A paleoclimatic perspective on the 21st Century glacier loss on Kilimanjaro

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ABSTRACT

Assessing the significance of the current glacier loss on Kilimanjaro demands a temporal perspective that is as well constrained as possible. This paper provides that context by drawing on both older and very recent direct measurements and ancillary observations of the ice fields and the analyses of the ice cores collected from them in 2000. Ice retreat mechanisms observed there today are consistent with the preservation of the oldest ice in central deepest part of the Northern Ice Field. While the ice cores from Kilimanjaro were a challenge to interpret due to the absence of annual layers, the ice-core-derived paleoclimate histories published by Thompson and others (2002) are further confirmed by more recent paleoclimate records from tropical East Africa.

RECENT RETREAT OF THE KILIMANJARO ICE FIELDS

Another paper in this volume “Tropical glaciers, recorders and indicators of climate change, are disappearing globally” discusses the widespread retreat of modern glaciers throughout the Tropics. Assessing the significance of this recent glacier loss requires placing it in a temporal perspective derived from the best data available. Ice-core derived climate reconstructions from a number of low-latitude glaciers contribute substantially to such a database.

The current shrinking and thinning of the ice fields on the summit of Kibo, the central peak of Kilimanjaro, are placed in a longer-term context using both direct observations and the reconstruction of Holocene climatic variations from the suite of six cores drilled there in 2000 (Thompson and others, 2002; 2009). Constructing the paleoclimate histories from these ice cores was a challenge due to the lack of annual resolution and the removal of the most recent five decades of record by surface ablation. Here we review the climate history provided by the Kilimanjaro ice cores, discuss recent observations and address the significance of the current retreat of its summit glaciers.

Osmaston (2004) presented an overview of past glaciations on Kilimanjaro, with the first known glaciations dated back ~500 ka BP. Based on evidence from cosmogenic ^{36}Cl dating of moraine boulders, he concluded that the main glaciation occurred from 17 to 20 ka BP, or around the Last Glacial Maximum (LGM). From his map of the moraines on the summit of Kibo the maximum ice coverage is calculated as 116.6 km^2, over 60 times larger than at present (1.82 km^2). However, there is no evidence that this ice survived the Bølling interstadial (~14.6 - 14.0 ka BP, calibrated) and ^{14}C dates on material from near the bottom of the Northern Ice Field (NIF) Core 3 (Thompson and others, 2002) suggest that the basal ice dates to the Early Holocene. Additionally, the $\delta^{18}O$ records from six low-latitude ice cores suggest that glacier growth on Kilimanjaro was contemporaneous with the onset of the African Humid Period (Thompson and others, 2005). Nevertheless, as the ^{14}C dates were measured on samples of small mass, it is important to consider additional lines of evidence to determine whether it is physically possible for the interior ice of the Northern Ice Field to be early Holocene in age.

To investigate this, it is instructive to examine the processes currently contributing to the shrinking of these ice fields. For example, Figure 1 documents the ice loss between 1999 and 2008 on the Furtwängler Glacier (FWG), a small ice field in the middle of the Kibo crater. In 1999 the FWG margin was an intact wall ~10 meters high (Fig. 1a); however, by 2006 the margin had retreated and collapsed, leaving a narrow remnant of the wall (Fig. 1b). Over the next two years all the ice along this section of the margin disappeared (Fig. 1c), thus demonstrating how rapidly these processes are occurring. The ablation is driven in part by melting. The retreating ice exposes more of the darker crater surface which absorbs more radiation and in turn accelerates glacier loss. Similar processes are underway along the vertical margins of all these ice fields, including the Northern Ice Field (NIF), which is the highest and largest ice field on Kibo. A photograph taken in 1999 from Uhuru summit peak looking north toward the NIF , with the FWG in the foreground (Fig. 2a), shows a section of the vertical margin of the NIF that contained three “steps” on the western side, which are detailed in the enlarged section (Fig. 2b). A more recent photo (2006) of the margin of NIF (Fig. 2c) shows that these three steps (see arrows) are active collapse features that have evolved from the top downward along the retreating margins during this seven-year period. Along much of the margin one now sees only the more recent ice which has collapsed from above; thus, older ice would be expected only in the center of the ice field. These photos demonstrate that these recent margin features are very active and are driven primarily by current climate change.

The vertical walls and steps observed on Kilimanjaro are not unique. In fact, they occur on glacier margins in Greenland (Hughes, 1989), in Antarctica (e.g., the glaciers in Taylor Valley; Lewis and others, 1999) on tropical ice caps such as Quelccaya ice cap, Peru (see cover photo of *Science*, 203(4386)) and on many glaciers across the Tibetan Plateau such as the Dunde and Guliya ice caps (see cover photo of *Science*, 276(5320)).

