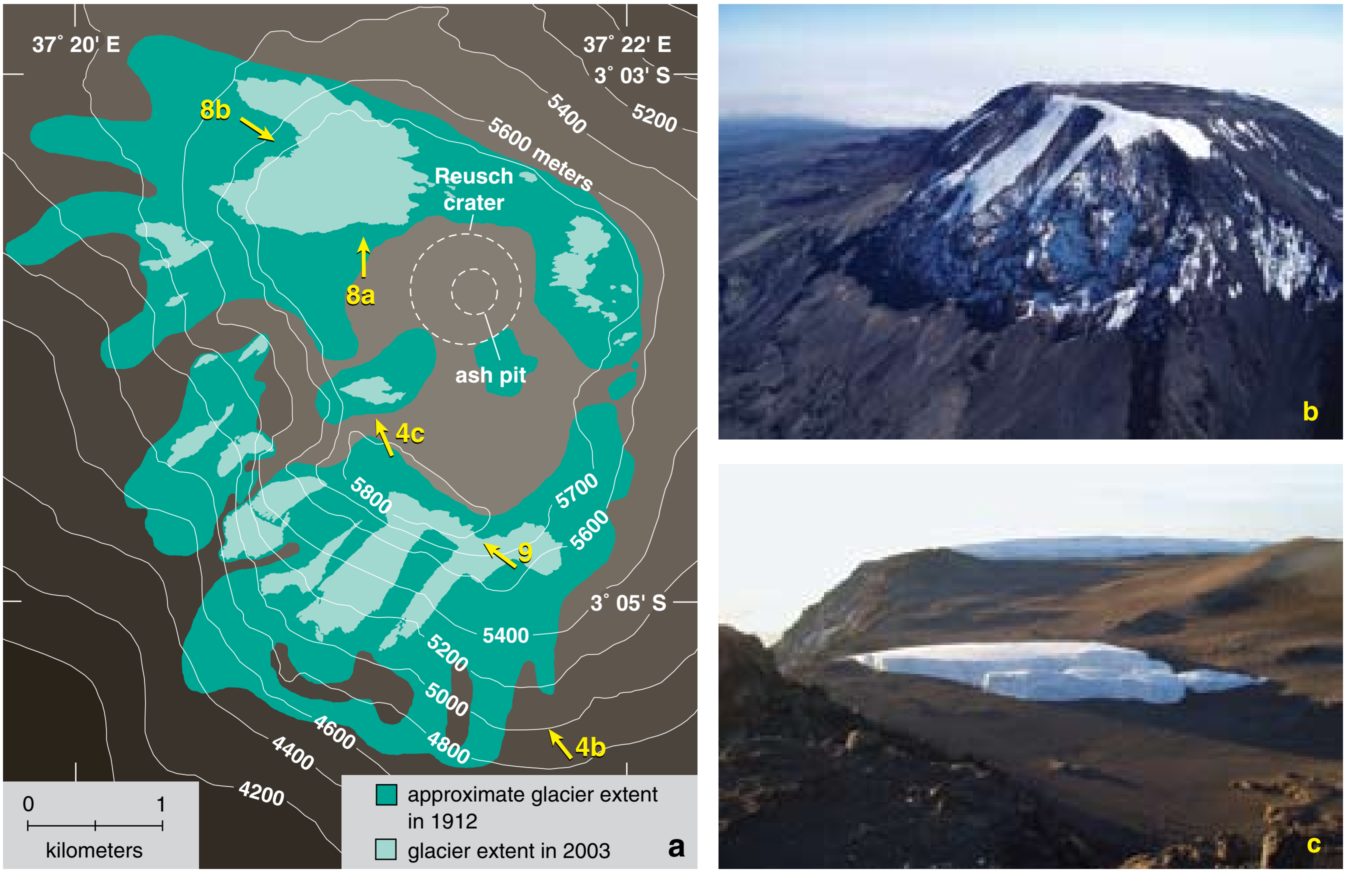


Figure 4. Kilimanjaro's ice is confined to its tallest volcanic peak, Kibo. The glaciers were explored in the late 19th century and surveyed in 1912, nearly a quarter-century before Ernest Hemingway endowed them with literary fame by titling a story "The Snows of Kilimanjaro." In 1912 the glaciers totaled 12.1 square kilometers in area; by 2003 that area had declined to 2.5 square kilometers *(a)*. The most rapid shrinking may have taken place between 1912 and 1953, when the area measured about 7 square kilometers. Arrows locate the vantage points of the two photographs at right, an aerial view of Kibo from the southeast *(b)* and a view of the plateau ice from south-southeast with the Northern Ice Field in the background. Additional arrows locate the views in Figures 8 and 9. (Map adapted from Cullen *et al.* 2006; photographs courtesy of Georg Kaser.)

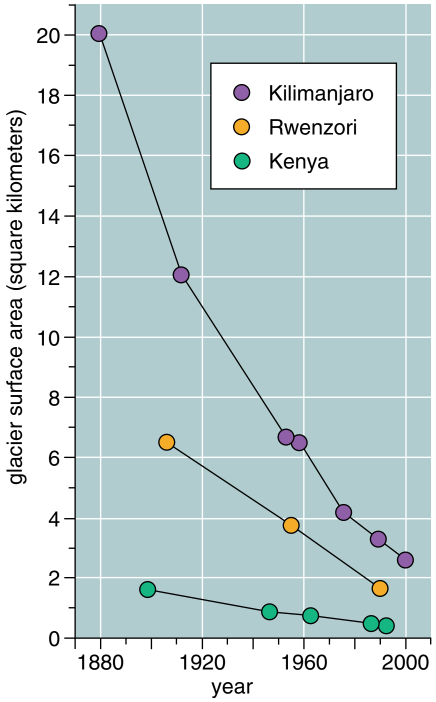


Figure 5. Surface-area measurements indicate that all the major glaciers of tropical East Africa (equator, *dotted line*) are shrinking. The pacing of these declines is at odds with the pace of global temperature change. Worldwide, many glaciers that are now in rapid retreat came into equilibrium or even advanced around the 1970s. The Kilimanjaro ice cap, by contrast, appears to have shrunk especially rapidly during the first half of the 20th century. (Graph adapted from Kaser *et al.* 2004.)

fall. This argument traces its roots to 19th-century European explorers, and has been substantially improved after field work by Kaser, Douglas K. Hardy of the Climate System Research Center at the University of Massachusetts, Amherst, Tharsis Hyera and Juliana Adosi of the Tanzania Meteorological Agency and others.

