ICE CORE RECORDS

Contents

Africa

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Long ice-core records from Africa are confined to the ice fields on the top of Kilimanjaro, which were drilled in 2000. Other glaciers such as the Lewis Glacier in Kenya and the Speke Glacier in Uganda have been investigated and their current retreat has been documented, but Kilimanjaro at 5893 m above sea level contains the highest and coldest ice fields on the continent, and thus, was determined to have the greatest potential to yield long, high quality records of climatic and environmental variation.

Located in northern Tanzania along its border with Kenya (**Figure 1(a)**), Kilimanjaro (3°04′S, 37°21′E) is the highest mountain in Africa and the largest of a group of volcanoes that continued to be active until at least the end of the Pleistocene (Downie and Wilkinson, 1972). It is a massive and relatively undissected volcano, which rises 5895 m above sea level from a 95 km × 65 km-wide base. Glaciers are believed to have existed on Kilimanjaro, as well as on Mount Kenya and in the Ruwenzori Range, throughout the Holocene (Rosqvist, 1990). In fact, glaciers existed on Kilimanjaro during several periods within the Quaternary, and evidence exists for three glaciations before 100 ka. This would suggest that no major eruptions have occurred in at least the last 500 ka.

A drilling program conducted in 2000 yielded six ice cores from three ice fields on the top of Kilimanjaro (Thompson et al., 2002). Kibo, the 2.5 km-wide caldera at the summit, contains several small ice fields (**Figures 1(b), 2(a)**, and **2(b)**), which are remnants of a former, more extensive glacier. Three ice cores were drilled on the largest, the Northern Ice Field (NIF), which was ~50 m thick in 2000. The Southern Ice Field (SIF), from which two cores were obtained, was ~20 m thick in 2000, while a small body of ice in the center of Kibo, the Furtwängler Glacier (FWG) was 10 m thick and was drilled for one core. In addition, the remnants of the Eastern Ice Field are still visible, often as isolated thin spires of ice (**Figure 2(c)**).

Meteorology of Equatorial East Africa

The climate records from the Kilimanjaro ice cores reflect variations in monsoon intensity. The annual climatic regime over East Africa is very similar to that of southern Asia, where the surface airflow is determined by the position of the leading edge of a monsoon trough. Along the east coast of Africa, the intertropical convergence zone (ITCZ) moves southward from about 2° S in October to 12° S by the end of December. It remains in this extreme southern position until the end of January, then starts slowly back on its northern journey until the end of April, when it is again located at 2° S. At this stage, the wind convergence zone moves north of the equator and forces the southwest monsoon northwards. As the ITCZ moves southward and then northward, the rains also move with it. During its southward movement, rains occur over Kenya, Uganda, and Tanzania from mid-October to mid-December. This period is locally known as the season of 'Short Rains.' This area receives rain again from about mid-March to the beginning of June during the northward migration of the ITCZ, during the season of 'Long Rains' (Asnani, 1993). During the 'Short Rains,' northeasterlies and northerlies replace the southeasterlies in the lower troposphere along the west coast of Africa in association with the build-up of the anticyclonic ridge over the Arabian peninsula. During the 'Long Rains,' southeasterlies push from the south in the lower troposphere along the coast until the low-level jet is established by the end of June.