ICE CORE DATING AND VALIDATION

Ice flow models have been used to date the older sections of ice cores since the first drilling program in Greenland in 1966 (Johnsen and others, 1992). The physics of ice flow is well established (Paterson, 2000) and has been successfully applied to glaciers around the world, including mountain-top glaciers, often with independent time checks on the model results. The first high altitude tropical ice cap dated to the base via a modeling approach is Quelccaya, the world's largest tropical ice cap (Thompson and others, 1982). Prior to drilling, the depth-age calculations suggested that a core to bedrock would cover at least 600, but no more than 1300 years. However, the cores drilled in 1983 contained ~1,500 years based on both isotopic and dust analyses and counting the visible annual layers (Thompson and others, 1985). Versions of this flow model have been used in subsequent calculations of the age of mountain glaciers in China, the Himalayas and the Andes in Peru. Model ages are routinely checked with independent dating techniques including AMS ^{14}C and cosmogenic dates, gas measurements, annual layer counting (where possible), and stable isotope matching with absolutely dated records (Thompson and others, 1997; 1998).

Reconstructing the time series for the Kilimanjaro ice cores was challenging. The procedure involved constructing a time scale for the NIF Core 3 (NIF3), which was drilled in the middle of the ice field and contained the longest record. The other five cores were then referenced to this 'master chronology' by matching common $\delta^{18}0$ features. We used the simplest age-modeling for a steady-state glacier of constant accumulation, the method first introduced by Nye (1963) and later used by Dansgaard and others (1969).

For any given ice field the ice core chronology can be more or less robust depending on the availability of different types of calibration points. For Kilimanjaro three time lines were selected to guide the application of the flow model (Thompson and others, 2002; online supplement). The year 1950 A.D., which is also the origin of the calibrated-radiocarbon timescale, was assigned at a depth of 1.6 m, consistent with the ^{36}Cl bomb horizon. Other time lines came from comparison with regional paleoclimate records that cover the last millennium (e.g., Verschuren and others, 2000). A basal age was assigned using the U/Th dated Soreq Cave speleothem isotope record that contained $\delta^{18}O$ events that are likely contemporaneous (and inversely correlated) with $\delta^{18}O$ events in NIF3. Finally NIF3 was dated back to 11.7 ka by applying the finite-Nye flow model. The model results are supported by 15 AMS ^{14}C dates (Thompson and others, 2002; Table S1). While the masses of the sample material used for carbon dating were very low, this analysis on organics frozen in the ice at the top of a mountain like Kilimanjaro does not suffer from many of the issues which plague AMS ^{14}C dating in other archives (e.g. reservoir effects, "old carbon" contamination). The AMS dates of ~9010 years BP at 47.4 meters, and of ~9360 years BP at 48.43 meters, support the model ages and the presence of old ice near the bottom in the center of the NIF. While it is very easy to contaminate old carbon with modern carbon during sample preparation, it is very hard to contaminate a sample with old carbon and thus the dates on material found near the bottom of the NIF3 core are very likely robust.

The key factors determining the length of the time series contained in a glacier are accumulation rate, ice thickness and temperature at the ice-bedrock interface. The latter is the most critical control on the basal age. If a glacier is frozen to the bedrock then time cannot be removed. Hence, relatively thin mountain top glaciers (as opposed to valley glaciers) may contain very long histories. For example, over 500 ka of climate history is preserved in the 308-meter Guliya ice cap in the Western Kunlun of China (Thompson and others, 1997). The ice temperature measured at the base of the NIF on Kibo was

$-0.4^{o}C$ in 2000. The climate record from the center of the NIF may seem long in light of the thickness (49.0-m) of the glacier; however, the basal temperature in 2000, under the current warm conditions, precludes removal of ice from the bottom.

The ice core records from the six Kilimanjaro ice cores show that the individual ice fields differ significantly in age. The youngest ice field (Furtwängler) is only a little over 200 years old at the bottom while the two cores from the Southern Ice Field (SIF) date to ~ 1.5 ka at the base. Two ~50-meter cores from near the southern margin of the NIF are both ~4 ka at the bottom. Together these records show that the ice fields on Kibo have expanded and contracted throughout the Holocene, with the center of the NIF (reflected in the NIF3 core) apparently surviving the variable climate conditions throughout the Holocene.

FWG was the only ice field found to be water saturated during the 2000 ice core drilling, which can be seen in Fig. 3 where water is shown pouring out of the core barrel during a core extraction. The temperature throughout the FWG was at the pressure melting point ($0^{o}C$) during that field season. The effect of this saturation on the soluble chemistry of the ice is illustrated by comparing the anion and cation concentrations in the Northern Ice Field Core 3 (Fig. 4a) and in the FWG core (Fig. 4b). For example, the sulfate concentrations in FWG are uniformly low except for a basal spike from material entrained from the substrate. While melting has removed most of the soluble anions and cations from the FWG ice column, the 49-meter NIF3 core does not show similar evidence of melting and percolation throughout its 11,700 year history (Fig. 4a).

The visible stratigraphy of the ice provides another line of evidence demonstrating how the changes now observed on the Kilimanjaro ice fields are unusual in the context of the past ~11.7 millennia. The observed surface lowering on the NIF (Thompson and others, 2009) is partially the result of surface melting, a recent phenomenon confirmed by the stratigraphy of NIF3. The upper 65 cm of the core is the only portion containing elongated bubbles and open voids that are characteristic of extensive melting and refreezing. These features are not observed in any other sections of the core (Thompson and others, 2002 online supplement; Thompson and others, 2009). This observation, along with the soluble chemistry data, confirms the absence of surface melting and percolation during the previous ~11,700 years.

