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Tropical Glaciers, Climate Change, and Society

FOCUS ON KILIMANJARO (EAST AFRICA)

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In recent years glaciers in the tropics have been recognized as particularly valuable indicators (proxy data) of climate change (e.g., Houghton et al. 2001). Not only do they provide insight into regional climate variations from remote high-altitude sites but they also show a greater variety in terms of climate sensitivity than mid- and high-latitude glaciers (Kaser 2001; Kaser et al. 2004*a*). While the mass balance of the latter glaciers is strongly tied to air temperature (Ohmura 2001), tropical glaciers are most sensitive both to atmospheric moisture content (e.g., cloudiness and therefore incoming solar radiation) and to precipitation and thus the reflection of solar radiation on the glacier surface (the so-called albedo) (e.g., Hastenrath 1984; Kaser and Noggler 1991; see Kaser et al. 2004*a* for a review). Studying the behavior of tropical glaciers and the associated climatic controls therefore involves studies on the important link between air temperature and moisture changes (cf. Pielke 2004).

The most characteristic feature of low-latitude climate is that seasonality is due entirely to the annual cycle of moisture (see Hastenrath 1991 and Asnani 1993). In general, this cycle results mainly from the north-south oscillation of the Intertropical Convergence Zone (ITCZ), one of the significant circulation patterns in our climate system. The ITCZ is a zone of strong convection and rainfall that passes through the equatorial regions twice a year and reaches the boundary of its oscillation zone (the outer tropics) once a year. Thus, the oscillation of the ITCZ induces a succession of rainy and dry seasons. The contrast between hygric seasons is small in regions with moisture influx from extensive rain forests, and therefore these regions are more or less humid year-round. The monthly variation in air temperature, however, is small throughout the tropics, even at high altitudes (Hardy et al. 1998). Figure 12.1, A, depicts the annual cycle of rainfall at Moshi, at the foot of Kilimanjaro, in equatorial Tanzania. The so-called long rains occur between March and May, and there is a secondary peak of rainfall in November and December ("the short rains") when the ITCZ moves more rapidly across the Kilimanjaro region. Long-term air temperature data at Moshi (Vose et al. 1992) underline the thermal homogeneity of tropical climate, since monthly means vary less than 5 °C. The vertical

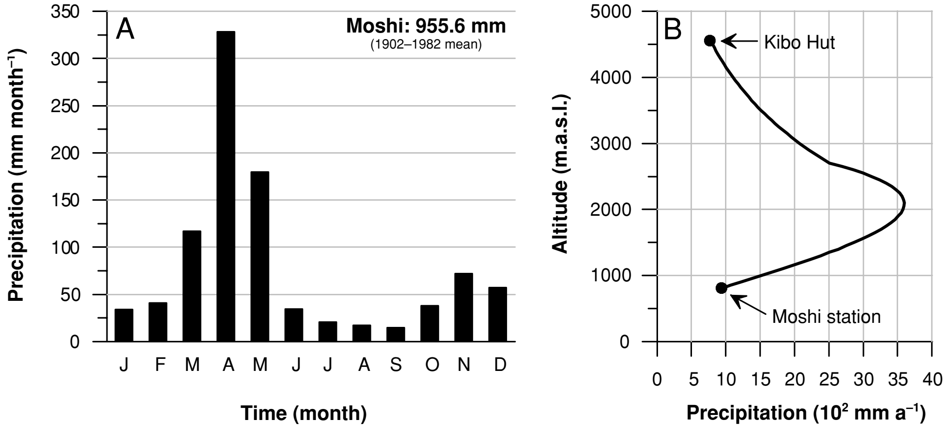

FIGURE 12.1. (A) Mean annual cycle of precipitation at Moshi (813 m a.s.l.), equatorial East Africa, 1902–82, and (B) vertical distribution of annual precipitation on the southern slope of Kilimanjaro. Data from the Global Historical Climatology Network climate data set (Vose et al. 1992); vertical distribution derived from the precipitation-altitude relation after Røhr and Killingtveit (2003), with Moshi as reference station.

distribution of rainfall on the southern slopes of Kilimanjaro (Figure 12.1, B) exhibits the pattern typical of tropical mountains, with a belt of maximum rainfall at mid-altitude locations (Hastenrath 1991). The annual cycle of tropical climate outlined here has a particular impact on energy exchange at the glacier-atmosphere interface and therefore induces the special sensitivity of tropical glaciers to moisture variability (Kaser et al. 2004*a*).

According to the definition introduced by Kaser (1999) (Figure 12.2), tropical glaciers occur in regions where three zones coincide: (1) the astronomic tropics, (2) the area of oscillation of the ITCZ, and (3) any zone in which the diurnal air temperature amplitude exceeds the annual amplitude. This means that almost all tropical glaciers (>99% with respect to glacier surface area [Kaser 1999]) are found in the South American Andes. There are, however, four other glaciated massifs in the tropics, and they are equally important as climate indicators. Three of them, Rwenzori, Mt. Kenya, and Kilimanjaro (summarized to one point in Figure 12.2), lie in equatorial East Africa (Hastenrath 1984). Moreover, a small glaciation remains in the mountains of Irian Jaya in Indonesia (Kincaid and Klein 2004). Apart from brief periods (e.g., Georges 2004), all tropical glaciers have suffered severe mass loss over the past century (Kaser 1999), capturing the attention of scientists and others around the world. Regional studies referring to South America (e.g., Favier, Wagnon, and Ribstein 2004) as well as to East Africa (e.g. Kruss 1983; Mölg, Georges, and Kaser 2003) demonstrate the sensitivity of the glaciers to changes in moisture-related climate parameters.