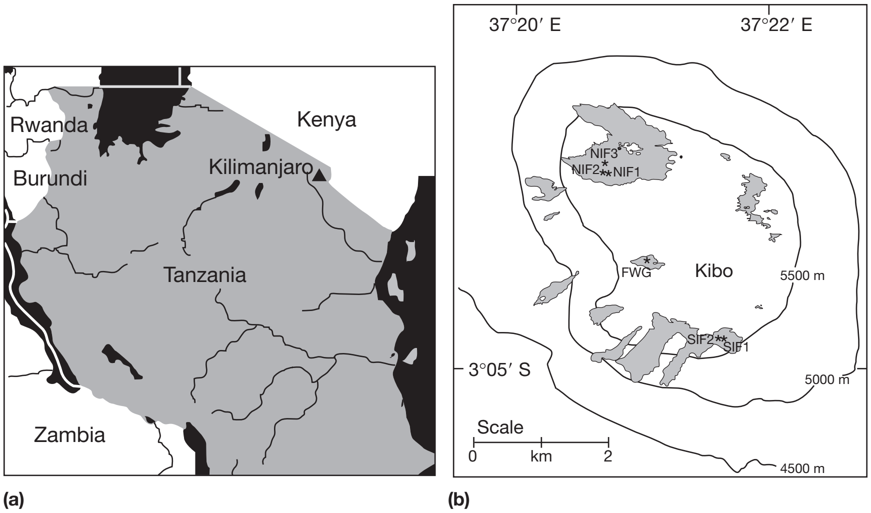

Figure 1 (a) Map of equatorial East Africa showing the location of Kilimanjaro in Tanzania. (b) The Kibo caldera on the top of Kilimanjaro, showing the ice fields in 2007 (shaded) with the locations of the six 2000 ice core drill sites.

Figure 2 (a) Kilimanjaro as seen from the south, with the southern lobes of the Southern Ice Field visible. (b) The Northern Ice Field (background), and the Furtwängler Glacier (foreground), as seen from the Uhuru peak, the summit of Kilimanjaro. (c) A remnant of the Eastern Ice Field.

The Ice Core Records

Five of the six cores drilled were analyzed for stable isotopic ratios of oxygen (^{18}O and ^{16}O). Figure 3(a)–3(e) shows these records as 10-year averages ending at AD 1950, which is close to where a dated tritium signal was located (in 1951/52). The tops of the ice fields are rapidly disappearing; therefore, dating above the known chronology marker is difficult. Figure 3 shows the marked reproducibility of the climate signal from ice cores drilled from one end of Kibo to the other. The shortest time series, that from the FWG (Figure 3(e)), indicates that its ice began accumulating around the middle of the seventeenth century, which was the beginning of the Maunder Minimum as well as a period of very high water levels in Lake Naivasha in Kenya (Verschuren et al., 2000; Figure 3(f)). This suggests that this small glacier in the middle of Kibo originated and grew during a pluvial phase in the East African climate history, which was also the onset of the coldest part of the recent neoglacial period, called the 'Little Ice Age.' This is also marked by ^{18}O depletion (more negative $\delta^{18}O$) in the records from the

