Tropical Climate Instability: The Last Glacial Cycle from a Qinghai-Tibetan Ice Core


An ice core record from the Guliya ice cap on the Qinghai-Tibetan Plateau provides evidence of regional climatic conditions over the last glacial cycle. 36Cl data suggest that the deepest 20 meters of the core may be more than 500,000 years old. The δ18O change across Termination I is ~5.4 per mil, similar to that in the Huascaran (Peru) and polar ice cores. Three Guliya interstadials (Stages 3, 5a, and 5c) are marked by increases in δ18O values similar to that of the Holocene and Eemian (~124,000 years ago). The similarity of this pattern to that of CH4 records from polar ice cores indicates that global CH4 levels and the tropical hydrological cycle are linked. The Late Glacial Stage record contains numerous 200-year oscillations in δ18O values and in dust, NH4+, and NO3− levels.

The relative significance of 20th-century climatic and environmental changes must be assessed from the long-term global-scale perspective available from a spectrum of proxy histories, including those from ice cores. The Qinghai-Tibetan (Q-T) Plateau is one of the most imposing topographic features on Earth’s surface, having a mean elevation of ~4.5 km and an area of 2.5 × 106 km2, one-third the size of the continental United States. The sensible heat flux and latent heat released over the Q-T Plateau drive the intense monsoon circulation and strongly influence global circulation patterns (1). Consequently, this region experienced a pronounced summer precipitation cycle and 70 to 80% of the total is during the summer monsoon (2).

Glaciers covering an area of ~46,600 km2 (3) are scattered across the Q-T Plateau. Ice core histories are particularly important because reliable meteorological observations and complementary paleoclimatic records are limited here. Cores drilled in 1987 on the Dunde ice cap (4) along the northeastern side of the Q-T Plateau (Fig. 1) provide a history of conditions during both the Holocene and the latter part [back to ~40 thousand years ago (ka)] of the glacial stage. On the Dunde ice cap, the pre-Holocene ice was confined to the bottom 10 m of the core and thus yielded little detailed information about the glacial stage. Here we present a subtropical ice core record from China that extends through the entire Holocene-Wisconsinan sequence.

In 1992 we recovered a 308.6 m core to bedrock from the Guliya ice cap (5) located at 35°17′N, 81°29′E in the far western Kunlun Shan on the Qinghai-Tibetan Plateau, China (Fig. 1). The Guliya ice cap (summit elevation 6710 m above sea level) covers ~200 km2 and is part of an ice mass extending over 8000 km2 in the western Kunlun Shan. The ice cap is surrounded by vertical ice walls 30 to 40 m high and has internal temperatures of ~15.6°C at 10 m, ~5.9°C at 200 m, and ~2.1°C at its base. Pit studies and accumulation stake measurements in 1990 and 1991 indicate that the ice cap receives ~200 mm (H2O equivalent) of accumulation per year.

The Guliya core. The core was recovered (Fig. 1) using an electromechanical drill in a dry hole to 200 m and a thermal drill with an alcohol-water mixture from 200 m to bedrock (308.6 m). No hiatus was observed in the core, and the visible layers were horizontal throughout. The entire length of the frozen core was analyzed by cutting 12,628 samples for oxygen isotopic (δ18O) measurements, 12,480 samples for dust concentrations, and 9681 samples for anion Cl−, NO3−, and SO42− concentrations. δ18O values are a proxy for past atmospheric temperature over northern Tibet (6), and the Guliya δ18O record shows five intervals of low (more negative) δ18O values between 150 and 265 m (Fig. 2). Ice in the lowest 40 m has high (less negative) δ18O values. Between 150 and 260 m, the average concentration of dust (diameters of 0.63 to 50.0 μm) is 6% higher than in the ice above this interval and 37% higher than concentrations in the ice immediately below it. From 180 to 260 m, the ice with lower δ18O values also has high dust concentrations, and below 290 m the dust content increases 10-fold. The highest concentrations are just above the bedrock contact, where a number of small pebbles in the lowest 10 cm represent basal material.

