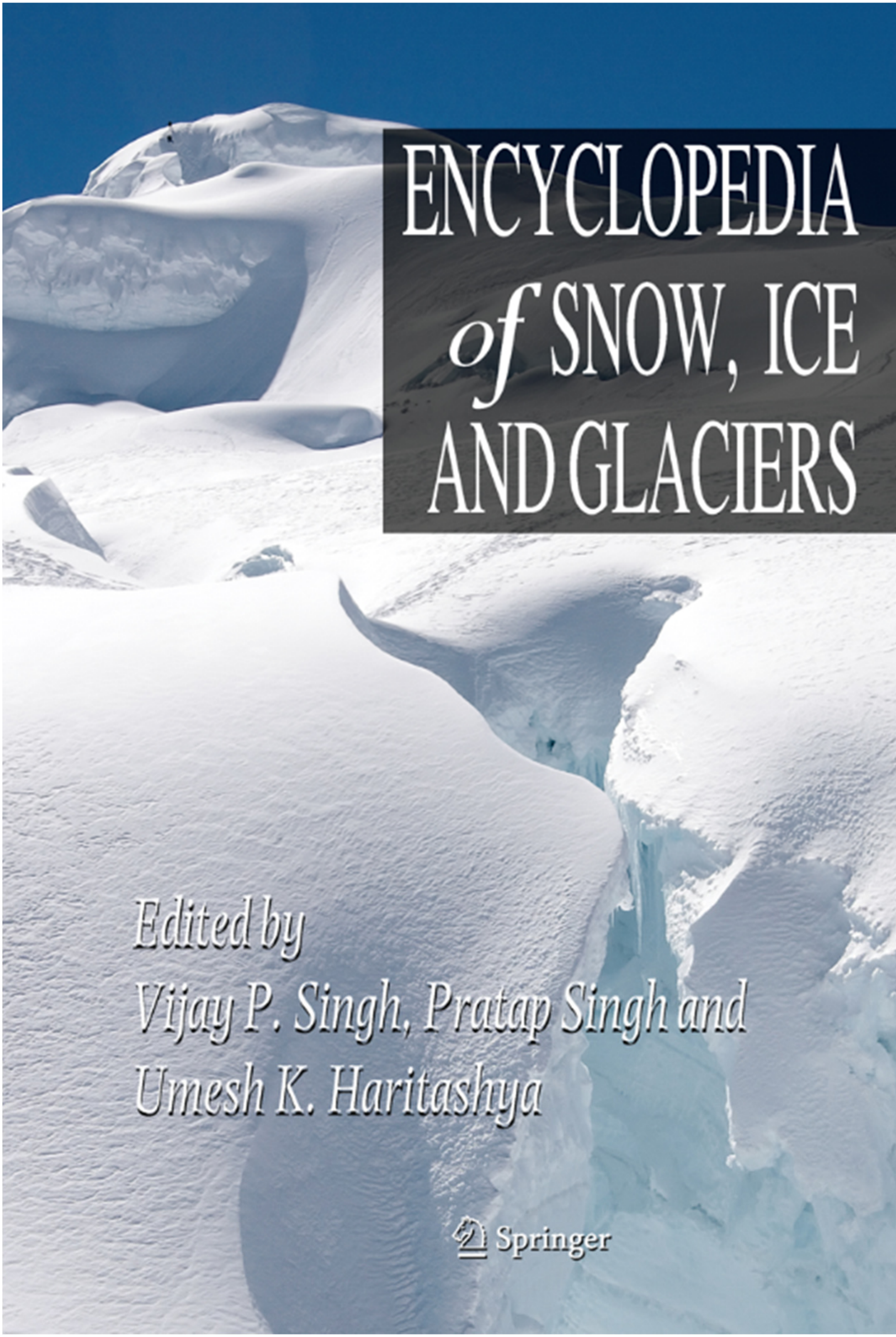

ENCYCLOPEDIA of SNOW, ICE AND GLACIERS

Edited by
Vijay P. Singh, Pratap Singh and
Umesh K. Haritashya

Springer

ENCYCLOPEDIA of EARTH SCIENCES SERIES

Encyclopedia of Earth Sciences Series

ENCYCLOPEDIA OF SNOW, ICE AND GLACIERS

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and in South America as well as in Alaska, it is wind known as a Williwaw.

Alpine valleys produce their own local wind systems as a result of thermal differences. The cold air slides down the slope under gravity during night. The radiative cooling of the ground surface under clear and calm conditions during night provides colder air near the surface. The nighttime downslope movement of the colder air is referred to as katabatic winds. The anabatic wind is developed prior to the daytime, whereas katabatic drainage is developed in the night. The katabatic winds usually flow gently downslope with low speed, but greater speeds are also experienced when the depth of cold air is large and the slope is higher.

