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Ice core evidence for asynchronous glaciation on the Tibetan Plateau

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Abstract

Over the last two decades, ice core records have been systematically recovered from low-latitude, high-elevation ice fields from across the Tibetan Plateau (TP) and each core has provided new information about regional climate and environmental change. When viewed collectively, these ice core histories provide compelling evidence that the growth (glaciation) and decay (deglaciation) of large ice fields in the lower latitudes are often asynchronous with high-latitude glaciation and deglaciation that occur on Milankovitch time scales. Here, we examine the evidence for asynchronous glaciation on the TP as recorded in ice cores from the Guliya ice cap on the northwestern margin, and the Puruogangri ice cap and Dasuopu glacier in central Tibet and along the southern margin of the TP, respectively. We contend that although stable isotopic records from Antarctica, Greenland, Tanzania, Peru, and Bolivia suggest global-scale cooling during the last glacial stage, over much of the TP precipitation is a stronger driver of glaciation. Here, we present evidence suggesting that glacier expansion on the southern and central TP is driven mainly by variations in monsoonal precipitation that is modulated by precession-driven insolation changes. The basal (oldest) ice in the Puruograngri and Dasuopu ice fields was deposited in the early to mid-Holocene, while ice near the base of Guliya is more than 500,000 yr old.

1. Introduction

Half of the Earth's surface lies between 30°N and 30°S, where ~70% of the world's inhabitants live and conduct their activities. Much of the climatic activity of significance to humanity, including monsoons and El Niño, occurs in these lower latitudes. Thus, it is imperative to expand our knowledge of past tropical climate variability to facilitate our understanding of contemporary climate changes in the region, and across the globe. The urgency for this knowledge derives from the accumulating evidence for a strong and sustained increase in the Earth's globally averaged temperatures since the 1970s that is superimposed upon a more gradual warming over the 20th Century. Concurrent with the warming in recent decades is the rapid retreat and, in some cases, the disappearance, of ice caps and glaciers around the world.

As the Earth's atmosphere is thermodynamically nonlinear, tropical glaciers can be very sensitive to climate change. In the absence of any other forcings, cooler tropical temperatures during the Last Glacial Maximum (LGM) should lead to decreases in ablation rates, thereby increasing the mass of the glaciers. At high altitudes in the tropics, there is an additional amplification of the cooling due to the effects of atmospheric moisture. As global surface temperatures decrease, atmospheric humidity also generally decreases (Broecker, 1997). A reduction in moisture increases the environmental lapse rate (of temperature), which enhances cooling at higher elevations such that additional glacier expansion might be expected. Under a warming Earth scenario, the situation would be reversed and increased temperatures would contribute to the retreat of glaciers. Thus, a change in surface temperature would modify the atmospheric humidity profile, thereby affecting the environmental lapse rate. The result is that a surface temperature change should be amplified at high altitudes in the tropics. Porter's (2001)

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review of tropical snowline depression during the last glaciation suggests an average altitudinal depression of ~900 m, from which he inferred a temperature decrease of 4.7 ± 0.8 °C at the glacial maximum after adjusting for a sea-level fall of 120 m. Estimating LGM temperature changes from ELA depression remains controversial (Osmaston, 2006). Porter's calculations do not include the influence of precipitation changes on glacier mass balance and assumes synchronous snowline depression at the LGM. A more recent review of tropical snowline depression (Harrison, 2005) suggests large spatial variability with modest depression in the Himalayas (~100 m) and the greatest depression in the southern Andes and Papua New Guinea (~800–920 m).

Earlier studies appealed to a thermally driven mass balance, i.e., hemispheric asynchroneity of cool summers due to precessional forcing. Although much effort has been expended to assess the extent to which the continental ice sheets fluctuate in synchrony with glaciers throughout the world (e.g., Broecker and Denton, 1990), earlier ideas on the origin of glaciations suggested asynchroneity between the hemispheres. This idea dates back to Adhémar's calculation in 1842, shortly after Agassiz hypothesized the existence of ice ages. This hypothesis formed the basis of the astronomical theory of climate change presented by Croll in 1875 and refined by Milankovitch in 1930 (see review and references in Imbrie and Imbrie, 1979).