Two of the anions (Cl− and SO42−) originate primarily from surface dust, including dust from salt flats and lake beds that dot the western side of the plateau. The current average Cl− and SO42− concentrations on the Guliya ice cap are ~50% and 23% lower, respectively, than those on the Dunde ice cap, which is nested among several major deserts on the northeast side of the plateau (4). The probable precursors of NO3− in the snowfall are tropospheric nitrogen species (for example, NH4+ and NO3−) originating from sources such as soils, vegetation, and lightning (7). As with the high dust concentrations, high concentrations of Cl− and SO42− are associated with low δ18O values between 180 and 250 m. In the lowest 18 m of the core, the concentrations of Cl−, SO42−, and NO3− decline sharply, whereas dust concentrations increase by two orders of magnitude. These different aerosol patterns suggest that environmental changes affected their respective source areas differentially then.

Time-scale development. Interpretation of the paleoclimatic information within the Guliya core requires development of a time scale. Most of the ice core history (for example, strata older than 2 ka) is preserved below 120 m, where substantial thinning precludes counting layers. We used the apparent correlation between atmospheric CH4 levels and stadial and interstadial events inferred from δ18O values in polar

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cores (Fig. 3) to establish the Guliya time scale for the past 110,000 years. The linkage between the polar records and the Guliya record is reasonable because low-latitude moisture and temperature fluctuations likely have driven global atmospheric CH₄ concentrations (8), particularly during the LGS (Late Glacial Stage), when the high northern latitudes were covered with ice and the extent of vegetation was restricted (9).

We thus could match (10) the top 266 m (110 ka) of the Guliya δ¹³O record (Fig. 3B) with the GISP2 CH₄ record (Fig. 3A). The characteristic magnitudes and shapes of most of the interstadial peaks and stadial valleys of the GISP2 CH₄ record are reproduced in the Guliya δ¹³O record. Changes in global atmospheric CH₄ concentrations (11) reflect the balance of the primary sources (terrestrial emissions driven by changes in temperature and precipitation) versus the efficiency of the primary sink (oxidation by OH⁺). Ice older than 110 ka in the GISP2 and GRIP cores is folded (12). Thus, below 266 m (Fig. 3B, light blue) we assigned a single tie point between the Guliya δ¹³O and the Vostok 8d records (Fig. 3C). The Guliya δ¹³O pattern appears similar to the Vostok Eemian CO₂ record (13) (Fig. 3C). Stage 6 ice is not clearly indicated in the Guliya δ¹³O record; thus, construction of a time scale in this manner before 132 ka is precluded. Figure 3, A and C, illustrate the polar CH₄ (11) and stable isotope records (14, 15) on a time scale (16) that correlates the Vostok record with the SPECMAP record (17). Thus, the Guliya δ¹³O record is linked by extrapolation to the SPECMAP chronology, under the assumption that the methane fluctuations in high-latitude ice cores are synchronous with stable isotope variations in western China.

Our proposed time scale requires that annual layers have thinned rapidly with depth in the upper part of the ice cap. This type of flow is different from that in polar ice sheets, where vertical strain rate in the upper half is nearly constant, but it is similar to deformation in the Dunde ice cap (4). Measured annual layer thicknesses in the upper 75% of the Dunde core indicate that vertical strain rate in the upper half of the ice cap decreases rapidly. For the nearly two-dimensional flow around the borehole on Guliya, measured surface velocities show a surface vertical strain rate that is two to three times the average longitudinal strain rate, consistent with the vertical strain rate profile on Dunde. This anomalous flow is supported by (i) the temperature profile, which is more linear with depth than expected if horizontal advection is important, and (ii) the ice crystal orientations, which lack the tightly clustered vertical c-axis orientation with depth that is expected when deformation is dominated by simple shear. These orientations suggest that the shear stress does not increase as rapidly with depth as predicted by a laminar flow model, and that longitudinal stresses dominate the effective shear stress throughout most of the ice depth.