TROPICAL EAST AFRICA PALEOCLIMATE RECORDS

Tropical East Africa paleoclimate records since 1.5 ka BP

Since publication of the Kilimanjaro ice core results (Thompson and others, 2002) several new paleoclimate records have appeared that support the general interpretation of the original ice core record on decadal to millennial time scales. A comparison with the TEX 86-inferred lake surface water temperature (LST) record from Lake Tanganyika on the Tanzanian border (Tierney and others, 2010) with the Kilimanjaro ice core $\delta^{18}O$ records is shown in Figure 5. This new record demonstrates that the late-twentieth century warming in Lake Tanganyika is unprecedented over the last 1.5 ka BP. However, since the tops of all six ice cores drilled from the summit of Kilimanjaro in 2000 are missing due to the mass loss from the surface it is impossible to compare the changes over the last ~50 years. The similarities between the LST and the $\delta^{18}O$ time series are apparent over the previous ~1500 years, albeit with a slight offset. The lacustrine temperature record points to an increase in LST of 2^{o}C since 1900 (Tierney and others, 2010) which is higher than the 1.3^{o}C temperature rise measured instrumentally since 1913 (Verburg and others, 2003). Moreover, the charcoal data from these lake cores show a systematic decrease (wetter conditions) from the late 1800s to the present, similar to the instrumental trend for the greater East African region (Hulme and others, 2001). The unprecedented temperature rise since 500 AD coupled with wetter conditions in East Africa point to temperature as an important driver for recent loss of glaciers throughout equatorial Africa as argued by Taylor and others (2006).

Tropical East Africa millennial-scale paleoclimate records

Incoming solar radiation (insolation) increased over the tropical Northern Hemisphere (NH) during the Early Holocene as Earth recovered from the last glacial stage. NH insolation peaked at ~9 ka BP and decreased toward the present (Fig. 6a). The shape of this insolation curve is consistent with the $\delta^{18}O$ record over the Holocene in two tropical ice cores: Huascarán (9^{o}S) (not shown) in the Cordillera Blanca of Northern Peru (Thompson and others, 2005), and Kilimanjaro (3^{o}S) in Tanzania, East Africa (Fig. 6d). Although Huascarán is located in the Southern Hemisphere, its stable isotope record follows the NH insolation curve because the predominant source of its precipitation is the tropical North Atlantic (Thompson and others, 1995). A more recent record of total solar irradiance (Steinhilber and others, 2009), based on ^{10}Be measured in ice cores, is presented in Figure 6b. Reductions in solar output centered ~5.5 ka and ~7.5 ka are broadly consistent (considering possible ice core dating uncertainties) with isotopic enrichment in the Soreq Cave speleothem record (Fig. 6c) from Israel (Bar-Matthews and others, 1999) and isotopic depletion in the Kilimanjaro ice cores (Fig. 6d). One of the most dramatic Middle Holocene abrupt climate events occurred around 5.2 ka. Evidence of this event is expressed in the Kilimanjaro record as a sharp but short-lived depletion in ^{18}O suggestive of an abrupt and extreme cooling episode (Thompson and others, 2002). It was also the most prominent climatic event of the last 13,000 years in the Soreq Cave record and is present in numerous climatic, biological, and archeological records from around the world. Many tropical paleoclimate records, especially those located in the African/Asian monsoon region, indicate that climate conditions turned either sharply arid or more humid ~5 ka (Magny and Haas, 2004), and records from East Africa suggest increased aridity around this time (Chalie and Gasse, 2002).

A number of proxy climate records from the tropics chronicle an abrupt climate event roughly one millennium after the Middle Holocene cold event. The event appears from ~4.0 to 4.5 ka BP in various records that extend from South America to northern Africa and eastern China. It appears to be associated more with extreme decreases in effective moisture than with temperature changes. In addition to the Kilimanjaro NIF3 record (Fig. 7a), it is recorded in marine cores from the Indus delta region (Staubwasser and others, 2003, not shown) and the Gulf of Oman (Cullen and others, 2000) (Fig. 7b) where an abrupt spike in carbonates has been chemically traced to an archeological site (Tell Leilan) in Syria, the home of the ancient Akkadian culture (Weiss and others, 1993). Lake records from equatorial Africa *(*Gillespie and others, 1983) indicate that water levels decreased greatly (Fig. 7c), as did levels in western Tibet (Gasse and others, 1991; 1996) which are not shown. Other records contain evidence of a contemporaneous, sudden and marked episode of aridity. The Soreq Cave speleothem record (Bar-Matthews and others, 1999) shows an abrupt decrease in δ^{13}C within the 4.2 to 4.5 ka BP window, implying lower precipitation. Palynological data from north-central China also suggest a cold, dry period from 3.95 to 4.45 ka BP, which is inferred by a sudden decrease in tree pollen concentration (Xiao and others, 2004). A speleothem $\delta^{18}O$ record from Southern China shows multiple dry periods coinciding with Bond (1.5 ka) events in the North Atlantic (Wang and others, 2005). Some of these, including the one at 4.2 ka BP, occurred during periods of strong variability in solar activity.