The idea of asynchronous glaciation between the low latitudes and the high latitudes has been in the literature for some time (Heine, 1975, see Gillespie and Molnar, 1995, for review: Benn and Owen, 1998). A primary obstacle in addressing this hypothesis has been the lack of solid dates in many low-latitude sites. Phillips et al. (2000), using cosmogenic nuclide dating, suggest that maximum ice advances in the Himalayas of Pakistan occurred at 60, 30, and 5–7 ka. For the western Himalayas, Owen et al. (1997, 2001, 2002, 2005) used cosmogenic nuclide dating to suggest that on millennial time scales, glacial oscillations apparently reflect periods of positive mass balance coincident with times of increased insolation. During these periods, the South Asian summer monsoon strengthened and/or extended its influence further north and west, thereby enhancing high-altitude summer snowfall.

Here, we investigate ice core-derived climate records from the Tibetan Plateau (TP) to determine whether advance and retreat of glaciers in this region of High Asia have been asynchronous. Stable isotopic records of climatic variation have been developed from the Guliya ice cap (35°17′N, 81°29′E), located in the western Kunlun Shan on the far northwestern margin of the Plateau, the Puruogangri ice cap (33°55′N, 89°05′E) in the center, and the Dasuopu glacier (28°23′N, 85°43′E) at the top of the Himalayas on the south-central margin (Fig. 1). The Dasuopu ice core history is the best-dated of the three records.

2. Physical controls on the lengths of the TP ice core records

The length of time preserved in an ice cap is determined primarily by three parameters: (1) its annual net mass accumulation; (2) its thickness and (3) its basal temperature. Here each factor is discussed with specific reference to the three ice core histories considered in this paper. The net mass accumulation varies from a low of 220 mm water equivalent per year (w.e./yr) on the Guliya ice cap and increases eastward to 440 mm w.e./yr on Puruogangri and reaches a maximum of 1300 mm w.e./yr on Dasuopu, the site farthest to the south. The increasing precipitation gradient from north to south is confirmed by records from nearby meteorological stations. Fig. 1 illustrates the observed average monthly precipitation distribution across the TP along north–south and east–west transects. Over much of the southeastern part of the Plateau, 70–80% of the annual precipitation falls in the boreal summer (June–August, or JJA), and hence the net annual accumulation record from the Dasuopu ice core represents mainly summer monsoon-derived snowfall. The current distribution of precipitation across the Plateau (Fig. 1) illustrates the regional differences in the contribution of moisture from monsoonal flow and from the winter westerly flow; note the east to west progression in the onset of monsoonal precipitation. In the east (Fig. 1, station 7) the summer monsoon is well underway by May, while in central Tibet (Fig. 1, stations 1, 2, 3, and 4) it is delayed until June. Further west, the onset is even later (July at station 6), and on the extreme western margin of the TP, the precipitation is well distributed throughout the year, indicating nearly equivalent contributions from the summer monsoon and the winter westerly disturbances (Fig. 1, station 5).

According to the Nye steady-state model, the lower the long-term annual average accumulation, the greater the number of years that will be contained in an ice sheet of a given thickness (Nye, 1963). Although the number of years in an ice core record increases inversely with the mean annual accumulation rate, the number of years increases directly with glacier thickness. Fig. 2 illustrates a dome-shaped ice cap where cores would generally be drilled at or near the divide from which the ice flows radially outward. Under ideal conditions, the central dome would also be the thickest part of the ice cap, but this is not always the case as the bedrock topography is rarely flat. For example, the first core drilled on Puruogangri was 118.4 m long and it reached the ice–bedrock contact, whereas it is not clear that the second core, 214.7 m long, reached the glacier bed. The second core is not discussed further here.