In 2001 Hardy had invited Kaser to join him and some television journalists in the filming of a documentary on the ice retreat on Kibo. For about a year and a half, Hardy's instruments had been deployed on the Kibo summit, measuring weather; Kaser had been studying tropical glaciers for almost a decade and a half. The team set up tents just below one of the most impressive ice cliffs that delineates the Northern Ice Field on its southern edge. During a full five days and nights on the plateau, we observed the ice and discussed the mechanisms that drive the changes, a discussion stimulated from time to time by penetrating questions from the two journalists. Kibo's volcanic ash provided a drawing board, and a ski pole served as the pencil as a picture of the regime of the glaciers on Kibo grew clearer. Thus was formed the basic hypothesis that still drives our research and that our subsequent field measurements of mass and energy balance have largely confirmed, one in which local air temperature and its changes would play only a minor role. Here is the evidence.

Time and Temperature

Observations of Kilimanjaro's ice from about 1880 to 2003 allow us to quantify changes in area but not in mass or volume. The early European explorers Hans Meyer and Ludwig Purtscheller were the first to reach the summit in 1889. Based on their surveys and sketches, but mainly from moraines identified with aerial photographs, Henry Osmaston reconstructed (in 1989) an 1880 ice area of 20 square kilometers. In 1912, a precise 1:50,000 map based on terrestrial photogrammetry done by Edward Oehler and Fritz Klute placed the area at 12.1 square kilometers. By 2003 that area had declined to 2.5 square kilometers, a shrinkage of almost 90 percent. Much of that decline, though, had already taken place by 1953, when the area was 6.7 square kilometers (down 66 percent from 1880). Over the same period, ice movement has been almost nil on the plateau and slight on the slopes. There are indications that the slope glaciers at least are coming into equilibrium.