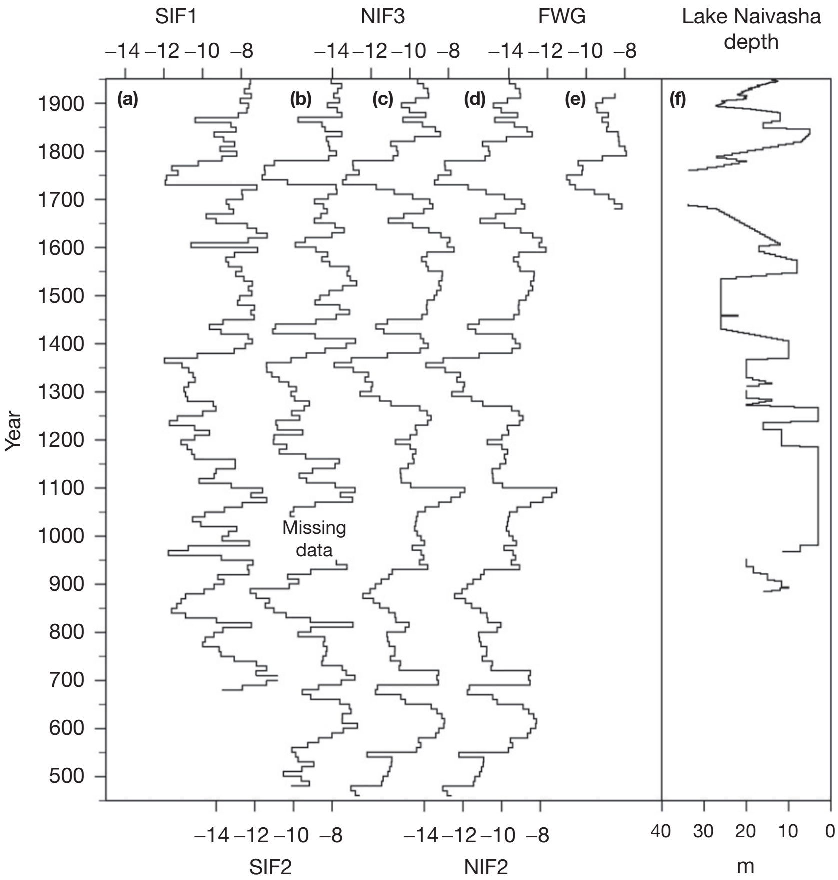

Figure 3 Ten-year averages of isotopic ratios of ^{18}O–^{16}O ($\delta^{18}O$) from (a) Southern Ice Field Core 1, (b) Southern Ice Field Core 2, (c) Northern Ice Field Core 3, (d) Northern Ice Field Core 2, (e) the Furtwängler Glacier, and (f) water levels from Lake Naivasha in Kenya over the last 1100 years (Verschuren et al., 2000; data archived at the World Data Center for Paleoclimatology, Boulder, CO, USA).

SIF and the NIF (**Figure 3(a)–3(d)**). The records from the SIF extend back to AD 500–700, suggesting that this ephemeral glacier began to form during this interval.

A high-resolution record of Holocene climate conditions for eastern Africa is provided by NIF Core 3 (NIF3). Fifty-year averages of soluble aerosols, insoluble dust, and $\delta^{18}O$ are shown for the past 11 700 years (**Figure 4**). Lower aerosol values (chloride, nitrate, ammonium, potassium, magnesium, and sulfate) after ~1800 years ago suggest wetter conditions, which may have contributed to the accumulation of the SIF. The Kilimanjaro ice fields therefore appear to be sensitive to climatic changes in East Africa, responding relatively quickly to regional changes in effective moisture balances.

Major Climatic Events Recorded in the Kilimanjaro Record

The African Humid Period

During the African Humid Period (11–4 ka), generally warmer and wetter monsoon conditions prevailed in response to the precession-driven increase in solar radiation (Nicholson and Flohn, 1980; Street and Grove, 1979). Lakes in the region rose as much as 100 m above today's levels (Street-Perrott and Perrott, 1990). For example, Lake Chad expanded from 17 000 km^2 to cover an area comparable to that of the Caspian Sea today (Broström et al., 1998; Grove and Warren, 1968; Street and Grove, 1979). Calculations of the hydrological balance (Kutzbach, 1980) suggest that annual precipitation over the Lake Chad Basin was as high as 650 mm, compared with 350 mm today, and mean precipitation over the Ziway-Shala Basin in Ethiopia was also calculated to be 47% higher than today. The Magadi Natron basin on the border between Tanzania and Kenya contained a lake that was 50 m deeper than today and had an area of 1600 km^2 in the early Holocene (Hillaire-Marcel and Casanova, 1987). After ~4000 years, African lake levels dropped as conditions became cooler and drier.

In the ice-core record, the African Humid Period is documented by isotopic enrichment (less negative $\delta^{18}O$), at least until 6.5 ka, and lower concentrations of species such as magnesium, calcium, sulfate, and nitrate (**Figure 4**). Contemporaneously, fluoride and sodium were at their highest levels, which is interpreted as intermittent periods of rapidly fluctuating lake levels within the longer period of overall high lake stands. Sodium and fluoride rich alkaline volcanic rocks in the East African Rift Valley are the source for these anions (Hecky and Kilham, 1973), and when the rocks are weathered, the products that are deposited in lakes form fluoride salt crusts during evaporation, known as trona (Nanyaro et al., 1984), or