To further test our time scale, we assumed that the vertical strain rate has the Class I form discussed by Thompson et al. (18), and then we derived an accumulation rate history consistent with the Guliya time scale. The vertical velocity was computed as a function of depth, and the accumulation rate was adjusted between 18 primary
match points until the calculated ages agree with the transferred time scale. The inferred accumulation rate during the early and mid-glacial was similar to the current value but dropped to ~40 mm a⁻¹ between 35 and 7 ka. These values are not unreasonable, and suggest that the mid- to late glacial stage climate was much drier than at present, in which the decrease in accumulation rate was similar to that observed in polar ice cores (19).

Evidence for old ice (>500 ka). Ice older than 100 ka can be dated using 36Cl, which has a half-life of 3.01 × 10⁵ years (20). Analysis of 27 samples showed that the 36Cl activity decreases from the surface to the bottom of the Guliya core (Fig. 2). The age of the near-bottom ice, below the applicability of the CH4-d18O dating, can be estimated by substituting the activities of the bottom four samples into the radioactivity decay equation. The initial activity (36Cl0) is assumed to be equal to the modern (pre–nuclear testing) activity and the decay constant (λ) is 2.30 × 10⁻⁶ a⁻¹. The modern activity was estimated as the average of the 36Cl values for the 11 sections of core shown in the box in Fig. 4A. Each sample’s 36Cl was calculated by substituting the measured value of 36Cl and the estimated age into the decay equation. The average 36Cl, for the past ~100,000 years is 0.328 × 10⁴ atoms per gram (Fig. 4B). The result (Fig. 4A) illustrates that the ice below a depth of 290 m in the ice is 36Cl-dead, indicating that the ice >500,000 years old, although true ages cannot be determined. In this simple calculation, we assumed that the production rate was unchanged before 100 ka.

Cosmogenic radioisotopes can also be used to synchronize ice cores and sedimentary archives (21, 22). We measured 36Cl activities for a section of core from 178 to 187 m (Fig. 2; also point 4 in Fig. 4A). The section was cut into a continuous sequence of nine samples representing ice deposited around 35 to 40 ka according to our time scale (Figs. 3 and 4B). The 36Cl concentration in one sample of that sequence is roughly twice the average concentration for all other samples younger than 110 ka. Within the uncertainties of the ice core time scales, this 36Cl event may be correlated with a high 10Be and 36Cl event recorded in the Antarctic cores from Vostok and Dome C (21) and from Byrd Station (23) around 40 ka. A similar event is present in sediment cores from the Gulf of California (24) and Mediterranean Sea (25). The presence of this 36Cl marker in the predicted time scale we developed. The 36Cl spike occurs in a single sample representing about a 500-year period.

The last glacial–interglacial cycle. The last glacial stage (Wisconsin/Würm) part of the Guliya record (~10 to 110 ka) is punctuated by a sequence of stadial and interstadial events (Fig. 3B), similar to those in the GISP2 (14), GRIP (25), and Vostok (15) cores and in the SPECMAP (16) record. Unlike the polar d18O records (Fig. 3, A and C), the Guliya d18O values and the polar CH4 concentrations are comparable between the interglacials and interstadials. These variations suggest that atmospheric CH4 concentrations were affected primarily by variations in the vigor of the tropical hydrological cycle (8) rather than by processes in the polar regions. The d18O values of the interstadials in Guliya also imply that subtropical climate was forced more strongly by precession (23 ka) than by obliquity (41 ka) (evident in the more negative d18O values of ice representing Stages 2, 4, and 5d). Precessional dominance is expected in the mid-latitudes of the Northern Hemisphere either directly from solar forcing (caloric summer insolation) or from a moisture feedback amplification of the 23-ka cycle (26).

d18O values decrease during the major stadials, and the lowest values are at the Late Glacial Maximum (LGM), consistent with the d18O patterns in polar records. The d18O increase of 5.4‰ from the LGM to the Holocene is also similar to that in polar cores (14, 15) and in the Huascaran core (27) (Table 1). These data contribute to the growing body of evidence (28, 29) that the tropical climate was cool and variable during the last glacial cycle. Because the precipitation regime on Guliya is monsoon- al, a strong link is expected between the precipitation and the atmospheric dynamics over the Q-T Plateau.