The geographic extent of this drought extends to South America as seen in several paleoclimate proxy records. For example, stable isotope analyses of planktonic foraminifera from the Amazon fan show that the highest $\delta^{18}O$ values in the Holocene (suggestive of reduced Amazon River flow) occurred ~4.5 ka BP (Maslin and others, 2000), almost contemporaneously with a depletion of ^{18}O in a core from Lake Junin, Peru (Seltzer and others, 2000). Evidence for Middle Holocene aridity on the Altiplano comes from Lake Titicaca, on the border between Peru and Bolivia. Here the percent of freshwater plankton reached its lowest levels between 5 ka and 2 ka BP, and the percent of saline diatoms increased at ~ 6 ka BP (^{14}C age) and reached a maximum at ~3.6 to 4.0 ka BP (^{14}C age) (Baker and others, 2001). Tapia and others (2003) provide a more refined time line for climate variation in this interval using the Lake Titicaca record of percent saline planktonic taxa, which confirms that although water levels were low between 3 and 6 ka BP, the lowest levels were achieved at ~4.5 ka BP.

The Huascarán ice core from the Cordillera Blanca of Northern Peru contains a large dust spike that is dated between 4.0 and 4.5 ka BP (Fig. 7d) (Davis and Thompson, 2006). The dust originates from the African west coast where it is entrained by the northeast trade winds during austral summer (the wet season in the Cordillera Blanca) and is carried, along with moisture, across the tropical North Atlantic and the Amazon Basin. Saharan dust which has been transported during the austral summer has been found in the Amazon Basin (Swap and others, 1992). The dust that was deposited on Huascarán during the Middle Holocene was most likely transported in this manner during centuries of extreme aridity both in Africa and South America (Davis and Thompson, 2006). The large dust spike in the Kilimanjaro record, which is dated around 4.0 ka BP (Fig. 7a), was also the product of this "mega drought" that may have lasted a few centuries, during which time the Northern Ice Field, presently the largest on the mountain, dramatically decreased in size (Thompson and others, 2002).

CONCLUSIONS

Although the ice cores that were recovered in 2000 from ice fields on the summit of the Kibo crater were difficult to date, there is compelling evidence that the longest time series extends to the Early Holocene. These multiple lines of support include (1) ^{14}C dates consistent with the ice-age model results, (2) the appearance of Middle Holocene features confirmed by numerous paleoclimate proxy records throughout the tropics, and (3) a new lake core record covering the last 1.5 ka that supports the Kilimanjaro time series. The ongoing shrinking and thinning of the ice fields on Kibo are placed in a much longer-term perspective by the ice-core derived climate histories. Visible inspection of the NIF3 core confirms that the current surface melting is unprecedented in the last 11.7 ka. Significant recent melting of the much smaller FWG is documented by the "washing out" of aerosols throughout the ice, and the water-saturation of the glacier was noted during drilling. By 2009, 86% of surface area of the ice that covered the mountain in 1912 had been lost, and 27 percent of the areal coverage present in 2000 disappeared in the following decade (Thompson and others, this volume). Kilimanjaro's ice loss is consistent with widespread glacier retreat in the mid- to low latitudes.

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FIGURE CAPTIONS

Figure 1. The rapid retreat of the Furtwängler Glacier between 1999 and 2008 is illustrated with particular reference to the southern margin. In 1999 (a) the margin was intact, but by 2006 (b) the glacier was bifurcating and this wall had thinned dramatically (c). By 2008 the FWG had separated into two parts (d), and the breach in the wall was complete (e).

Figure 2. The southern margin of the Northern Ice Field in 1999 (a) contained three "ledges" indicated by the arrows in (b). By 2006 the margin had collapsed and rapid surface lowering had occurred (c, d).

Figure 3. During the 2000 drilling of the Furtwängler Glacier water poured from the drill barrel after each run, illustrating the glacier was water-saturated throughout.

Figure 4. The records of major anions and cation concentrations from the Northern Ice Field Core 3 (top panel) and the Furtwängler Glacier ice core (lower panel) illustrate the effect of melting on the soluble aerosol concentrations throughout the glacier.

Figure 5. Comparison of the lake surface temperature record from Lake Tanganyika (Tierney and others, 2010) with the δ^{18}O records from the five ice cores recovered on Kilimanjaro shows numerous common features.

Figure 6. Comparison of (a) tropical Northern Hemisphere summer insolation and (b) total solar irradiance (Steinhilber and others, 2009) through the Holocene, with (c) the δ^{18}O record from the Soreq Cave (Israel) speleothem and (d) the Kilimanjaro δ^{18}O ice core record (as 50-yr averages) illustrates the relationship between variations in tropical insolation and the tropical stable isotope records through the Holocene, and between the isotope records which both record the abrupt climatic cooling at ~5.2 ka BP.