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KILIMANJARO

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Definition

Kilimanjaro is Africa's highest mountain (5,895 m), located in northern Tanzania just south of the Kenya border (3°4′S; 37°21′E). At the seasonally snow-covered summit, the extent of glacier ice is now less than 2 km^2, roughly half of that remaining on the continent.

Overview

The cryosphere is sparsely represented in Africa, primarily on a small handful of the continent's highest mountains. Among these is Kilimanjaro, the "white roof of Africa," whose glaciers have achieved notoriety far out of proportion to their size (miniscule), importance as a water resource (negligible), or potential contribution to sea-level rise (zero). Yet, Kilimanjaro's summit mantle of *Snow* (qv) and *Ice* (qv) is starkly beautiful, and thus among the mountain's most fascinating, distinctive, and best-known attributes. Thousands of international visitors are attracted annually, bringing valuable tourism revenue to Tanzania.

Geographic setting

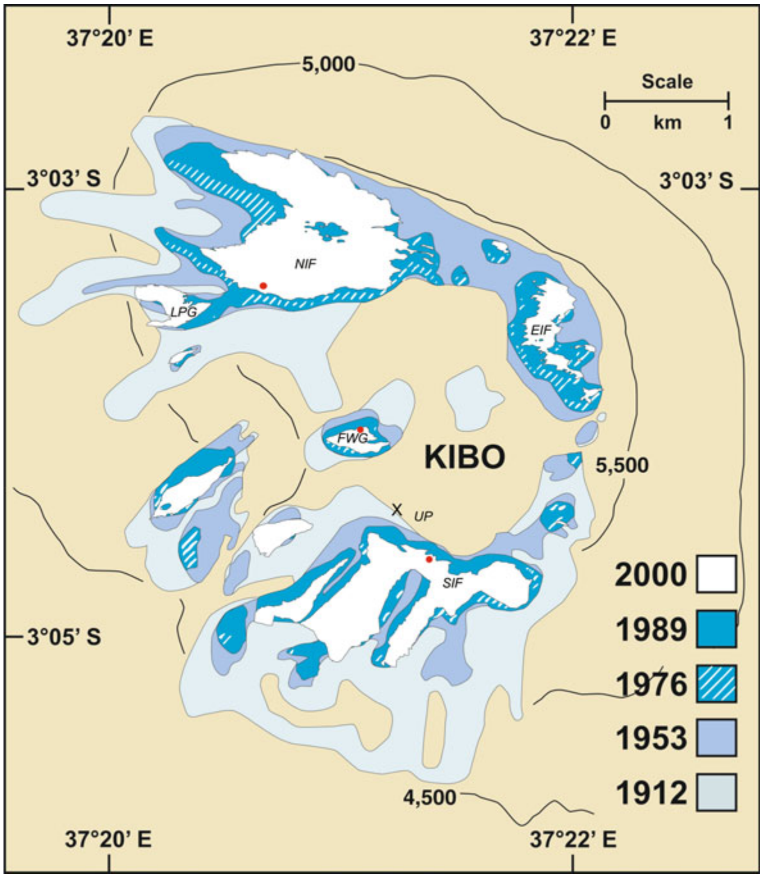
Kilimanjaro is a massive, dormant volcano in Tanzania, built up of both lava flows and pyroclastic material, situated roughly equidistant (~300 km) south of the Equator and west of the Indian Ocean. Three primary volcanic centers are thought to have been active sequentially since the Pleistocene, which together form the Kilimanjaro massif: Shira (4,005 m), Mawenzi (5,140 m), and Kibo (5,895 m). At the apex of Kibo is a relatively flat caldera measuring 1.9 by 2.7 km (Figure 1); Uhuru Peak is the highest point along the southern scarp, ~180 m above the caldera floor.

History of cryospheric research on Kilimanjaro

The earliest scientific discussion of snow and ice on Kilimanjaro began with the initial European "discovery" of the snowcap by Johannes Rebmann in 1848. English Geographers were incredulous, and dismissed Rebmann's report for more than a decade (Meyer, 1891). Hans Meyer climbed nearly to the crater rim in 1887, reaching the summit 2 years later on 6 October 1889 (Meyer, 1891). Additional European scientists soon reached the summit area and published their qualitative findings. Logistical constraints rendered ascents and fieldwork considerably more difficult than at present, yet virtually every account describes features and processes not unlike those of today. Most also discuss the decreasing extent of ice, and many predict disappearance – within decades – of either individual glaciers or all of the mountain's ice.