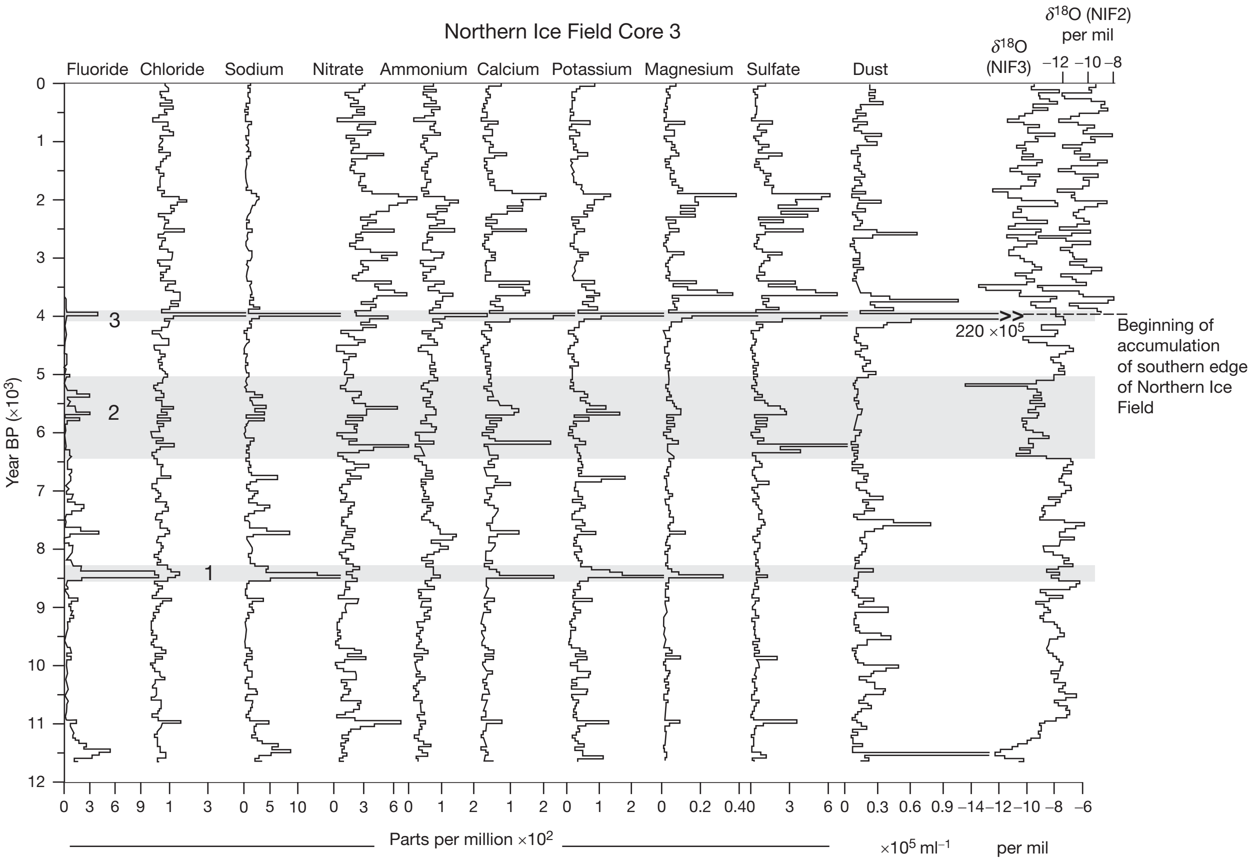

Figure 4 Fifty-year averages of concentrations of ion species and dust from NIF3, and stable isotopic ratios of ^{18}O–^{16}O in NIF3 and NIF2. Abrupt climate events are marked by gray bars and events 1, 2, and 3 are discussed in the text.

magadi in the local vernacular. Periods of high runoff concentrate sodium and fluoride in the lakes, and when lake levels fall due to evaporation, trona precipitates and provides an aerosol source for the Kilimanjaro ice fields.

Abrupt climate events

Early Holocene

The fluoride concentrations between 8.4 and 8.2 ka are the highest in the Kilimanjaro record (marked as '1' in **Figure 4**), and are in fact the highest yet reported from any ice core. These high levels are nearly coincident with the large, abrupt reduction in methane (CH_4) in the European Greenland Ice Core Program (GRIP) core (Blunier et al., 1995), and with the largest ^{18}O depletion in the Holocene portion of both the GRIP and the Greenland Ice Sheet Project (GISP) 2 records (Alley et al., 1997). The peak fluoride and sodium levels suggest abrupt and intense lake level decreases accompanying a regional desiccation event. It is possible that the relatively short-term global CH_4 decrease was linked, and perhaps even preceded, by tropical hydrological changes leading to aridity, particularly in Africa.