The remainder of this chapter will concentrate on the retreating glaciers of Kilimanjaro, which have experienced considerable media coverage in recent years. The next section summarizes what we know about the climatic controls of this ongoing retreat, and the following one illustrates the creative stance required for designing future research. The final section shows how the findings from this basic research can be linked to social activities and needs.

KILIMANJARO GLACIERS AND CLIMATE: WHAT WE KNOW

The current glacier recession on Kibo, the glaciated cone of the Kilimanjaro massif, started in about 1880, following at least some decades of stability (Hastenrath 2001). Description and monitoring of this recession began with the early explorers (Meyer 1900; Klute 1920) and resulted in the first detailed map, by Klute (1920), showing the glacier extent in 1912. Hastenrath and

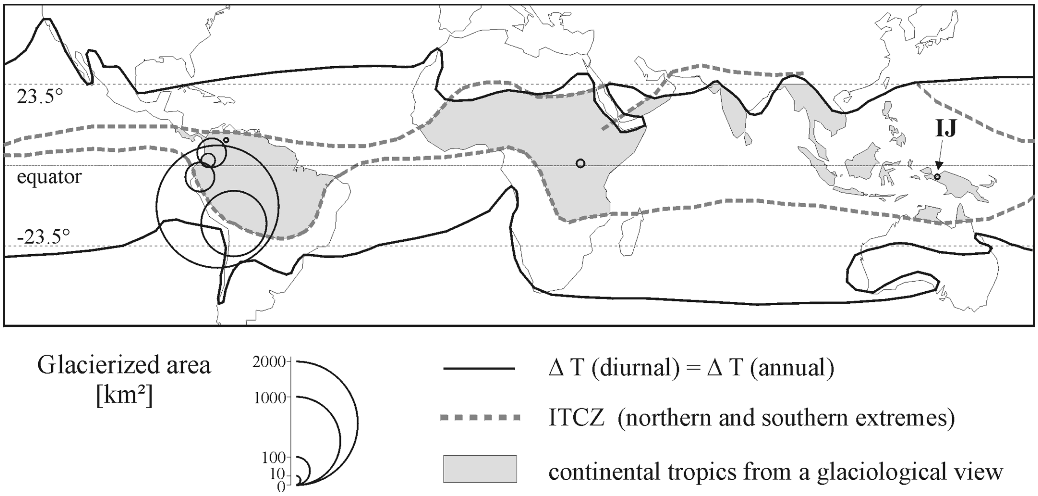

FIGURE 12.2. Global distribution of tropical glaciers at the end of the twentieth century (after Kaser and Osmaston 2002). Circles indicate the glacier surface area in respective countries (IJ indicates Irian Jaya).

Greischar (1997) and Thompson et al. (2002) have derived further glacier extents for different times in the twentieth century. Figure 12.3 summarizes the findings of these studies and illustrates the strong recession in the course of the twentieth century. In the year 2000, only 2.6 km² of glacier surface area were left (Thompson et al. 2002) of the ~20 km² estimated in 1880 (Osmaston 1989). The glaciers on the summit plateau have a peculiar shape, with vertical ice walls at their margins and a near-horizontal surface. The glaciers on the steep slopes of Kibo show a simpler, sometimes nearly rectangular shape. To understand the connection between glaciers and climate, it is essential to distinguish these three glacier regimes (Kaser et al. 2004*b*): the vertical ice walls on the plateau (regime 1, Figure 12.4, A), the horizontal glacier surfaces on the plateau (regime 2, Figure 12.4, A), and the slope glaciers below the plateau (regime 3, Figure 12.4, B). Basal melting due to geothermal heat (Kibo is a dormant volcano) has probably had a limited effect on modern glacier retreat (Kaser et al. 2004*b*), but this is not entirely clear.

Although the recession of the Kibo glaciers was recognized early, the climatological reasons for it have remained speculative until recently and, in the past few years, have repeatedly been attributed to anthropogenic global warming. Consequently, research on Kilimanjaro's summit climate and the recession of the glaciers was begun in 2000 (e.g., Hardy 2002; Thompson et al. 2002; Kaser et al. 2004*b*) and studies of the physics of climate-glacier interactions in more recent years (e.g., Mölg and Hardy 2004). The studies to date rely primarily on data collected by the University of Massachusetts automatic weather station on the horizontal surface of the Northern Icefield (Figure 12.3) since February 2000. Two new stations were installed in February 2005 by the University of Innsbruck in front of an ice cliff (AWS2) and at the transition into the southern slope glacierization (AWS3) to measure conditions of glacier regimes 2 and 3, respectively. Recorded data show that this high-altitude climate reveals the general features of tropical climate as described above, although precipitation exhibits greater intraannual and interannual variability than expected. Mean annual temperature at the summit is −7.0 °C, with monthly means varying only ~2 °C around the annual mean.