This pacing of change is at odds with the pace of temperature changes globally, which have been strongly upward since the 1970s after a period of stasis. Other glaciers share this pacing, with many coming into equilibrium or even advancing around the 1970s before beginning a sharp retreat.

Temperature trends are difficult to evaluate, owing to the paucity of relevant measurements, but taken together the data presented in the 2007 report from the IPCC (Intergovernmental Panel on Climate Change) suggest little trend in local temperature during the past few decades. In the East African highlands far below Kilimanjaro's peaks, temperature records suggest a warming of 0.5–0.8 degree during 1901–2005, a nontrivial amount of

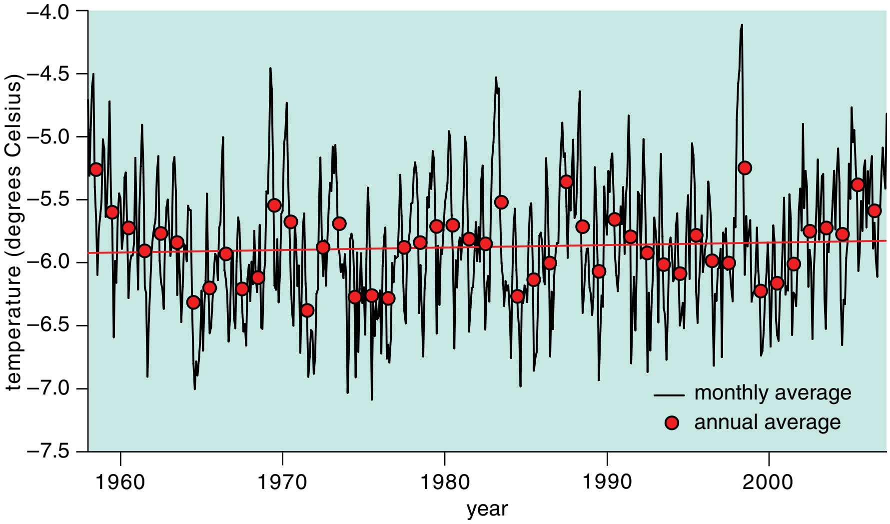


Figure 6. Only sparse temperature records are available for the area around Kilimanjaro. However, there now exists a record of weather-balloon readings at the summit altitude; these have been amplified by "reanalysis," the use of a global dynamical model capable of generating consistent fields of temperature where observations are lacking. The resulting data indicate that monthly average temperatures around the Kilimanjaro summit have fluctuated between –4 and –7 degrees Celsius since 1958; no significant warming trend is seen when a line is fitted to these points. (Data from the National Centers for Environmental Prediction/National Center for Atmospheric Research; compiled by Doug Hardy, University of Massachusetts, Amherst.)