Middle Holocene

An abrupt decrease in δ^{18}O from 6.5 to 5.3 ka ('2' in **Figure 4**), culminating in another sharp isotopic depletion at 5.2 ka, is suggestive of a millennium-long climatic cooling. The interval of more negative ^{18}O values from 6.5 to 5 ka is nearly contemporaneous with a 'second humid period' (6.5–4.5 ka) when conditions were wetter than today, but drier than the early Holocene 'first humid period' (Nicholson and Flohn, 1980). During this time, the Ziway-Shala Basin attained its highest levels before dropping rapidly to near modern low levels by 4 ka (Street-Perrott and Perrott, 1990). The abrupt cooling event at the end of this second humid period about 5.2 ka is recorded as the largest ^{18}O depletion in the NIF record. This climatic change recorded in Kilimanjaro ice is contemporaneous with the largest ^{18}O enrichment in the Soreq cave speleothem record in Israel (Bar-Matthews et al., 1999), a decline in both lake levels in northern Africa (Sirocko et al., 1993; Street and Grove, 1976; Street-Perrott et al., 1990) and vegetative cover in India (Swain et al., 1983), and the lowest Holocene CH_4 concentrations in the GRIP ice core (Blunier et al., 1995). Documentary evidence ranging from northern Africa to Arabia (Weiss, 2000) also confirms this abrupt climate change. Around 5300 years ago, hierarchical societies formed in the Nile Valley and Mesopotamia, while Neolithic settlements in the inner desert of Arabia were abandoned (Uerpmann, 1990). This century-scale rapid cooling and drying event correlates with the Late Uruk abrupt climate change around 5.2 ka that is suggested to have altered environments outside the Mesopotamian lowlands (Weiss, 2000).

The second abrupt climate event recorded in the middle Holocene, dated around 4200 years ago ('3' in **Figure 4**), is associated with a visible dust layer (30 mm thick) and very high aerosol concentrations in NIF3. This is interpreted to represent a century-scale hiatus in ice accumulation due to a prolonged period of weaker monsoon activity. During this time, evidence indicates that the NIF decreased in size and that its southern ice wall retreated substantially. The $\delta^{18}O$ record from NIF2 actually begins at the chronological level of this event (**Figure 4**), which means that this part of the ice field began to reform only after the end of the drought. The ice field was most likely much larger by the end of the African Humid Period, but contracted very quickly during this dry interval. Thus, it appears that the major dust layer in NIF3 was formed during extremely dry conditions either before or during the retreat of the NIF margin.

This drought appears to have been widespread throughout the tropics, especially in those regions affected by monsoon circulation, and its climatic effects were experienced throughout northern and tropical Africa, the Middle East, and western Asia (Gasse and Van Campo, 1994; Pachur and Hoelzmann, 2000; Street-Perrott and Perrott, 1990). Water levels dropped in tropical east African lakes (Street-Perrott and Perrott, 1990), there was a very large influx of carbonate dust that was transported from Syria into the Gulf of Oman (Cullen et al., 2000), and the event is marked by a sharp increase in carbon isotopic ratios in the Soreq cave speleothem (Bar-Matthews et al., 1999). The drought was so severe that it has been considered instrumental in the collapse of a number of civilizations from North Africa to India (see articles in Dalfes et al., 1997). The possibility that the drought extended beyond Africa, Asia and the Middle East into South America is suggested by the dust record in an ice core from the Andes of Northern Peru (Davis and Thompson, 2006). As the drought ameliorated, the NIF began to accumulate mass and reestablish itself over a larger portion of the crater rim.