Figure 7. Evidence for the abrupt Middle Holocene dry period in the tropics is visible in (a) the dust concentrations from NIF3 (Thompson and others, 2002), (b) the carbonate

abundances in the Gulf of Oman marine core (Cullen and others, 2000), (c) the lake levels in tropical Africa (Gillespie and others, 1983), and (d) the dust concentrations from Huascarán in Northern Peru (Davis and Thompson, 2006).

Figures

Figure 1

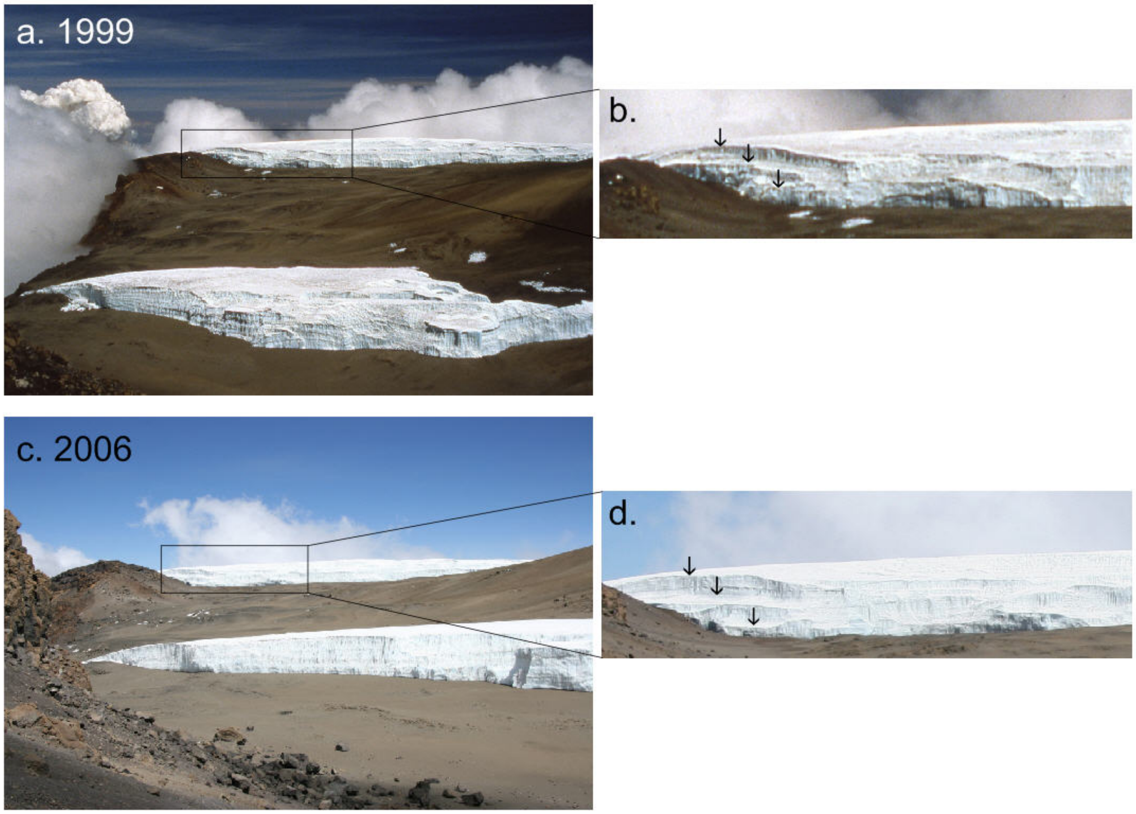


Figure 2

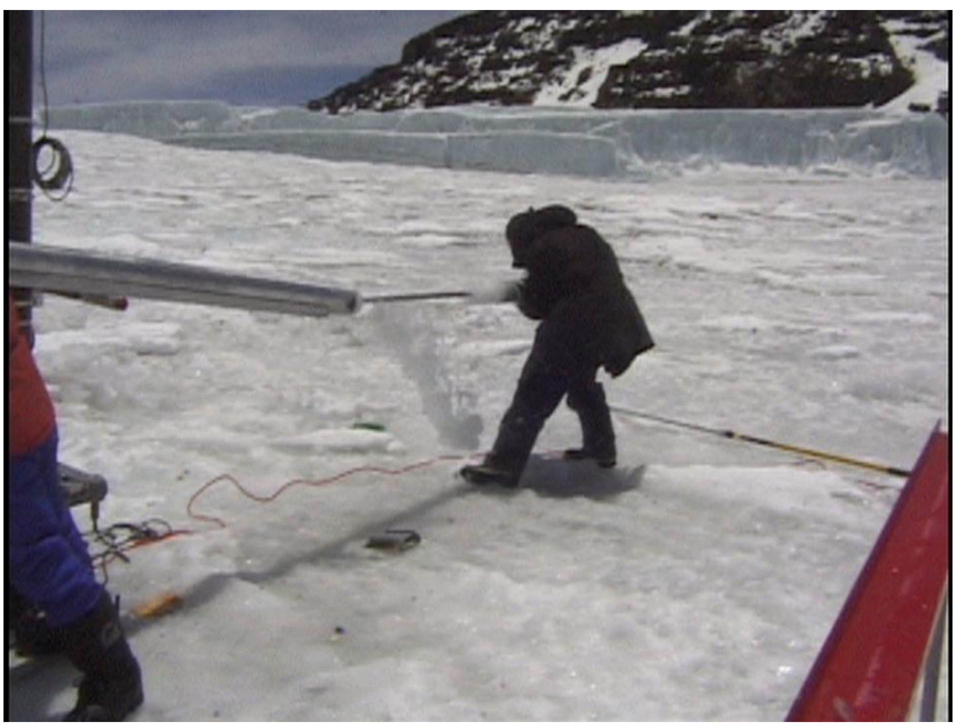
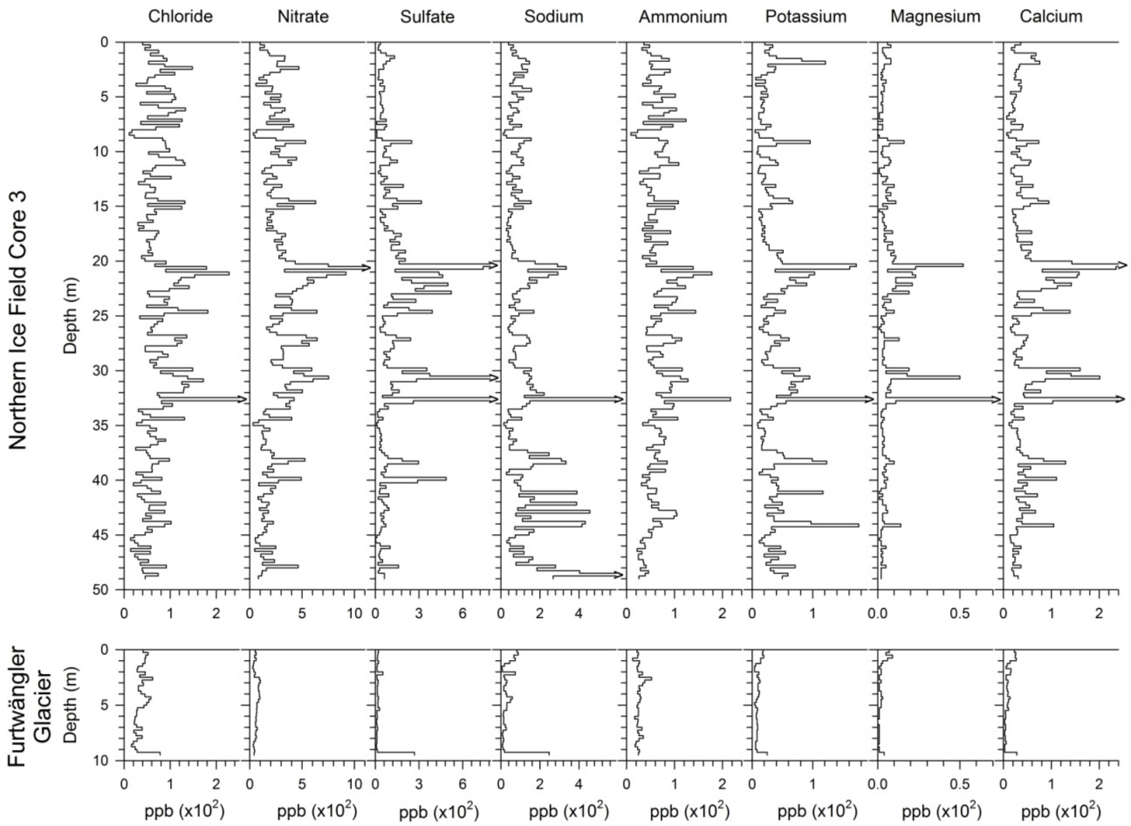


Figure 3



Chloride
Nitrate
Sulfate
Sodium
Ammonium
Potassium
Magnesium
Calcium
Northern Ice Field Core 3
Depth (m)
Furtwängler Glacier
Depth (m)
ppb (x10²)