Mid-twentieth-century perspectives on Kibo's summit and slope glaciers were provided by Humphries (1959), Downie and Wilkinson (1972), and Hastenrath (1984). Henry Osmaston (1989) then published an analysis of glacier *Moraine* (qv) as mapped from aerial photographs, which for the first time quantified the nineteenth century extent of glaciers on the mountain. Hastenrath and Greischar (1997) built upon Osmaston's work and provided the first cartographic documentation of ice recession. Thereafter, a resurgence of research on Kibo began in February 2000 with *Ice Core* (qv) drilling, aerial photography, and installation of an automated weather station (AWS) on the Northern Icefield (Hardy, 2002; Thompson et al., 2002). A *Network of Stakes* (qv) has expanded steadily since 2000 to represent most of the glacierized area at the summit, and two additional AWS are now operating on summit glaciers (Mölg et al., 2008).

Today, as during the nineteenth century, snow and ice on Kilimanjaro are again controversial. A new ice-extent map released in 2001 was accompanied by a prediction that the glaciers could disappear within 20 years (Irion, 2001). Kilimanjaro was quickly employed to symbolize the impacts of global warming (e.g., Greenpeace, 2001). However, cautious statements by scientists such as Kaser et al. (2004, p. 337) that "... mass loss on the summit ... is little affected by air temperature," or Mote and Kaser (2007, p. 325) that "... loss of ice on Mount Kilimanjaro cannot be used as proof of global warming," were eagerly



Kilimanjaro, Figure 1 Kibo peak of Kilimanjaro, with remnants of the *ice cap* (qv) that once encircled the summit. The crater is the area surrounded by ice and labeled "KIBO." Contours are in meters. Solid circle symbols indicate location of 2000 ice-core drilling sites (Thompson et al., 2002), and the ice extent is shown for five epochs (1912–1989 after Hastenrath and Greischar (1997), 2000 after Thompsen et al. (2002)). NIF, EIF, and SIF are the former Northern, Eastern, and Southern Ice Fields (respectively), *FWG* Furtwängler Glacier, *UP* Uhuru Peak (5,895 m), and *LPG* Little Penck Glacier. Automated weather stations currently operate near the NIF and SIF drill sites.

embraced by those seeking to cast doubts about global warming (e.g., GES, 2004). Resolution of the modern-time controversy awaits a comprehensive understanding of how Kilimanjaro's summit climate has been impacted by large-scale atmospheric circulation changes; this effort is well underway (Mölg et al., 2009; Thompson et al., 2009; Winkler et al., 2010).

Climate

Kilimanjaro rises 5,000 m above the surrounding plains, extending halfway through the tropical atmosphere to ~506 hPa. Climate varies dramatically and sharply with elevation, causing the mountain's dramatic ecological zonation. Whereas air temperature drops steadily and uniformly with elevation, the annual precipitation amount increases and then decreases with elevation. Southern and southwestern slopes reach a maximum annual total at ~2,200 m (Hemp, 2006), but northern slopes are drier (Coutts, 1969; Hemp, 2006). This precipitation pattern accounts in part for the asymmetrical distribution of glaciers on Kilimanjaro.

Precipitation at the summit annually totals only ~10% of that received by the forest below, and snow is the predominant form of precipitation at elevations above the mean annual freezing-level altitude, roughly 4,700 m (Hastenrath, 1984). Snowfall can occur at any time of year, but is primarily associated with northern Tanzania's two seasonally-wet periods, the November–December "short rains," and the "long rains" of March to May. Summit climate is thus best defined by seasonal humidity fluctuations, and by strong diurnal cycles driven largely by the tremendous daily fluctuation in incoming solar radiation; the following synopsis is based on AWS measurements made on the Northern Ice Field (NIF) since 2000 (Hardy, in prep.).

Summit climate is most stable through an extended dry season centered on July and August. This interval is characterized by annual minima of humidity, snowfall, air temperature, and wind speed, and by increasing solar irradiance after the solstice minima.

By the middle of September, the beginning of an important seasonal change is marked by rapidly increasing wind speed, and an increase in air temperature. Solar irradiance gradually reaches an annual maximum as the sun moves into the southern hemisphere. Humidity increases slowly during September, rapidly into October, and continues climbing steadily into December. The "short rains" typically begin in mid-October, although the timing and magnitude vary from year to year – with important implications for glacier mass balance. For example, September and October (and even November) can be a time of considerable ablation (e.g., Hardy, 2003), when net solar irradiance remains high in the absence of snowfall, accompanied by increasing turbulent energy transfer as wind speed, air temperature, and humidity are increasing.