Regarding glacier-climate interactions, two points can be highlighted: (1) The Kibo glaciers seem to be retreating mainly because of the dry climate and abundant solar radiation, and (2) they are extremely sensitive to variation in precipitation.

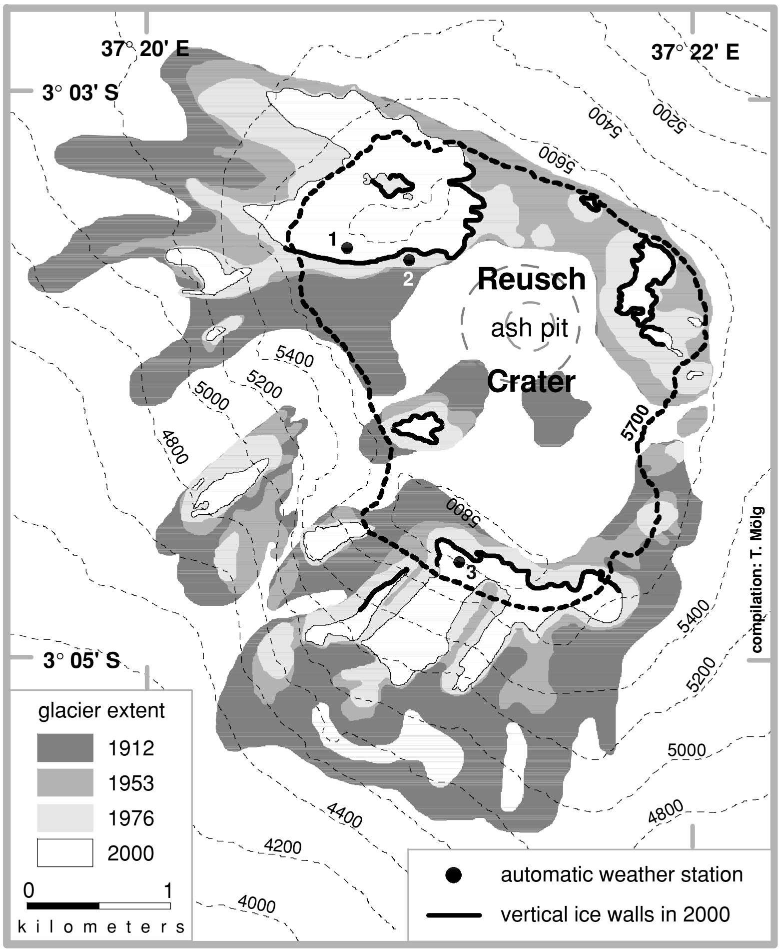

FIGURE 12.3. Glacier extents on Kibo in 1912, 1953, 1976, and 2000 (Hastenrath and Greischar 1997; Thompson et al. 2002); map contours in meters, UTM zone 37 projection. Also shown are the locations of the automatic weather stations (1–3) and the distribution of vertical ice walls (Mölg, Hardy, and Kaser 2003). The highlighted 5,700-m contour delimits Kibo's summit plateau approximately. Dashed circles indicate the conical Reusch Crater. Map compiled by T. Mölg, January 2003/December 2004.

The first point is supported by the model study of Mölg, Hardy, and Kaser (2003), who assumed an idealized ice cap covering the summit plateau in 1880, with a prescribed distribution of vertical ice walls according to early photographs (Meyer 1900). They then modeled mass loss at the ice walls (regime 1) between 1880 and 2000 as a function of absorbed solar radiation. Despite year-round negative air temperatures in the summit plateau area (Mölg and Hardy 2004), the high amounts of solar radiation provided enough energy for melting, which induced severe mass loss at the ice walls. After 120 years of simulation, the broken-up ice cap showed a spatial distribution of ice remnants strikingly similar to the real, observed pattern. This indicates that solar radiation maintains vertical ice wall retreat on the summit plateau in a climate with a lack of mass gain on the glaciers (i.e., a climate that has become too dry to maintain them). Preliminary model experiments on the climate sensitivity of slope glaciers (regime 3) also point to the effects of a drier climate (reduction in precipitation with accompanying reduction in cloudiness and increase in incoming solar radiation), which made slope

FIGURE 12.4. (A) The summit plateau Northern Icefield in July 2005, with a near-horizontal surface (glacier regime 1) and vertical ice cliffs at its margin (glacier regime 2). (B) The southern slope glaciers below the summit plateau in February 2005. (Photos by N. J. Cullen and T. Mölg, respectively.)

glaciers retreat from their 1880 extent. When longer time series from AWS3 become available, these experiments will be more robust.

The extreme sensitivity of the glaciers to variation in precipitation was pointed out by Hardy (2003) and established by Mölg and Hardy (2004) for the horizontal glacier surfaces (regime 2). They applied meteorological data recorded at the University of Massachusetts automatic weather station for 2000–2002 to an energy balance model that calculates all the energy fluxes involved in providing the energy for mass loss at the glacier surface and then verified the results by measured mass loss.