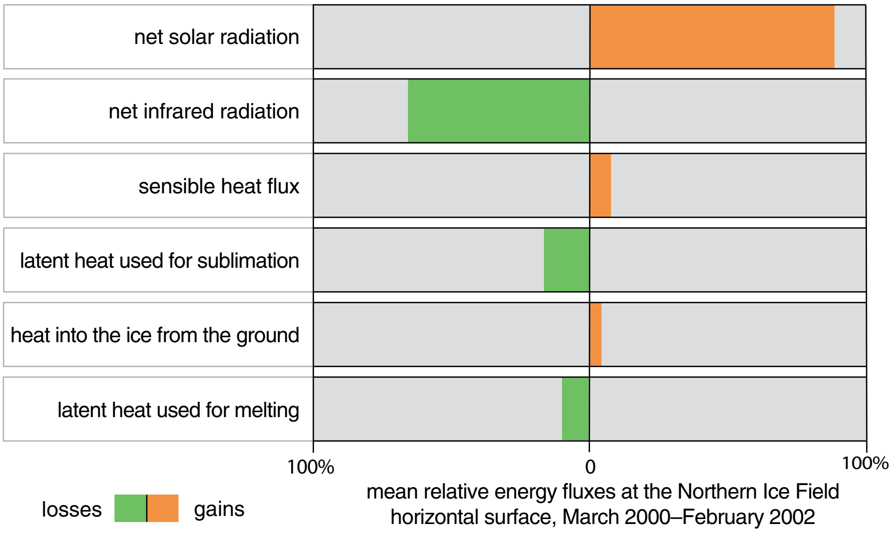


Figure 7. Instruments have recorded the energy fluxes toward and from the surface of the Kibo summit glacier. Radiative energy fluxes provide the basis of heat exchange. The net infrared flux is strongly negative, because infrared radiation is controlled by temperature, and the emitting temperature of the atmosphere is much lower than that of the glacier surface. The third largest flux is the latent heat that leaves the surface with sublimation. The energy used for melting is less than half as large, and meltwater refreezes in lower ice layers. Other fluxes make very small contributions. (Adapted from Mölg and Hardy 2004.)

warming but probably larger than the warming at Kibo's peak. For the free troposphere, a deep layer including Kibo's peak, the warming rate during the period 1979–2004 for the zone 20 degrees latitude north and south of the equator was less than 0.1 degree per decade—smaller than the surface trend for that time and not statistically different from zero. Averages over a deep layer of the atmosphere, however, may be a poor estimate of the warming at Kilimanjaro's peak, although it has been argued that the warming must be nearly the same at all longitudes in the tropics, given that rotational effects are small, imposing strong dynamical constraints.

Focusing on measurements of air temperatures at the 500-millibar air-pressure level (roughly 5,500 meters altitude) from balloons, one paper suggests a warming trend in the tropical middle troposphere from about 1960 to 1979, followed by cooling from 1979 to 1997, although this study has not been updated.

Two of the data sets used to derive the tropical averages above are "reanalysis" data sets, in which observations are fed into a global dynamical model, thereby providing dynamically consistent fields of temperature, winds and so on, even where there are no observations. At the reanalysis point closest to Kilimanjaro's peak, there seems to be no trend since the late 1950s. But like the balloon and satellite data, the reanalysis data can be unsuitable for documenting trends over time .

When pieced together, these disparate lines of evidence do not suggest that any warming at Kilimanjaro's summit has been large enough to explain the disappearance of most of its ice, either during the whole 20th century or during the best-measured period, the last 25 years.

Stuck in the Freezer

Another important observation is that the air temperatures measured at the altitude of the glaciers and ice cap on Kilimanjaro are almost always substantially below freezing (rarely above –3 degrees). Thus the air by itself cannot warm ice to melting by sensible-heat or infrared-heat flux: On the occasions when melting takes place, it is produced by solar radiation in conditions of very light wind, which allows a warm layer of air to develop just next to the ice.

A related line of evidence concerns the shape and evolution of ice. Stunning vertical walls of astonishing height (greater than 40 meters in places) tower over the visitor to Kibo's summit. These edges cannot grow horizontally but lose mass constantly to ablation (primarily to sublimation and intermittently to melting) when they are exposed to the sun—even when the air temperature is below freezing. Once developed, the near-vertical edges will retreat until the ice is gone, since no snow can accumulate on these walls.

The careful observer notes another striking fact about these walls: They are predominantly oriented in the east-west direction. This too implicates solar radiation, whose intensity is modulated by a seasonal and daily pattern of cloudiness: The daily cycle of deep convection over central Africa means that afternoons, when the Sun is to the west, are typically cloudy. The equinox seasons when the Sun is overhead are also cloudy, whereas when the Sun is to the south or north (solstices), the summit is typically cloud-free. For the same reason, the edges of the ice are retreating more slowly on the west, southwest and northwest sides.