Abrupt climate changes in the LGS. Between 15 and 33 ka, the ice core record contains approximately 100 18O oscillations with amplitudes from ~2 to 21‰ and an average period of 200 years (Fig. 5A). The Greenland ice core d18O record (25) also reveals abrupt warm events, called Dansgaard-Oeschger (D-O) events, during Stage 2. These are postulated to reflect large changes in the temperature and atmospheric circulation around Greenland on centennial to millennial time scales and have been attributed to abrupt changes in

Table 1. d18O values (%) for Guliya, Huascaran (27) and GISP2 (14, 36), along with dδ values for Vostok (15), averaged over the 3200 years following and preceding the deglaciation sequence (~10 to 18 ka). The 200- and 400-year averages shown in Fig. 3 were used in the calculations. Note that averages for two time intervals (LGM: 18–21.2 ka and 21.0–24.2 ka) are shown for the Vostok core to account for the ~3000-year lead time (43), and the d18O equivalents (δδ = 8618O + 10) are shown in parentheses.

<table>
<thead>
<tr>
<th>Core</th>
<th>Early Holocene (6.8 to 10.0 ka)</th>
<th>LGM (18.0 to 21.2 ka)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guliya (west China)</td>
<td>−13.1</td>
<td>−18.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Huascaran (Peru)</td>
<td>−16.6</td>
<td>−22.9</td>
<td>6.3</td>
</tr>
<tr>
<td>GISP2 (Greenland)</td>
<td>−34.6</td>
<td>−39.7</td>
<td>5.1</td>
</tr>
<tr>
<td>Vostok (Antarctica)</td>
<td>−435.9 (−55.7)</td>
<td>−471.8 (−60.2)</td>
<td>36.0 (4.5)</td>
</tr>
<tr>
<td>Vostok (21.0 to 24.2 ka)</td>
<td>−479.2 (−61.1)</td>
<td>43.3 (5.4)</td>
<td></td>
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</tbody>
</table>
the thermohaline circulation in the Atlantic Ocean (29). In the Greenland cores, the D-O events, lasting several millennia, coincide with reduced levels of dust and high \(\delta^{18}O\) values and thus are quite different from the Guliya \(\delta^{18}O\) oscillations. Short-term (~200-year) cycles have also been found in records from marine cores from the west side of the Antarctic Peninsula (30). One possible forcing mechanism is solar variability because there is evidence of a 200-year cycle in sunspot activity (31, 32).

Many of the peaks are marked by high concentrations of ammonium (NH\(_4^+\)), and NO\(_3^-\) (Fig. 5, D and E) and are preceded slightly by an increase in the percentage of coarse (diameters >1.0 \(\mu m\)) dust (Fig. 5, B and C). An increase in NH\(_4^+\) concentrations in the GRIP core are attributed to reductions in North American ice cover (33), because vegetation and other biological activity are major natural sources. Similarly, NH\(_4^+\) concentrations, and to a lesser degree NO\(_3^-\) concentrations, from the Guliya core may reflect the extent of deglaciated area on the Q-T Plateau or Eurasia.

The mechanisms causing these abrupt, oscillatory changes in environmental conditions are not clear. Variations in climate over Asia and the strength of the southeast Asian monsoon may be linked to the disappearance of high-elevation snow fields (34, 35). Reduced snow cover would lower the albedo, whereas the exposed soils would increase the radiative heating of the surface. Thus, glacial stage conditions may have been punctuated by brief, decade-long to century-long periods of reduced snow cover. We postulate that warmer conditions reduce snow cover on the plateau; as a result, dust is more easily entrained into the atmosphere. When mild conditions are sustained, increased biological activity would increase atmospheric NH\(_4^+\) and NO\(_3^-\) concentrations. The large \(\delta^{18}O\) oscillations (up to 22‰) cannot be accounted for solely by temperature variations. A likely mechanism may involve changes in the position of the semipermanent high-pressure system over the Q-T Plateau in response to an altered surface thermal regime.