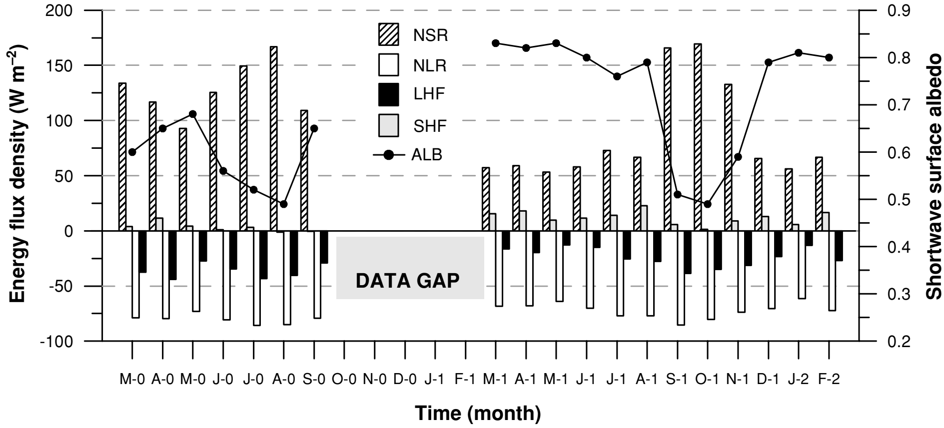

FIGURE 12.5. Energy-balance components at the weather station on the Northern Icefield between March 2000 and February 2002. *NSR,* Net shortwave (solar) radiation; *NLR,* net longwave radiation; *LHF,* turbulent latent heat flux; *SHF,* turbulent sensible heat flux; and *ALB,* shortwave albedo of the glacier surface. Positive values indicate energy gain for the surface, negative ones energy loss. For details of calculation see Mölg and Hardy (2004).

In contrast to the prevailing melting at the ice walls, mass loss on the horizontal surfaces is to a great extent due to sublimation, the direct conversion of water from solid to vapor (Mölg and Hardy 2004). Since sublimation consumes more energy per unit mass than melting, ablation rates on the horizontal surfaces are lower than on the ice walls (Kaser et al. 2004*b*). Figure 12.5 shows the main energy balance components at the weather station. Clearly, the energy balance is governed by variations in net shortwave radiation (i.e., absorbed solar radiation), which, in turn, are controlled by surface albedo. When albedo declines (e.g., between September and November 2001), net shortwave radiation sharply increases, which accelerates mass loss on the glacier surface. Albedo is a function of both precipitation amount and frequency. Local air temperature has hardly any impact at this site, given the small sensible heat flux. The albedo effect illustrated by Figure 12.5 for a 19-month period may certainly also exert a powerful long-term effect on glaciers.

What do other proxy data on East African climate tell us in this context? Several proxy sources support the notion that the climate of East Africa over the past 150 years was characterized by a sudden drop in moisture in the late nineteenth century and drier conditions during the twentieth. Among these proxies are the behavior of glaciers in the two other glaciated massifs of East Africa, Mt. Kenya (Kruss 1983) and Rwenzori (Mölg, Georges, and Kaser 2003), historical and modern accounts of lake levels (Hastenrath 1984; Nicholson and Yin 2001), reconstruction of lake levels from paleolimnological data (Verschuren, Laird, and Cumming 2000), and circulation and rainfall indices that link atmospheric and oceanic currents in the Indian Ocean since ~1850 to East African rainfall (Hastenrath 2001). To get a feeling for the magnitude of this moisture reduction, Nicholson and Yin (2001) applied a physically based water balance model to the lake-level record of Lake Victoria and estimated that mean over-lake precipitation in the 1860s and 1870s (likely coinciding with stable glaciers in East Africa) was about 20% higher than the twentieth-century mean reported by Yin and Nicholson (2002). For a much longer time scale, Thompson et al. (2002) concluded from an analysis of ice cores drilled on the Kibo glaciers in 2000 that glacier bevavior on Kilimanjaro during the Holocene (the past 10,000 years) coincided with well-known phases of African drought and humid conditions. This supports

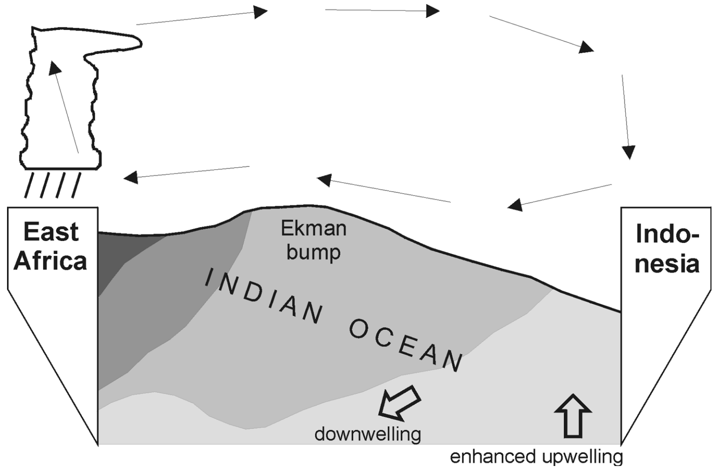

FIGURE 12.6. Vertical cross section at latitude 5°S illustrating ocean-atmosphere mechanisms of the anomalously strong East African short rains of 1997 (after Webster et al. 1999). The color scale from light to dark gray denotes increasing sea temperature; arrows indicate the direction of the atmospheric circulation.

the particular sensitivity of Kibo glaciers to precipitation of recent times.