The role of solar radiation in shaping the ice edges is evident in other features as well. As the ice retreats horizontally, it can leave behind knife-thin vertical remnants that eventually become so thin that they fall over and disintegrate. Like other explorers who came before them, Kaser and Hardy also noted the sculpted features called *penitentes* in the Kibo ice cap on several occasions. Penitentes are seen also in many places in the Andes and the Himalaya, where they are sometimes much larger. These finger-like features arise when initial irregularities in a flat surface result in the collection of dust in pockets, which accelerates melting in those places by enhancing absorption of solar radiation. The cups between the *penitentes* are protected from ventilation even as wind brushing the peaks of the developing spires enhances sublimation, which cools the surface.

If infrared radiation and sensible heat transfer were the dominant factors, these sculpted features would not long survive. Solar radiation and sublimation are sculptors; infrared radiation and sensible heat transfer are diffuse, coming equally from all directions, and so they are smoothers. The prevalence of sculpted features on Kilimanjaro's peak provides strong evidence against the role of smoothers, which are energetically closely related to air temperature.

Mass in the Balance

What is known about the mass balance of Kibo's ice? Detailed studies of mass and energy fluxes have shown that the mass balance on Kibo's horizontal surfaces is driven by the occurrence or lack of frequent and abundant snowfall. On Kilimanjaro, Hardy has measured the annual layering of snow

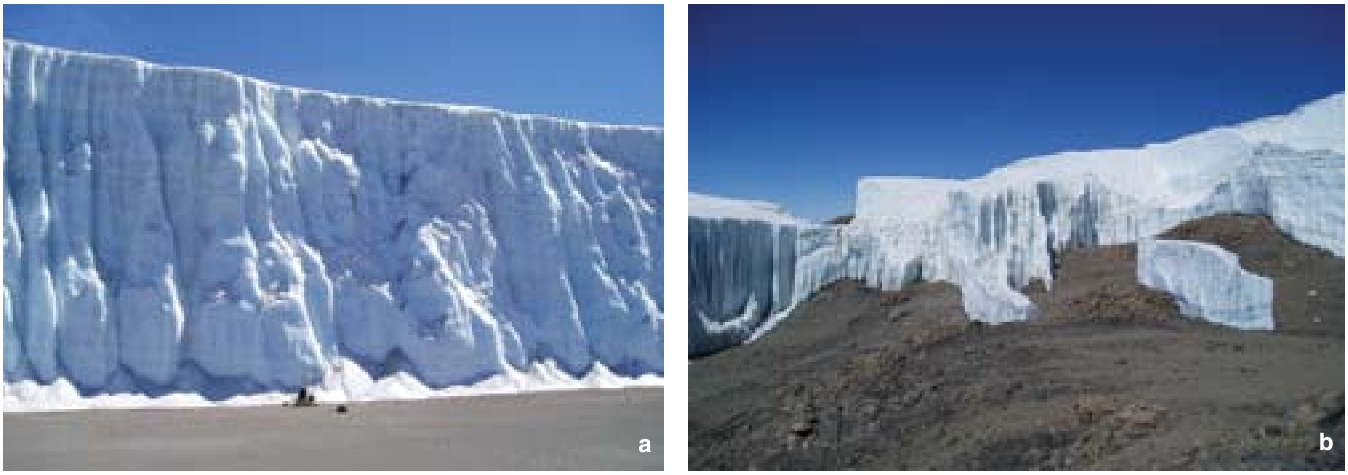


Figure 8. Visitors to the summit of Kilimanjaro are greeted by ice cliffs as tall as 40 meters in places *(a)*. (For scale, note the scientist checking instruments at the base of a 30-meter wall.) The south face of the Northern Ice Field, shown here, retreats when the Sun is to the south; the north face retreats when the Sun is to the north. A daily cycle of deep convection over central Africa makes most afternoons, when the Sun is to the west, cloudy, and the west, southwest and northwest edges are retreating more slowly. This pattern supports the notion that solar radiation is the culprit. The shrinking leaves separated ice features *(b)* that eventually become small enough to fall over. (Photographs courtesy of Georg Kaser.)

directly since 2000 using snow stakes. These measurements show that the horizontal surface of the mountain's Northern Ice Field has experienced two years of near-neutral mass balance. The largest net gain observed was in 2006 when the calendar year over East Africa ended with exceptional heavy and extended rains, associated with sea-surface temperature anomalies over the Indian Ocean, and snow blanketed much of the summit of Kilimanjaro for several months.