Deglaciation sequence. The termination of the LGS is at ~150 m in the Guliya core (Fig. 6A), where \(\delta^{18}O\) values rise in steps from a minimum at 158 m toward a reversal event between 146.5 and 149.5 m, which we interpret as the Younger Dryas (YD). Subsequently, \(\delta^{18}O\) values rise to early Holocene (Preboreal) values of ~13‰. The Guliya \(\delta^{18}O\) record contrasts with that from Greenland (Fig. 6B), which shows an abrupt rise followed by a decrease (cooling) from the early Bolling (~15 ka) to the YD (36, 37). The overall geometry of the ~5.4‰ \(\delta^{18}O\) rise on Guliya more closely resembles the deglaciation record from the Huascaran, Peru, ice core (27). This similarity (Fig. 6, A and C) suggests that the climatic link between the Guliya and Huascaran regions during Termination I is stronger than that between Guliya and Greenland.

Without a precise dating tool, we cannot exactly correlate \(\delta^{18}O\) features between the Guliya and Huascaran cores. Time scales for both cores have been determined by matching them to appropriate well-dated records. The Huascaran core (27) (Fig. 6C) was...
originally correlated with the $\delta^{18}O$ (G. bulloides) profile in ocean core SU81-18 (38–40). This correlation has been supported by subsequent studies (41), and the ice core record is also similar to $\delta^{18}O$ records from marine cores (42) from other nonpolar Northern Hemisphere sites (Fig. 6D). The date of the CH$_4$ minimum in the GISP2 core is 18.9 ka, and the $\delta^{18}O$ maximum for the SU81-18 core is at 17.5 ka (calibrated 14C age). Thus, we suggest that the timing of the LGM in the tropics and subtropics may allow the LGM to be coeval in all these records. Although the magnitude of the $\delta^{18}O$ deglaciation shift is comparable with that of other polar and equatorial ice core records, the onset in lower latitudes appears to pre-date the warming in central Greenland by several thousand years. A similar early warming in records from Antarctica and the Southern Ocean leads the warming in Greenland by 3300 years (43).

The Holocene. The relationship between high $\delta^{18}O$ values in the Guliya core and high atmospheric CH$_4$ levels continues throughout the Holocene as well. In the early Holocene, both CH$_4$ concentrations and $\delta^{18}O$ values are high (Fig. 3), whereas in the mid-Holocene both decrease. In the past 5000 years, both increase again. An early Holocene increase in $\delta^{18}O$ values in the Guliya and Huascarán cores (27) is also consistent.

Paleoclimate data, including African lake levels, pollen, archaeological evidence, and a climate model study (44), suggest that the tropics were moister during the early to middle Holocene (6 to 9 ka) in response to intensification of the monsoon. A coeval intensification of the monsoon over Asia is inferred primarily from lake levels and lake sediments, which indicate that the climate of central and northern China was warmer and wetter in the early to mid-Holocene (45, 46). The Guliya $\delta^{18}O$ record suggests that higher levels of atmospheric CH$_4$ in the early Holocene are correlative with warmer, moister conditions in the subtropics and argues strongly for a low-latitude methane source at that time.

REFERENCES AND NOTES

2. GEOD, Series 93-1, R. Bradley, Ed. (GBP-PAGES, Berne, Switzerland, 1993).
10. The time scale transfer [D. Paillard, L. Labeyrie, P. Yiou, Eos 77, 379 (1996)] involved 42 intermediate degree-to-age match points based on the most prominent features of each record. The selected features were spaced relatively evenly in time and a linear fit, assuming constant layer thickness, was used between successive points.
17. The time scale for the upper 50 k of GISP2 is based on visible layer counting and derived by correlation of the respective 818O records of atmospheric O2 (818Oatm) to transfer the Vostok chronology to GISP2 only below 50 k. A linear fit, assuming constant layer thickness, was used between successive points. A similar early warming in records from Antarctica and the Southern Ocean leads the warming in Greenland by 3300 years (43).