By mid-January the short rains are usually ending, with both humidity and snowfall dropping quickly to early February minima and a brief secondary dry period. The long rains then typically begin in early March, with humidity and snowfall continue increasing into April, and snow accumulation typically continues into May. Then, air temperature decreases rapidly, wind direction backs slightly from east toward north, and humidity drops drastically. By June, another dry season is beginning.

Mean annual temperature at the summit is approximately $-7°C$, with monthly means ranging only 1.3°C. On the NIF, daily temperature ranges between an average low of $-9°$ and an average maximum of $-4°C$. Thus, air temperature on the glaciers is consistently below freezing; extreme radiational cooling at night brings surfaces temperatures below $-15°C$ (to $-27°$), so a considerable cold content must be overcome each day before ablation of the snow or ice surface can occur.

Kilimanjaro glaciers

Currently, there are roughly eight glaciers on Kibo, some distinct and some in clusters as formerly larger bodies break up (Figure 1). These are all remnants of a once tenfold larger *ice cap* (*Ice Caps* qv) that encircled the volcano's summit in the mid-nineteenth century, filling at least portions of the crater itself while also spilling outward and down the slopes. The areal extent of this earlier ice cap – likely the maximum *Holocene* (*Holocene Glacier Fluctuations* qv) extent – was 20 km^2, as determined by mapping moraines (Osmaston, 1989). Subsequent ice recession through the twentieth century was "dramatic and monotonic" (Hastenrath and Greischar, 1997, p. 459), based on four area determinations averaging 26 years apart and with unknown errors; updated maps show continuing retreat (Figure 1; Thompson et al., 2002; Cullen et al., 2006; Thompson et al., 2009).

By the beginning of the twentieth century, many of the ice cap's broad lobes had been named after early explorers (see Hastenrath, 1984 for list). These names remain in use, despite morphological changes. On the south-facing slope below the crater's sharp southern rim, a Southern Ice Field has encompassed what are now or will soon be separate entities, the Heim, Kersten, Decken, and Rebmann Glaciers. Within the crater, the Furtwängler Glacier has been the only ice entity for several decades, splitting into two parts by 2007. Straddling the crater rim's north side, the Northern Ice Field (NIF) comprised slightly more than half of Kibo's total ice area until the 1970s, when an Eastern Ice Field (EIF) became distinct. Although the EIF has since broken into numerous entities, the NIF remains Kibo's largest body of ice. Extending down north- and northwest-facing slopes below the NIF are what remains of the Credner, Drygalski, and Great Penck Glaciers. The Little Penck Glacier, prominently visible today from western ascent routes, separated from the NIF during the 1990s (Figure 1) and has considerably decreased in area since 2000.

All ice masses on Kibo are here termed glaciers for discussion purposes, although most ice is now static and some entities are just tiny fragments. Ice thickness is poorly known due to limited measurements, with a probable maximum of ~50 m for the Northern Ice Field.

Little was known of energy and mass balance details on Kibo's glaciers until 2000, other than that the total ice area had been decreasing for over a century. However, early observations were astute; Geilinger (1936, p. 9), for example, recognized that glaciers on the outer slopes and those of the crater behaved differently "… with regard to the melting process." Building upon this distinction, Kaser et al. (2004) subdivided summit glaciers into (1) horizontal glacier surfaces, the typical glacier regime studied; (2) slope glaciers; (3) near-vertical margins; and (4) basal surfaces.

Horizontal glacier surfaces

Most glaciers on Kibo's summit have horizontal or nearly horizontal upper surfaces, unbroken by crevasses. At times the surfaces are flat and smooth, but this changes from year to year. On a whole-glacier scale, the surfaces are often comprised of "massive steplike features" (Gillman, 1923, p. 17); at smaller scales one sometimes sees "fantastic ice-shapes" (Sampson, 1965, p. 121) or ice "honeycombed in many places to a depth of over 6 ft, and weathered into countless grooves and ruts and pointed spikes" (Meyer, 1891, p. 147; see also Figure 2). Since 2000 this regime has been the focus of measurements and modeling (e.g., Mölg and Hardy, 2004; Mölg et al., 2008), and is today the best known of the four regimes. Mass balance here governs glacier thickness, and balance fluctuations are largely independent of ice area, in the absence of flow. Although details of mass exchange at this surface remained unknown until 2000, historical accounts suggest that twentieth century ice thickness probably never averaged more than about twice that of today.