Figure 4

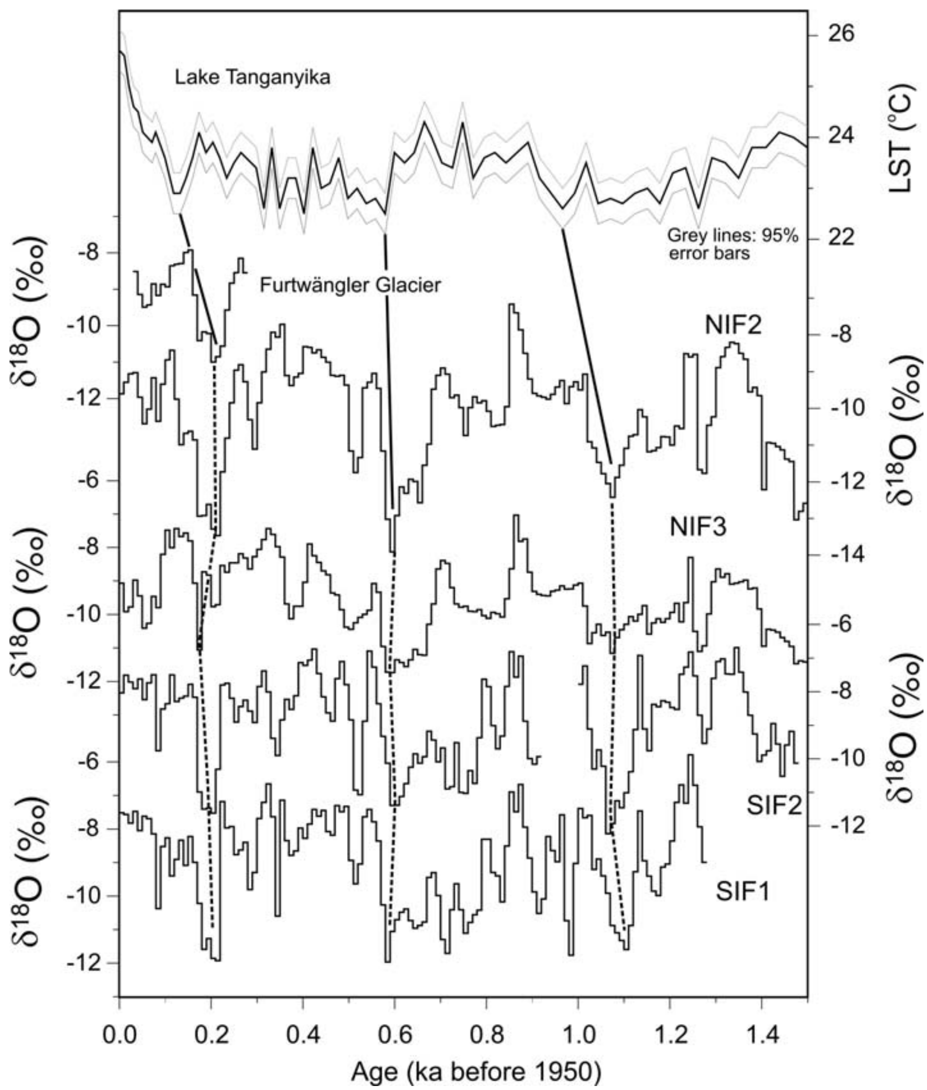

Lake Tanganyika
Grey lines: 95% error bars
Furtwängler Glacier
NIF2
NIF3
SIF2
SIF1
LST (°C)
δ18O (‰)
Age (ka before 1950)