Obviously snowfall is the main way to increase the mass of ice, but snowfall also has a role in the energy balance, one made even more important by the prominent role of solar radiation. The loss side of the balance is very much affected by the amount and even more by the frequency of snowfall: The surface of aged or polluted snow is dark and absorbs considerably more energy from solar radiation than does a white surface of fresh snow. When there is more energy available to a glacier's surface, sublimation increases. But even in below-freezing air temperatures, the same energy can increase melting if there is no wind. Meltwater from the surface is thought to be refrozen in lower ice layers; thus such melting does not necessarily constitute a loss for the ice cap as a whole. Indeed, an observer watching a slope glacier will rarely see more than a trickle of meltwater from the toe.

Figure 9. Sculpted finger-like features called "penitentes" are a striking feature on the Kibo ice cap, providing further evidence that warming is not at work there. Solar radiation and sublimation tend to create such features; infrared radiation and sensible-heat transfer smooth them. Nicolas Cullen of the University of Otago in New Zealand is silhouetted in this photograph taken by Georg Kaser during a recent field season.

Comparison of historic photographs indicates that over the past century the thinning of the plateau ice has amounted to perhaps 10 meters—a rate of loss that can be explained by snowfall insufficient to balance sublimation. The observed reduction of the ice's surface area has taken place mainly at the vertical edges, however, which is not explained by snowfall patterns.

The mass balance of the slope glaciers is somewhat different from that of the plateau ice. Retreating midlatitude glaciers typically lose most mass below the ELA and little or none above. The Kibo slope glaciers, though, show shrinkage at both top and bottom. Their history suggests that in 1900 they were already far from equilibrium, but their retreat appears to be slowing; that and their convex shape suggests that they are approaching a new smaller equilibrium between the (relatively constant) loss term and the smaller accumulation term.

Glaciers and Global Climate

The observations described above point to a combination of factors other than warming air—chiefly a drying of the surrounding air that reduced accumulation and increased ablation—as responsible for the decline of the ice on Kilimanjaro since the first observations in the 1880s. The mass balance is dominated by sublimation, which requires much more energy per unit mass than melting; this energy is supplied by solar radiation.

These processes are fairly insensitive to temperature and hence to global warming. If air temperatures were eventually to rise above freezing, sensible-heat flux and atmospheric longwave emission would take the lead from sublimation and solar radiation. Since the summit glaciers do not experience shading, all sharp-edged features would soon disappear. But the sharp-edged features have persisted for more than a century. By the time the 19th-century explorers reached Kilimanjaro's summit, vertical walls had already developed, setting in motion the loss processes that have continued to this day.

An additional clue about the pacing of ice loss comes from the water levels in nearby Lake Victoria. Long-term records and proxy evidence of lake levels indicate a substantial decline in regional precipitation at the end of the 19th century after some considerably wetter decades. Overall, the historical records available suggest that the large ice cap described by Victorian-era explorers was more likely the product of an unusually wet period than of cooler global temperatures.

If human-induced global warming has played any role in the shrinkage of Kilimanjaro's ice, it could only have joined the game quite late, after the result was already clearly decided, acting at most as an accessory, influencing the outcome indirectly. The detection and attribution studies indicating that human influence on global climate emerged some time after 1950 reach the same conclusion about East African temperature far below the peak.

The fact that the loss of ice on Mount Kilimanjaro cannot be used as proof of global warming does not mean that the Earth is not warming. There is ample and conclusive evidence that Earth's average temperature has increased in the past 100 years, and the decline of mid- and high-latitude glaciers is a major piece of evidence. But the special conditions on Kilimanjaro make it unlike the higher-latitude mountains, whose glaciers are shrinking because of rising atmospheric temperatures. Mass- and energy-balance considerations and the shapes of features all point in the same direction, suggesting an insignificant role for atmospheric temperature in the fluctuations of Kilimanjaro's ice.