Kilimanjaro, Figure 2 Three views of Kibo summit glaciers, taken: (**a**) September 28, 2008, (**b**) January 30, 2009, and (**c**) October 7, 2007. Note fluting of vertical walls (**a, b**) and horizontal-surface penitentes (bottom of image **a, c**). For scale, note people in image (**b**) and ablation stake at ice surface in image (**c**) (~0.5 m visible; upper right-hand corner of image).

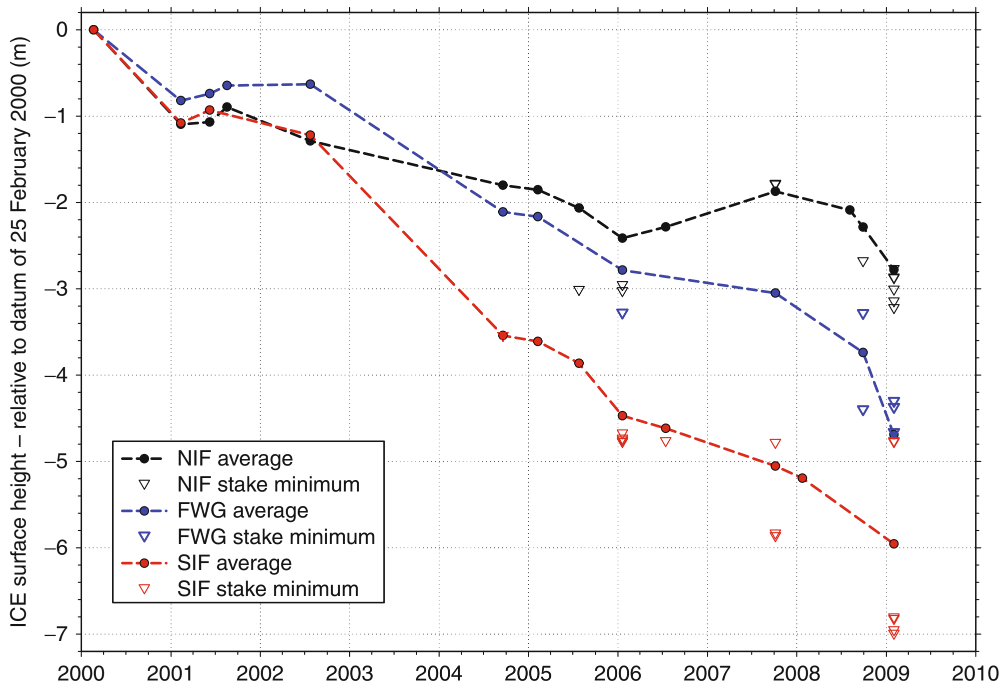
Horizontal and slope glacier surfaces on Kibo are typically comprised of hard glacier ice, appearing and behaving as expected for ablation-zone ice of density approaching 900 kg/m^3. A thin mantle of *Seasonal Snow Cover* (qv) blankets the ice during most wet seasons. Snow – or snow transitioning to superimposed ice – persists from one wet season to the next when snowfall is above average.

In the current climate at Kibo's summit, the horizontal surface, multiyear mass balance is negative – and the glaciers are thinning (Figure 3). Indeed, the hypothetical ELA has probably been above summit-level for some time (Humphries, 1959; Kaser and Osmaston, 2002). Nonetheless, speculation continues as to whether the ELA might be lower on the south slopes (e.g., Kaser and Osmaston, 2002; Mölg et al., 2009), despite little evidence.

Mass loss on horizontal surfaces is resulting from a predominance of negative energy balance, due to net radiation receipt as controlled by *Albedo* (qv; Mölg and Hardy, 2004; Mölg et al., 2008). Field measurements of mass balance support these modeling results. Mass is being lost from surfaces through both *sublimation* (*Sublimation from Snow and Ice* qv) and *melting* (*Melting Processes* qv); for a 1-year period March 2001 through February 2002, sublimation accounted for 86% of mass loss at the NIF AWS site. Yet, some areas clearly experience a higher proportion of melting, as a high degree of both spatial and temporal variability exists in surface characteristics and processes (Figure 3). Accordingly, simple generalizations based on point-scale modeling (e.g., Mote and Kaser, 2007) are questionable.

One important suggestion of recent field measurements is that the rate of mass loss from horizontal surfaces may be increasing (Thompson et al., 2009), even without a demonstrable change in forcing. Continuing ablation is concentrating particulate matter (i.e., dust) on an increasingly older surface, decreasing albedo and thus increasing net radiation receipt and accelerating ablation. Indeed, in the vicinity of the NIF weather station and *Ice Core* (qv) sites, the glacier surface is almost certainly older than 57 years, a figure based on ^{36}Cl measurements in the ice cores (Thompson et al., 2002). More recent ^{14}C-dating of organic material indicates that the surface could be over 300 years old (D. Hardy, 2004, 2009), although it is unlikely that the surface age is uniform, given the considerable spatial variability in accumulation and ablation patterns (e.g., Figure 3).