STRATEGY FOR FUTURE RESEARCH

Studies of the reasons for precipitation variability and changes in (East) Africa have focused on the El Niño Southern Oscillation (ENSO). These studies use statistical methods (e.g., principal components analysis or spectral analysis) to detect relations between the ENSO and rainfall anomalies in Africa (e.g., Nicholson and Entekhabi 1986). Our own future research, however, must particularly consider an aspect arising from a new understanding—that the variation of precipitation in East Africa is tied to the state of the climate of the Indian Ocean and related sea-surface temperature patterns. This has become obvious in both observational studies (e.g., Black, Slingo, and Sperber 2003) and modeling experiments (e.g., Latif et al. 1999). Generally, interannual sea-surface temperature variation in the Indian Ocean is controlled by two modes (An 2004)—the basin-scale mode, which induces a basinwide warming or cooling of the Indian Ocean surface, and the Indian Ocean zonal mode (or dipole mode [Saji et al. 1999]), which alters the east-west sea-surface temperature gradient. There is overall agreement that strong zonal-mode events lead to extreme precipitation over East Africa through unusually strong short rains (Webster et al. 1999; Saji et al. 1999; Black, Slingo, and Sperber 2003) such as those of 1997. The short rains of that year amounted to up to 260% of their mean in the Lake Victoria area and up to 400% in coastal Somalia (Birkett, Murtugudde, and Allan 1999). Figure 12.6 schematically illustrates the causal mechanisms of these extremes (Webster et al. 1999).

The cycle starts with enhanced (reduced) upwelling in the eastern (western) Indian Ocean basin, which completely reverses the climatological sea-surface temperature gradient of a slightly warmer Indian Ocean in the east to an Indian Ocean now warmer in the west. At the same time, anomalous surface easterly winds start to replace the common westerly winds. The persistence of changed upwelling conditions subsequently causes the development of a westward-moving "ridge" in the Indian Ocean, the so-called Ekman bump. The increased moisture influx to East Africa through the easterly winds promotes convection over the landmasses that finally leads to enhanced generation of clouds and rainfall over East Africa. Apparently, this system is maintained by a number of positive feedback loops, in the case of 1997 for three to four months (Black, Slingo, and Sperber 2003).

There is strong evidence that basin-scale-mode events are controlled mainly by the occurrence of ENSO events and follow them with a lag of about a season (An 2004). This supports the statistical view on the ENSO-rainfall correlation stated previously, although the basinwide warming during the ENSO is associated with much weaker precipitation excess than the sea-surface temperature gradient reversal during zonal-mode events (Birkett, Murtugudde, and Allan 1999). The cause of zonal-mode events remains controversial. Some studies link them to the ENSO (Black, Slingo, and Sperber 2003), while others consider them purely internal phenomena (Saji et al. 1999; Webster et al. 1999) initiated and maintained by the positive feedbacks in the Indian Ocean–atmospheric circulation system. An (2004) has recently added a valuable study to this discussion, showing physical evidence for a dynamic link between basin-scale-mode and zonal-mode events.

Whatever the precise cause of these modes is, it appears that glacier recession on Kilimanjaro reflects not just local or regional changes but changes in larger-scale tropical climate. Sea-surface temperature changes in the Indian Ocean, especially changed frequencies of sea-surface temperature anomalies, must therefore be considered as a possible reason for the drier climate in East Africa during the twentieth century. Nicholson (2000) notes that wetter conditions in the recent historical past in Africa may represent mainly the more frequent occurrence of conditions that in the twentieth century typically characterized brief periods (e.g., the conditions of the short rains of 1997).

In the light of the findings presented here, a strategy for future research must operate at several climatological scales. At the microscale, meteorological and glaciological measurements on the Kibo glaciers are expanding. These additional measurements will help to refine the existing climate and mass balance studies (Mölg, Hardy, and Kaser 2003; Mölg and Hardy 2004) and quantify the impact of the local climate on glaciers more precisely. These microscale studies will be combined with model experiments on the connections between local/regional climate and large-scale climate. The employment of a mesoscale model—a numerical circulation model of the atmosphere (or regional climate model in this context)—will enable us to explore a number of aspects of the situation. For example, do sea-surface temperature patterns in the Indian Ocean also govern snowfall at the high altitude of Kibo? This is quite likely, as the greater moisture potential during strong zonal-mode events is visible in vertical atmospheric profiles up to the middle troposphere (5,000–6,000 m) (Black, Slingo, and Sperber 2003). If sea-surface temperature patterns do determine Kibo snow, could a higher frequency of unusually strong short rains prior to 1880 have provided enough snow on Kibo to maintain the glaciers? The results of the microscale studies will provide a clue to the amount of additional local snowfall required to maintain a glacier. Finally, coming back to vertical profiles, how has the stability of the atmosphere, which is critical for convection and therefore the formation of precipitation, changed?