Figure 5

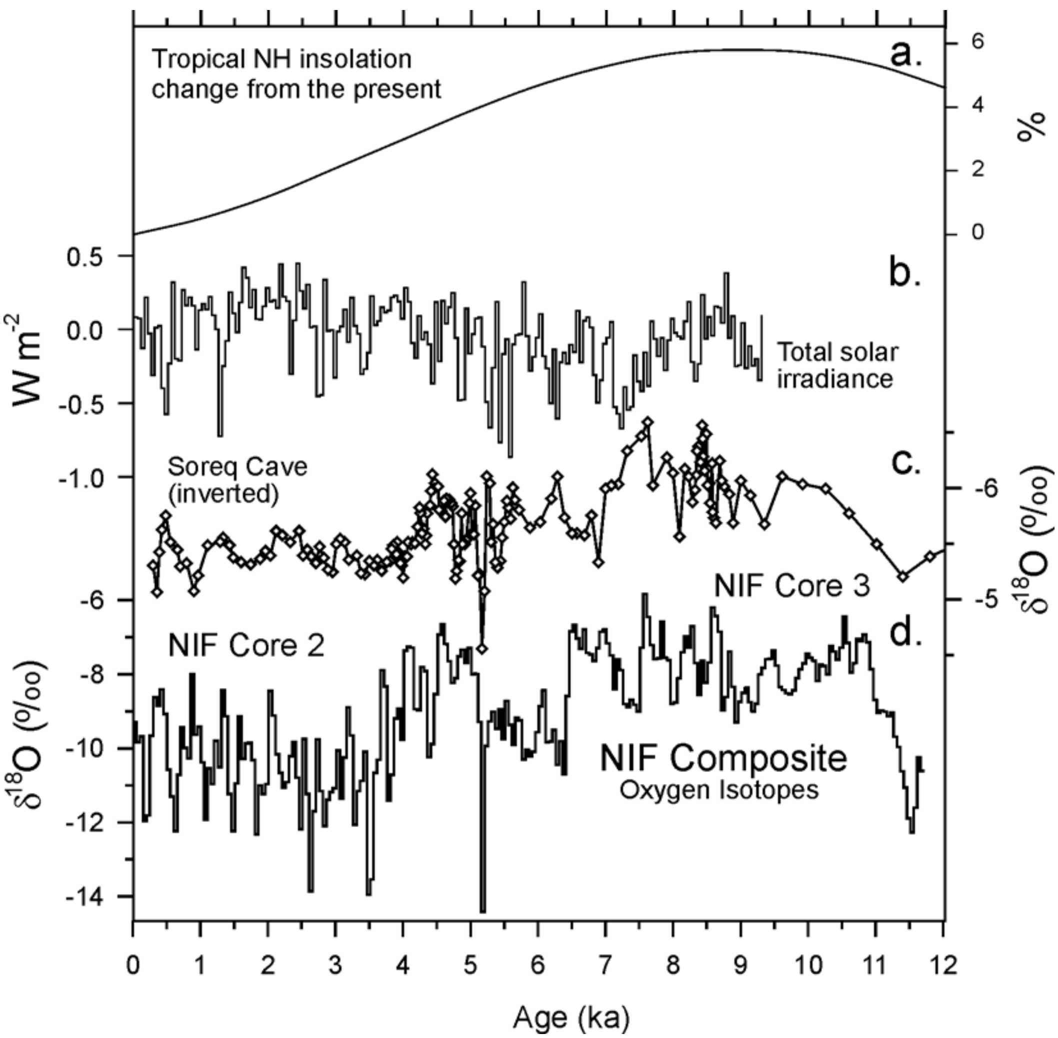
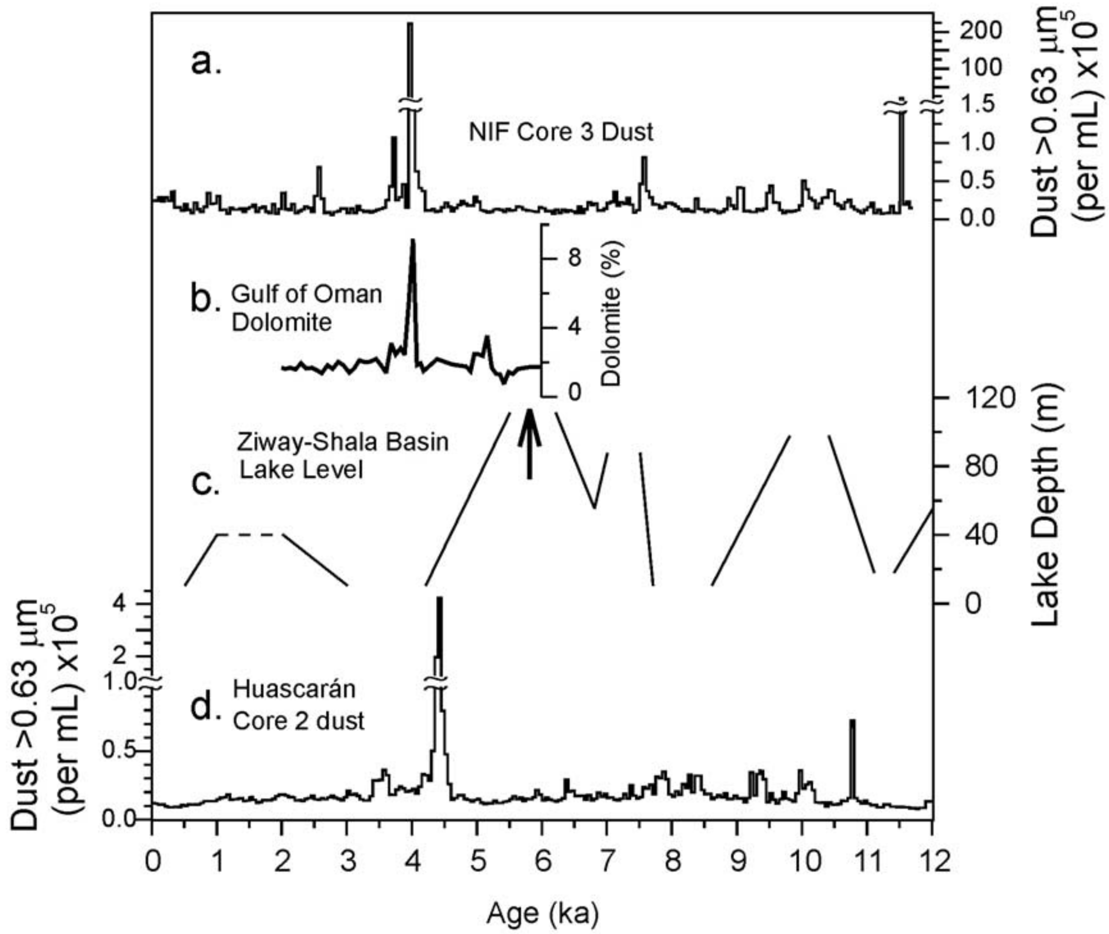

Tropical NH insolation
change from the present
a.
%
b.
W m^{-2}
Total solar
irradiance
Soreq Cave
(inverted)
c.
δ^{18}O (‰)
NIF Core 3
NIF Core 2
d.
δ^{18}O (‰)
NIF Composite
Oxygen Isotopes
Age (ka)

Figure 6



a.
NIF Core 3 Dust
Dust >0.63 µm (per mL) x10^5
b. Gulf of Oman Dolomite
Dolomite (%)
c. Ziway-Shala Basin Lake Level
Lake Depth (m)
d. Huascarán Core 2 dust
Dust >0.63 µm (per mL) x10^5
Age (ka)

Figure 7