Understanding horizontal-surface processes and mass balance is important, because these control what is revealed by ice cores penetrating through layers of accumulation, and previously exposed ablation surfaces. Six cores were drilled on Kibo through three different ice entities (see Figure 1). In the absence of reliable ^{14}C dates from the core, the resulting chronology was developed – necessarily – by assuming an invariant accumulation rate



Kilimanjaro, Figure 3 Ice surface height change on three Kibo summit glaciers, from measurements at mass balance stakes. In general, only one stake per glacier was monitored through 2004, and 3–19 stakes each subsequently; average values shown. Triangles symbolize minimum height change at individual stakes that ablated out and fell over between measurements (values were used in averages). Punctuating the overall thinning trend are intervals of positive mass balance due to superimposed ice formation. Resolution of height fluctuations between these discrete stake measurements is not possible.

(Thompson et al., 2002). This record, however uncertain (e.g., Gasse, 2002; Kaser et al., 2010), will endure until an alternative chronology is provided by better dating.

Slope glaciers

Glaciers currently extend down from Kibo's crater rim in only a few cases (Figure 1). These include the Kersten and Decken Glaciers on the south side, along with the Rebmann Glacier to a minor extent, all inclined at 30–40° and all remnants of the former Southern Ice Field. The Credner Glacier still extends down the northwest flank. Additional glaciers and small ice bodies remain on the slopes but are no longer connected to ice at the crater rim. These include the Heim and Great Barranco Glaciers on the southwest flank, and the Little Penck remnant on the west side. Even by the mid-1930s, Geilinger (1936, p. 12) referred to such ice as "... independent dead glaciers of the outer slopes."

At their late-nineteenth century maximal extent, revealed by moraines, slope glaciers extended down as low as 4,400 m (Osmaston, 1989), and as recently as 1971 there were seven tongues reaching below 4,870 m (Messerli, 1980). Today, glacier ice is scarce below 5,000 m, likely with an increasing proportion buried under a mantle of debris (Humphries, 1959; Downie and Wilkinson, 1972; Young and Hastenrath, 1991; Kaser et al., 2004).

To an even greater extent than for horizontal ice surfaces at the summit, some slope glacier surfaces are today quite dirty, due to deposition of wind-blown dust (e.g., Figure 2c). This inorganic matter is being concentrated, due to a prolonged period of negative mass balance, and is accelerating mass loss by changing the energy balance.

Slope glacier meteorological measurements begun in 2005 have allowed energy balance modeling for these surfaces. To date, energy and mass balance characteristics appear similar to those on the NIF horizontal surface, with even a slightly higher proportion of mass loss to sublimation (Mölg et al., 2008).

Near-vertical ice margins

Vertical or near-vertical margins are a special characteristic of Kilimanjaro's summit glaciers (Figure 2; Winkler et al., 2010). Typically, the vertical surfaces are fluted, and "sometimes slightly undercut at the base" (Downie and Wilkinson, 1972, p. 40). Such margins have been reported since the earliest observations (e.g., Meyer, 1891; Gillman, 1923).

Ablation at the vertical margins is driving the areal recession revealed by mapping (e.g., Hastenrath and Greischar, 1997). Although ice retreat is probably the best-documented environmental change occurring high on the mountain, our understanding of vertical-wall ablation processes remains incomplete, despite the important contribution of Mölg et al. (2003) confirming early speculation that retreat is governed by energy from direct solar radiation (e.g., Geilinger, 1936). Melting is the primary mechanism by which vertical walls retreat (lose mass), and measurements confirm that the ice temperature often reaches 0°C during the day when seasonally irradiated (Winkler et al., 2010). In addition, collapse features (calving) can be observed around most summit glacier margins, and must also be considered a mechanism of vertical margin ablation, as speculated by Downie and Wilkinson (1972).

Vertical ice exposures on Kibo nicely illustrate stratification, or the sedimentary banding associated with accumulation over time, and these can often be traced laterally for considerable distances. Notably, especially from the perspective of ice-core interpretation, some bands appear to represent buried surfaces that suggest a break in snow accumulation (i.e., missing time intervals), or at which "...there appears to have been marked erosion of the ice surface before further accumulations of snow" (Humphries, 1959, p. 477). Such unconformities are sometimes marked by dirt bands, which Downie and Wilkinson (1972, p. 42) described as locally common but "almost nonexistent" on a larger scale. Especially at the upper end of the southern glaciers, unconformities sometimes illustrate an angular discordance with the overlying stratigraphy, a phenomenon awaiting explanation.