The most critical control on the length of record preserved within an ice mass is the temperature at the ice/bedrock interface. Because ice compresses with depth (Fig. 2), it follows that the number of years contained in a specific length of ice core will increase with depth (see Paterson, 1994). Therefore, much of the climate record preserved in a glacier is often compressed into the bottom few meters. If a glacier has remained frozen to its bed

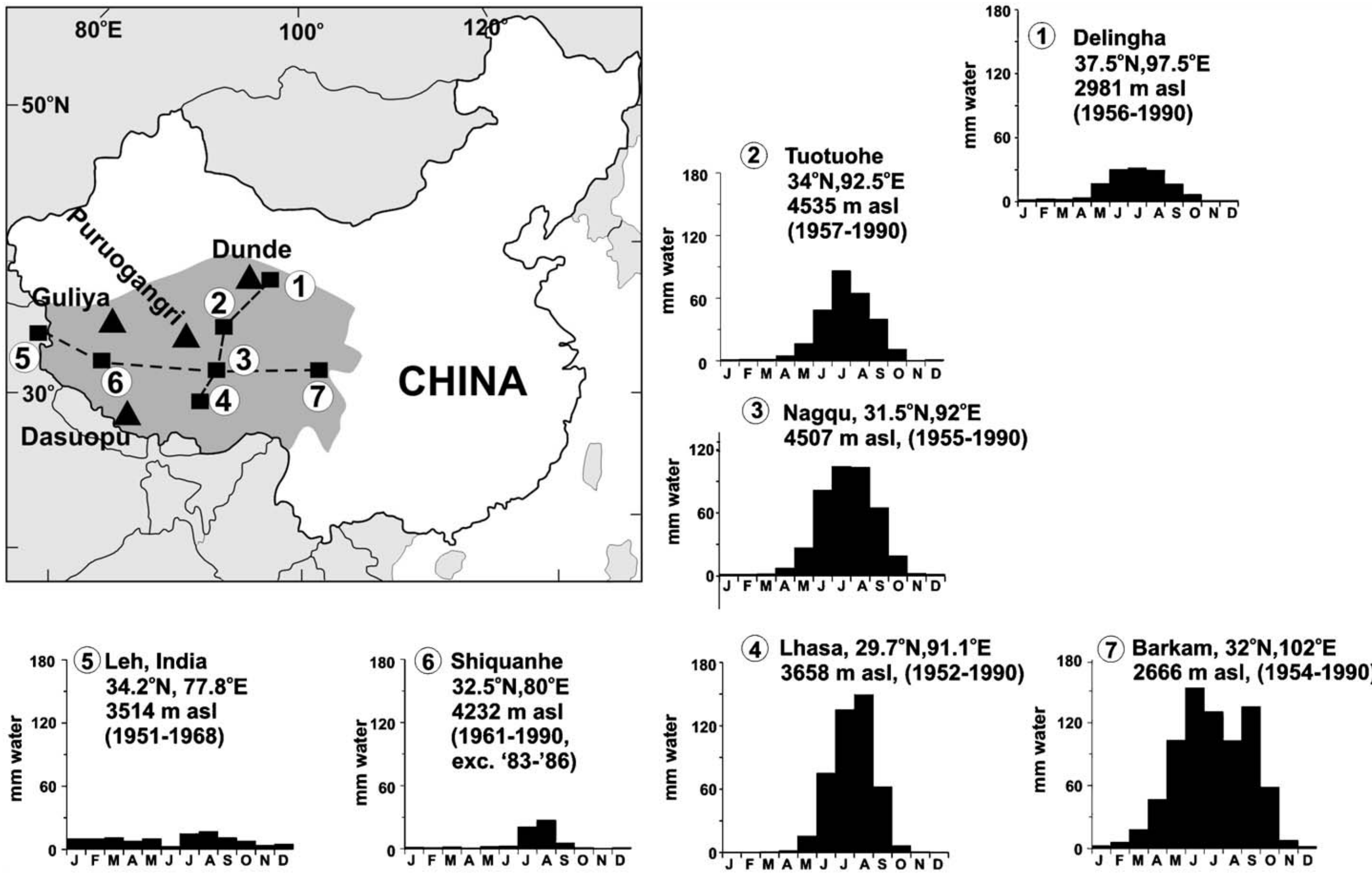

Fig. 1. Precipitation records along north–south and east–west transects on the Tibetan Plateaus how the monthly distribution of precipitation under current climate conditions where 70–80% falls in the boreal summer (JJA). The years included in each record are shown in parentheses. Precipitation data are from the Global Historical Climate and can be accessed at http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.GHCN/.v2beta/.prcp/.