It is possible, though, that there is an indirect connection between the accumulation of greenhouse gases and Kilimanjaro's disappearing ice: There is strong evidence of an association over the past 200 years or so between Indian Ocean surface temperatures and the atmospheric circulation and precipitation patterns that either feed or starve the ice on Kilimanjaro. These patterns have been starving the ice since the late 19th century—or perhaps it would be more accurate to say simply reversing the binge of ice growth in the third quarter of the 19th century. Any contribution of rising greenhouse gases to this circulation pattern necessarily emerged only in the last few decades; hence it is responsible for at most a fraction of the recent decline in ice and a much smaller fraction of the total decline.

Is Kilimanjaro's ice cap doomed? It may be. The high vertical edges of the remaining ice make a horizontal expansion of the ice cap more difficult. Although new snowfall on the ice can accumulate over the course of months or years, new snowfall on the rocky plateau usually sublimates or melts in a matter of days (with the notable exception of the period of several months of continuous snow cover in late 2006 and into 2007), partly because thin snow above dark rock cannot long survive as the loss processes reduce the reflective snow and expose the sunlight-absorbing rock. If the cap ice were much thicker and shaped in a way that allowed ice to creep outward, gentle slopes could develop along the edges; new snow would be buffered against loss and would accumulate. But steep edges do not allow such expansion.

Imagine, though, a scenario in which the atmosphere around Kilimanjaro were to warm occasionally above 0 degrees. Sensible and infrared heating of the ice surface would gradually erode the sharp corners of the ice cap; gentler slopes would quickly develop. If, in addition, precipitation increased, snow could accumulate on the slopes and permit the ice cap to grow. Ironically, substantial global warming accompanied by an increase in precipitation might be one way to save Kilimanjaro's ice. Or substantially increased snowfall, like the 2006–07 snows, could blanket the dark ash surface so thickly that the snow would not sublimate entirely before the next wet season. Once initiated, such a change could allow the ice sheet to grow. If the Kibo ice cap is vanishing or growing, reshaping itself into something different as you read this, glaciology tells us that it's unlikely to be the first or the last time.

Bibliography

Cullen, N. J., T. Mölg, G. Kaser, K. Hussein, K. Steffen and D. R. Hardy. 2006. Kilimanjaro Glaciers: Recent areal extent from satellite data and new interpretation of observed 20th century retreat rates. *Geophysical Research Letters* 33:L16502. doi:10.1029/2006GL027084

Gaffen, D. J., B. D. Santer, J. S. Boyle, J. R. Christy, N. E. Graham and R. J. Ross. 2000. Multidecadal changes in the vertical temperature structure of the tropical troposphere. *Science* 287:1242–1245.

Kaser, G. 1999: A review of modern fluctuations of tropical glaciers. *Global and Planetary Change* 22 (1–4):93–103.

Kaser, G., D. R. Hardy, T. Mölg, R. S. Bradley and T. M. Hyera. 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts. *International Journal of Climatology* 24:329–339. doi:10.1002/joc.1008

Mölg, T., D. R. Hardy and G. Kaser. 2003. Solar-radiation-maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *Journal of Geophysical Research* 108(D23):4731. doi:10.1029/2003JD003546

Mölg, T., and D. R. Hardy, 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research* 109:D16104.

Oerlemans, J. 2005. Extracting a climate signal from 169 glacier records. *Science* 308:675–677.

Osmaston, H. 1989. Glaciers, glaciation and equilibrium line altitudes on Kilimanjaro. In *Quaternary and Environmental Research on East African Mountains*, ed. W. C. Mahaney. Rotterdam: Brookfield, pp. 7–30.

Thompson, L. G., E. Mosley-Thompson and K. A. Henderson. 2000. Ice-core paleoclimate records in tropical South America since the Last Glacial Maximum. *Journal of Quaternary Science* 15:377–394.

Thompson, L. G., *et al.* 2002. Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa. *Science* 298:589–593.

Trenberth, K. E., *et al.* 2007. Observations: Surface and atmospheric climate change. Chapter 3 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, U.K., and New York: Cambridge University Press.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/Issue TOC/issue/981