A simple example with the Regional Atmospheric Modeling System (Cotton et al. 2003) will illustrate the approach envisioned. Figure 12.7 shows air flow past an idealized, bell-shaped Kilimanjaro massif that is 5,000 m higher than its surrounding plain and about 50 km in diameter at its base. The model was initialized in a horizontally homogeneous atmosphere with constant stratification (i.e., constant Brunt-Väisälla frequency) and then run for two scenarios (dry, wet) with a constant horizontal velocity at the inflow boundary, surface friction through a constant surface roughness ("no-slip"), nonrotational and three-dimensional. Despite the idealized assumptions, some interesting qualitative details emerge. The absence of pronounced vertical disturbances in the isentropes with only weak gravity wave activity indicates that the flow primarily goes around the mountain and confirms that Kilimanjaro is a good example of the "flow-around regime" discussed by Schär (2002). This implies that abundant precipitation on the summit can form only with convection present, and this creates a direct link to the large-scale scheme (Figure 12.6) in which convection is also one of

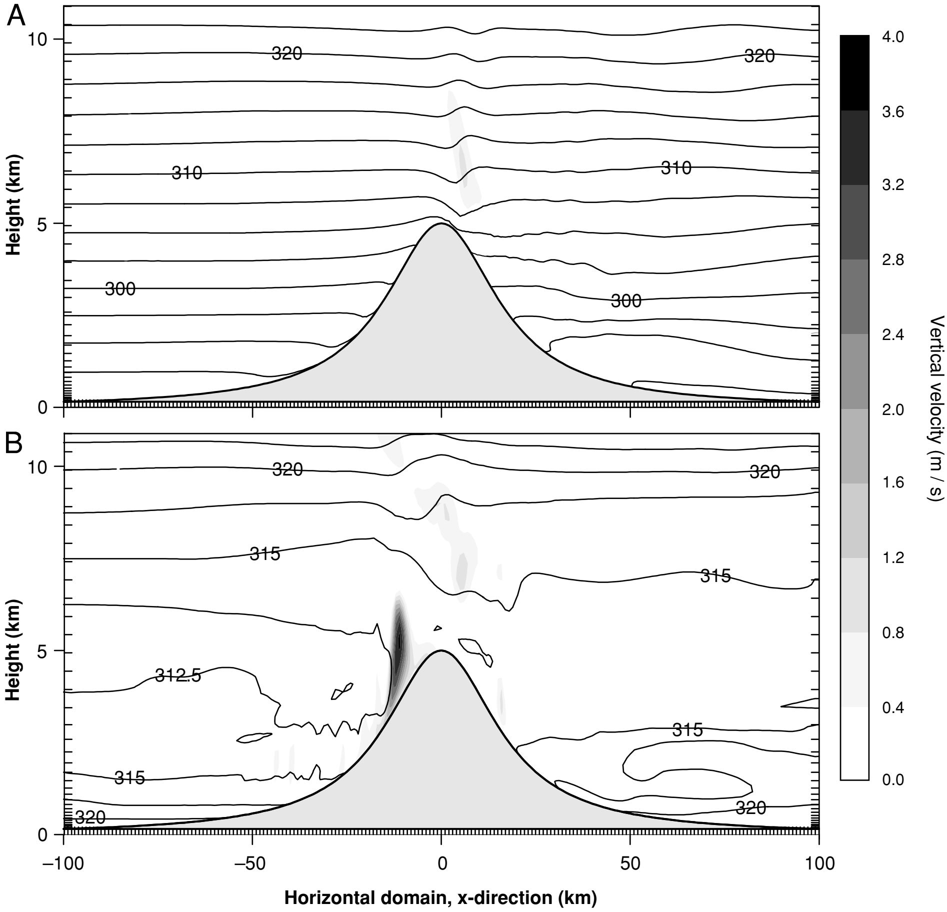

FIGURE 12.7. Vertical cross section of air flow past an idealized Kilimanjaro massif after six hours of integration in a 3-D model atmosphere: (A) dry with 0% relative humidity (RH), and (B) wet (RH = 100% until 5,000 m a.s.l., then linear decrease to 0% at 10,000 m a.s.l.). Shown are isolines of equivalent potential temperature (isentropes) with a 2.5-K spacing and gray-shaded contour surfaces of the upward-directed component of vertical velocity (spacing 0.4 m/s). Air flow follows the isentropes approximately and is from left to right with a constant background flow of 10 m/s. Note the vertical exaggeration of the plots.

the key processes. In fact, the sensitivity experiment (Figure 12.7, B) shows that strong moisture influx in the lower half of the troposphere decreases atmospheric stability and promotes convection near the summit on the windward side that is visible in accelerated upward winds. Plots of horizontal and vertical fields of cloud water content and wind vectors (not shown) confirm that the vertical winds indeed indicate convective cells (and not numerical noise), as these fields show great similarity to characteristic convective patterns (e.g., isolated regions of high cloud water content occur together with pronounced updrafts [Fuhrer and Schär 2005]). Hence, changes in atmospheric stability and related convection, influenced by the local topography (Figure 12.7) as well as the mesoscale transport of moisture to East Africa (Figure 12.6), seem decisive for snowfall on Kibo—which again underlines the need to approach the problem at various scales.

TROPICAL GLACIERS AND SOCIETY

The climate research on retreating tropical glaciers described previously has direct implications for practical measures in response to glacier retreat.