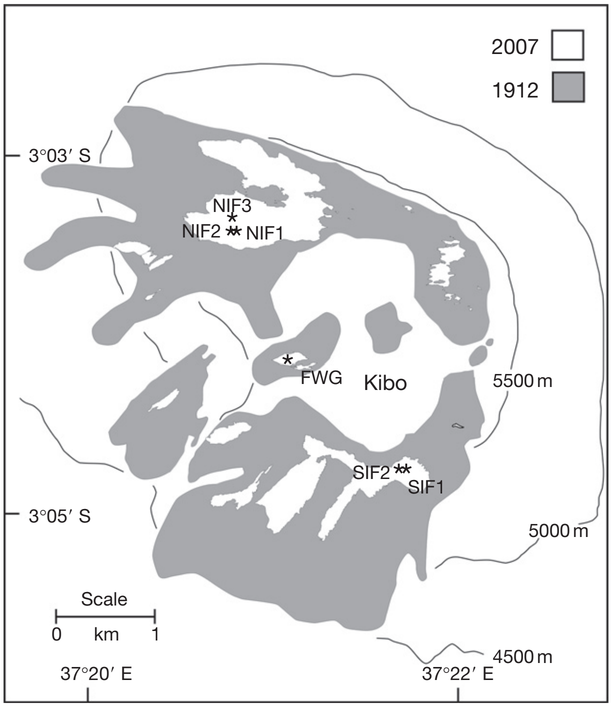

Figure 5 Extent of the Kibo ice fields in 1912 (shaded) and 2007 (white). The 1912 ice extent is from Hastenrath and Greichar (1997), the 2007 ice extent is from Thompson et al. (2009).

Recent Retreat of East African Glaciers

All of the ice fields and glaciers in tropical East Africa are currently undergoing rapid retreat. Since ~1850 the Lewis Glacier on Mt. Kenya has decreased from 0.69 to 0.20 km^2, losing 71% of its surface area (Allison and Peterson, 1976), and from 1963 to 1992 alone it lost 40% of its mass (Hastenrath and Kruss, 1992). In fact a 1978 expedition to the Lewis Glacier, which sought to ascertain its suitability for drilling, confirmed that the ice was too warm (due to its low elevation and the recent warming) to preserve a useful climate record (Thompson, 1979). The surface area of the Speke glacier in the Ruwenzori Range in Uganda has decreased 74% from 6.51 km^2 in 1906 to 1.67 km^2 in 1990 (Kaser, 1998). Likewise, the ice cover on Kibo has retreated 85% (~12 to ~2.6 km^2) from 1912 (Hastenrath and Greichar, 1997) to 2007 (**Figure 5**), and 26% of the ice that was present in 2000 has disappeared (Thompson et al., 2009). The ice on the Northern and Southern Ice Fields thinned about 3.6 and 24%, respectively from 2000 to 2007, while the ice on the FWG in the center of the crater thinned 50% from 2000 to 2009. At this rate, the FWG will disappear by 2018 and the remaining ice fields over the following decade, making the top of Kilimanjaro completely ice free for the first time in 11 ka.

There is no definitive consensus for the cause of the recent glacier retreat in East Africa. The discussion has been conducted in the scientific literature (e.g., Kaser et al., 2004; Mölg and Hardy, 2004; Mölg et al., 2009; Thompson et al., 2009, 2011) as well as in the media. The vertical lifting of the 0 °C isotherm resulting from increasing atmospheric warming has been cited, as has decreasing moisture in the region. The linear relationship, close to the meteoric water line, between $\delta^{18}O$ and deuterium isotopic ratios (δD) in the ice cores indicates that the disappearance of the ice fields on the top of Kilimanjaro is driven by melting (Thompson et al., 2011) rather than by sublimation (Cullen et al., 2007). In the Ruwenzori Mountains, which fall on the border between Uganda and D.R. Congo, both field work and satellite imagery show that the glaciers have decreased by ~50% in aerial extent from 1987 to 2003 (Taylor et al., 2006). This was synchronous with an increasing trend in air temperature of ~0.5 °C per decade over the last four decades. Limnological studies in this region confirm that the beginning of the modern glacier recession occurred with a warming regional climate and not with hydrological changes (Eggermont et al., 2010a,b; Russell et al., 2008). However, regardless of the cause(s), the disappearance of the ice fields in East Africa, particularly on Kibo, will have negative economic implications for the local populations as the ice is important for both the tourist industry and for the agricultural activities on the lower slopes.

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