Basal surfaces

Kibo glaciers rest primarily on volcanic sand, and to a lesser extent on bedrock. During February 2000 ice-core drilling (Thompson et al., 2002), the NIF basal temperature was −0.4°C, and 0°C was measured within the SIF. The NIF 10-m-depth temperature of −1.2°C suggests that meltwater is transporting heat energy into the glacier, given the −7°C mean annual air temperature.

Little is known about the spatial variability and magnitude of geothermal heat flux on Kilimanjaro, especially relative to that beneath the glaciers. However, fumeroles are present within the inner crater, and even prior to their first observation by W.H. Tilman in 1933, Jäger (1909), Gillman (1923), and Geilinger (1936) all speculated that volcanic heat might be influencing ice recession. Local-scale glacier impacts, apparently due to steam venting, have been observed and reported (e.g., Kaser et al., 2004).

Kilimanjaro snow

Snow on Kibo is ephemeral, meaning that within a relatively short period of time (i.e., minutes to months) it either ablates and disappears, or is transformed into glacier ice. Here, the term snow refers exclusively to solid precipitation, or that which has accumulated as snow cover on either glacier or crater surfaces. Although glaciers are a perennial and long-term feature of Kilimanjaro, snow cover is not – and the historical literature indicates that snow has always come and gone at high frequency (~annual).

Few early explorers or mountaineers made snow depth measurements, but a seasonal absence of snow has been noted since the first observations. For example, Meyer (1891, p. 316) remarked that in October "...when all the snowfields had disappeared, there was likewise comparatively little snow to be met with on the ice-cap." Sampson (1965, p. 123) wrote that from August to October "the chances of finding any snow patches... are very poor at heights over ~4,000 m." Additional evidence for the seasonal absence of snow in the past comes from historical photographs, which cannot easily quantify snow depth but nicely document times when snow is absent.

Snowfall events can be brief, such as those associated with afternoon convection (e.g., graupel), or can persist for multiple days. Wet-season events are typically of longer duration and yield the greatest accumulation. Within the past decade, seasonal snow accumulation on the glaciers of ~1 m has been noted at least twice (early in 2001, 2007; D. Hardy, 2004, 2009), with lesser accumulations on unglacierized portions of the crater. Anecdotal accounts from guides suggest that snowfall magnitude has diminished in recent decades, although no reliable long-term station data for precipitation exist from above ~1,800 m on Kibo. The greatest documented accumulation is that reported for the 1961–1962 combined wet seasons, involving "snowfall of over six feet," much of which "...was still present more than a year later" (Segal, 1965, p. 126). The extent to which this interval was unusual remains unknown, as summit visitation is much less frequent during the wet seasons.

Once deposited, ablation of snow cover from glacier and crater surfaces involves both melting and sublimation, based on observations and energy balance modeling (Mölg and Hardy, 2004; Kaser et al., 2004; Mölg et al., 2008, 2009). Of these two processes, melting is the more readily observable, both on and off the glaciers. Although sometimes difficult to distinguish from ice melt, evidence for snowmelt includes icicles, supraglacial meltwater ponds, areas of thin, water-saturated snow, and rarely, meltwater runoff. Melting at the summit is not a recent development, for Humphries (1959, p. 477) observed "melting ice and pools of melt water at the summit during the day." Sublimation of snow is often indicated by the presence of penitentes (Figure 2a, c), which form over both ice and crater surfaces in the intense radiation environment on Kibo (cf. Lliboutry, 1954). With fully developed penitentes, melting ice or wet crater sand may be present between the spikes. Although present recently in sufficient density and height to impede glacier travel, penitentes are transient features, today and in the past. Gillman (1923, p. 18) for example, did "not come across penitents" on his single trip to the summit, yet their presence in 1929 was noted by Geilinger (1936). As with other aspects of the cryosphere on Kibo, spatial and temporal variability render generalizations difficult.

Lastly, recent research highlights the extreme sensitivity of horizontal glacier surfaces to the variability of snowfall frequency and amount. By governing albedo variability, and thus net receipt of solar radiation, snowfall has emerged as the key atmospheric variable controlling ablation and mass balance (Hardy, 2003; Mölg and Hardy, 2004; Mölg et al., 2008, 2009). Figure 3 illustrates that the system is especially sensitive to the interannual variability of snowfall during the short rains (November–December).