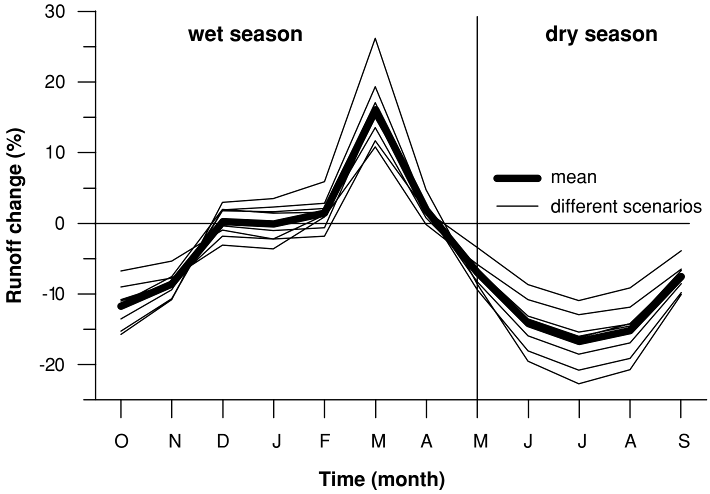

FIGURE 12.8. Changes in future runoff in the Llanganuco catchment area, Peru, with respect to runoff for 1961–90 (after Juen, Georges, and Kaser 2005). Thin lines represent calculations based on different climate scenarios for either 2050 or 2080 (see Juen, Georges, and Kaser 2005 for details), while the bold line shows the cycle of change averaged over all scenarios. The time axis follows the hydrological year (i.e., starts with October).

Most important in this context is that tropical glaciers are essential water resources in the glaciated regions of the Andes, acting as a buffer in the water cycle (Ribstein et al. 1995; Kaser et al. 2003; Juen, Georges, and Kaser 2005). Especially in the dry season, the water available for residents comes almost exclusively from the glaciers (Kaser et al. 2003) and supplies big cities (e.g., Lima) in which water is already scarce. Because of ongoing population growth and the Westernization of lifestyles, water demand is expected to increase. Addressing this issue, Juen, Georges, and Kaser (2005) have modified an existing tropical glacier mass balance model (Kaser 2001) to calculate runoff from glaciated catchment areas and applied their modified model to different scenarios of future climate as suggested by a climate prediction of Hulme and Sheard (1999). Figure 12.8 shows their results for the 33.5%-glaciated catchment area of Llanganuco, Peru. Regardless of which scenario is taken as a reference, dry-season runoff for the years 2050 and 2080 shows a significant decrease. This relationship between water demand and predicted availability in dry seasons points to a serious problem in the future.

Whether the Kibo glaciers contribute significantly to water resources in the Kilimanjaro area is currently under discussion and is vitally important. However, a significant role for them as a water source must be rejected (cf. Kaser et al. 2004*b*). First, as we have seen, a significant part of glacier mass loss is due to sublimation. Our model experiments for two automatic weather stations show that the horizontal glacier surfaces and slope glaciers in the vicinity of the summit plateau lose ~70% of their mass through sublimation. Second, where ice does melt (primarily at the vertical ice walls), it quickly evaporates in the dry atmosphere. During all our field trips, we have observed small meltwater "ponds" at the base of the cliffs but not perennial runoff from them. Third, the Kibo glaciers are very small. If one were to melt all the glacier volume found on the mountain in 2000 (2.6 km^2 surface area × ~25 m mean thickness [Thompson et al. 2002]) and then distribute the melted mass over the entire Kilimanjaro massif (say, 50 km × 80 km), it would amount to only a ~16-mm water column—approximately the amount that can easily be provided by one heavy rain shower. Although certain local communities may have gotten their water from slope glacier runoff in the recent past (cf. Sky Channel News, Johannesburg, August 28, 2002), the majority of the region's population (~1 million) is found in the lowlands of Kilimanjaro (Hemp 2005), whose springs are fed by water from the rain forest belt (see Figure 12.1, B). The maximum zone of annual precipitation is found in the altitude bands around ~2,200 m a.s.l., which coincide exactly with the rain forest belt (Hemp n.d.). Lambrechts et al. (2002) report that 96% of the water flowing from Kilimanjaro originates in the rain forest belt. The maintenance of Kilimanjaro's forests must therefore have highest priority in terms of water supply to the regional population (Agrawala et al. 2003)—an enormous challenge in light of the current land use changes.

In contrast to the limited significance of the Kibo glaciers to hydrology, they show an exceptionally high touristic potential. Thousands of tourists each year are attracted by Kibo and its equatorial ice, and this underscores the need to assess future ice loss. Using a physically based model, Mölg, Hardy, and Kaser (2003) estimate that the plateau glaciers will disappear around mid-twenty-first century if vertical ice wall retreat continues in the present fashion. Thompson et al. (2002) predict the demise of all the glaciers (i.e., both plateau and slope) by 2015–2020. However, from our preliminary model experiments it is not clear yet that the slope glaciers will disappear. Some scenarios indicate that they are likely to stay longer than the plateau glaciers, though probably only in certain areas and to a limited extent. A more precise assessment of this issue will be one of the goals of our project. Agrawala et al. (2003) think that the further retreat or vanishing of glaciers will not reduce Kibo's touristic appeal decisively, as seasonal snow will maintain Kibo's white cap. This characteristic landscape element will be present, however, only during limited periods of the year (i.e., in wet seasons). During dry seasons, when the greatest number of visitors come to Tanzania and Kenya, the glaciers are typically the only natural phenomenon keeping the peak of Kilimanjaro white. Social science research could examine the influence of changing glaciers on tourist appeal in more detail. In any case, the important differentiation between glacier ice and seasonal snow cover must be considered not only in the public discussion of glacier recession but also in consideration of the human perception of the mountain.