Summary

Currently, there are ~8 distinct ice entities on Kibo, together covering a total area of less than 2 km^2 and all remnants of a once larger ice cap. The summit glaciers are relatively flat, with near-vertical margins, and the slope glaciers today are concentrated on the mountain's southwest- and northwest-facing flanks. Glaciers on Kilimanjaro are a product of climatic conditions at the summit that no longer exist, as no area of accumulation has existed for many decades and perhaps since the current recession began. Today, as in the past, snow cover on the mountain is seasonal and subject to considerable interannual variability. Measurements and modeling in recent years have demonstrated that the mass and energy balances on horizontal ice surfaces are very sensitive to the magnitude and frequency of snowfall events – perhaps increasingly so as dirt concentration increases on exposed, ablating ice surfaces.

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Cross-references

Albedo
Holocene Glacier Fluctuations
Ice
Ice Caps
Ice Core
Melting Processes
Moraine
Sublimation from Snow and Ice

KUNLUN MOUNTAINS

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Definition

Kunlun Mountains extend about 2,500 km from the Pamirs/China in the west to the Mount Yuzhu in Sichuan, China, in the east, and have an average elevation of 5,000 m. Their highest mount, Muztag, is 7,723 m. In this region there are 6,580 glaciers with a total area of 10,844 km^2, and an ice volume of 1,175 km^3, which corresponds to about 72% of the glacier area in the whole Kunlun (Liu, 2000). The West Kunlun Mountains lies in the western part of the Tibetan Plateau; the largest glaciers mostly 20–30 km long are distributed in the high mounts between Tianshuihai Pass and the southern Yurunkax River basin; and the alpine type glaciers are usually developed on the West Kunlun where the lands are severely cut and highly shadowed. Ice cap (flat-topped glacier), slope glaciers, and the valley glaciers are mainly developed on the south slope due to advantageous topographical and climatic conditions.

Introduction

Researchers have estimated increasing greenhouse gases which can cause change in regional temperature and precipitation. The change in climate may have affected the hydrological cycle, such as precipitation form, snow accumulation and meltwater, evapotranspiration, streamflow, and its recharge to groundwater as well (IPCC, 2007).

The landform of the southern Tarim basin is characterized by the three huge mountains: the Pamirs/China, the West Kunlun, and Karakoram Mountains; all rivers originate from the mountains and drain into their basins (Figure 1). Typical snow and glacier-fed rivers, the Hotan and Keriya, are from the glaciated center at the largest icecap, and Guliya from the West Kunlun flow into the Tarim basin.

The land surface on the upstream of the watersheds is characterized by snow and glacier cover and a little grassland, and on the downstream by Gobi and desert where rainfall seldom produces runoff due to strong evaporation except for storm rainfall. Since their upper streams are covered by a great number of glaciers and snowpacks where there is much precipitation in summer, stream flow occurs also in the summer (June–September), and there is a close linear relationship between summer flow and air temperature, as the former contributes 70–90% of stream water annually. With the rise in temperature and increase in rainfall, the maximum monthly runoff in July contributes about 30% of the annual runoff, and the minimum in February or March contributes only 1.2–1.8%. Eighty percent of their drainage areas are over an altitude of 3,000 m; it means streamflow is closed to the exchange between heat and water within the glacier system in the high mountains. Meanwhile, due to hot weather and rainy season in July and August annually, their combined role causes annual maximum floods. According to hydrological records, more than 90% of the maximum floods occur during the period of late July to early August.

The Hotan River basin is the largest basin in the west Tibet Plateau and includes parts of the Karakoram and the south territories of the Tarim basin in the west China. The basin covers an area of approximately 34,558 km^2, which encompasses a wide variety of climatic conditions, including the periglacial, the alpine permafrost, and desert zones. Glaciers, snow cover, and patterned ground features associated with continuous and discontinuous permafrost are found in the south, while agriculture and stock raising are important economic activities in the northern part. Figure 1 shows the features of permafrost regions in west China and in the Hotan River basin. The drainage area is located in the seasonal frozen ground and alpine permafrost region. The elevation ranges from 1,860 to 7,167 m with an average altitude of 4,200 m estimated by the DEM, and the low limit of alpine permafrost is about 4,400 m, thus approximately 45% of the basin lies within the continuous and discontinuous mountain permafrost zones (Zhou et al., 2000).

The Hotan River consists of two large subbasins: the Yurungkax in the east and the Karakax in west. There are a great number of glaciers in the upstream above 4,800 m, with a total area of 5,127.15 km^2 (Yang and An, 1990). Hydrometeorological records indicate a simple