A final issue of societal concern is land use change and related shifts in vegetation zones on Kilimanjaro's slopes, which have impacts on water availability and probably on local climate as well. The change is characterized by a decline in forests in the course of the twentieth century. Hemp (n.d.) shows that montane forests and subalpine *Erica* forests lost 9% and 83% of their areas, respectively, within only a few decades (1976–2000). While the former have been destroyed primarily by (illegal) deforestation (but also by agriculture and settlement [Mchallo 1994]), the sharp reduction of subalpine cloud forests is due to the increase in fires as a result of increasing aridity and the subsequent replacement of *Erica* forests with *Erica* bush. Whereas the bush vegetation plays only a marginal role in the local water balance, the forests are essential for filtering and storing water and for intercepting fog (i.e., collecting of cloud water). The strong areal retreat of forests thus significantly affects Kilimanjaro's water supply. The loss in the subalpine belt between 1976 and 2000 alone corresponds to the annual water demand of Kilimanjaro's population if reduced fog interception is counted (Hemp n.d.). Changes in vegetation also have a significant impact on regional and local climate (e.g., Pitman et al. 2004). Generally, the decrease in vegetation cover reduces moist static energy in the atmospheric boundary layer and therefore leads to less convection and rainfall (see examples in Pielke et al. 1992). This makes it likely that a local anthropogenic forcing through deforestation is being superimposed on the large-scale forcing by the Indian Ocean circulation cell. Strict control of the forests is therefore desirable because of their importance for water supply to the lowlands and their possible effect on moisture conditions in the highest reaches of Kibo. The latter will be tested in the mesoscale part of the project through an explicit soil and vegetation submodel coupled with the Regional Atmospheric Modeling System (cf. Cotton et al. 2003).

The societal significance of Kilimanjaro's glaciers nowadays is clearly linked to recent tourism. Many climbers come to see ice and snow under the equatorial sun, while others are drawn by the fact that Kilimanjaro is the highest peak in Africa. When the German geographer Hans Meyer first reached Kibo's summit plateau in 1889 (Meyer 1900) he could not anticipate that 100 years later more than 10,000 people, mainly from Europe and the United States, would ascend the mountain each year (Mchallo 1994). Kibo's attraction was unimaginable even for Europeans in 1848: The missionary Johannes Rebmann's report of the discovery of the mountain's snow cap was dismissed for more than a decade (Meyer 1900). However, after the first efforts to ascend it in the 1860s and 1870s, the mountain's cultural significance for European colonists rose sharply, particularly because of its enormous height. Today's highest point (Uhuru Peak, 5,895 m a.s.l.), for instance, was named "Kaiser-Wilhelm-Spitze" under the German colonial movement (1885–1918) and declared Germany's highest mountain. At the same time, the mountain with its snow and ice cap had—for many centuries—a place in the myths of African tribes living at the base of Kilimanjaro (Gratzl 2000): they viewed it as the shining "house of god," something that one should not approach too closely but adore from a distance. This status has obviously changed, and the long-lasting myth is overshadowed by Kilimanjaro's touristic potential. Many local people today accompany visitors on the mountain (as porters and guides) and rely on that potential. To avoid abuse and overuse of this great natural icon by the stream of tourism (Mchallo 1994), further studies in the cultural, physical, and social sciences are needed, with snow and ice on Kilimanjaro apparently creating an interface between the disciplines.

CONCLUDING REMARKS

The strong retreat of tropical glaciers over the past century provides eminently useful proxy data for the current discussion of climate change. Both field-supported energy balance experiments (e.g., Wagnon et al. 2001; Mölg and Hardy 2004) and pure modeling studies (e.g., Mölg, Georges, and Kaser 2003) indicate the particular sensitivity of tropical glaciers to moisture-related climate parameters and the importance of moisture changes for their behavior. This is true for Kilimanjaro's glaciers, although the peculiar environmental setting of this free-standing mountain requires a special approach to the problem (i.e., the identification of different glacier regimes). The results to date indicate that the glaciers on Kilimanjaro are retreating mainly because of the reduction of moisture in the late nineteenth century. The related local changes in precipitation amount and frequency seem to reflect larger-scale changes in tropical climate, particularly in the Indian Ocean, that merit further investigation. Glacier recession on Kilimanjaro thus demonstrates that global climate change is more complex than local warming, and this is a further argument for studying tropical glaciers as climate proxies.

The relevance of tropical glaciers to society is primarily reflected in their provision of water supplies in parts of South America, mainly during the dry season. As hydroclimatological studies predict a decline in meltwater runoff during the dry season in the coming decades (Juen, Georges, and Kaser 2005), serious future conflicts have to be expected, and this calls for sensitive policy making. Besides the aspect of water supply, tropical glaciers have high touristic potential. Ongoing glacier changes therefore raise interesting questions for combined social and psychological studies. Would a Kilimanjaro that has lost the ice cap on its summit plateau, for instance, continue to be anchored in the minds of people around the world? Climate studies on tropical glaciers represent the first step toward understanding the current changes in these significant symbols of nature and for reconstructing their past and predicting their future.

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