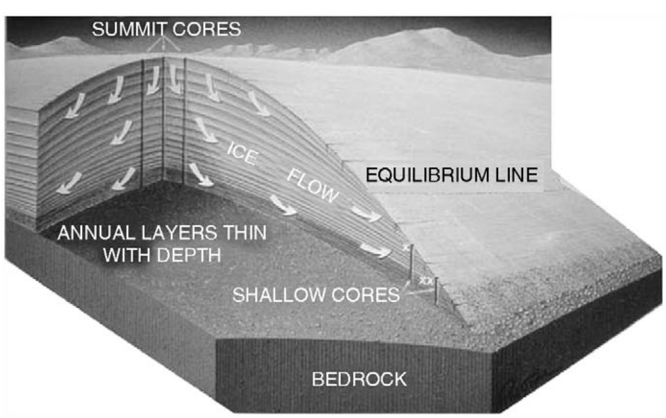

Fig. 2. Schematic of a dome-shaped ice cap illustrating ice flow from the ice divide (where "summit cores" would ideally be recovered) along with the thinning of the annual layers with depth.

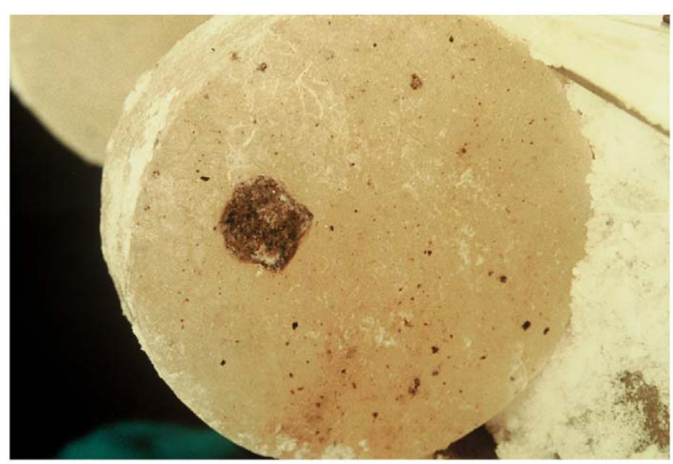

Fig. 3. The bottom of the Dasuopu ice core contains macroscopic particles, rock fragments and brown coloring that are characteristic of basal ice.

through time, then ice is not removed from the bottom and the entire history should be preserved. The temperature at the ice/bedrock contact for the 308-m long Guliya ice core is −2.1 °C, for Puruogangri it is −6.2 °C, and for Dasuopu it is −13.8°C (Thompson et al., 2000). Clearly each of these ice fields is frozen to its bed. The Dasuopu ice cap is the coldest non-polar site, from which a deep ice core has been recovered.

When ice cores are drilled, there is always a question whether or not the entire ice sequence has been recovered.

Field work on each of these projects included multiple monopulse radar soundings at and around the boreholes to ascertain the anticipated lengths of the cores to be extracted. For each of these three sites, we are confident that the core extended to (or very close to) the glacier bottom. For example, as the drill head approaches the ice/bedrock interface, an abundance of coarse particles and even small rocks or pebbles will become visible in the ice recovered, as illustrated by the bottom ice from one of the cores from the Dasuopu glacier (Fig. 3).

3. Dating of the ice core records

The degree to which temperature and/or precipitation control the ratio of ^{18}O to ^{16}O ($\delta^{18}O$) on sub-annual time scales in glacier ice from the TP remains controversial and open for further investigation. However, on decadal or longer time scales, it is a reliable qualitative indicator for regional temperature (Thompson, 2000). The $\delta^{18}O$ records from the Guliya, Puruogangri, and Dasuopu ice cores are illustrated in Fig. 4. The $\delta^{18}O$ record for each core is shown as 1-m averages on its respective depth scale (Fig. 4a–c) and as 400-yr averages on its respective age scale (Fig. 4d–f).

The longest ice core record, both in length and in time, is from the Guliya ice cap, and it provides evidence of regional climatic conditions over the last glacial cycle (Thompson et al., 1997) (Fig. 4a, d). The $\delta^{18}O$ change across Termination 1 (end of the late glacial stage ~13 ka) is ~5.4 per mil, similar to that found in tropical cores such as Huascarán (Peru) (Thompson et al., 1995) and Sajama (Bolivia) in the South American tropics (Thompson et al.,

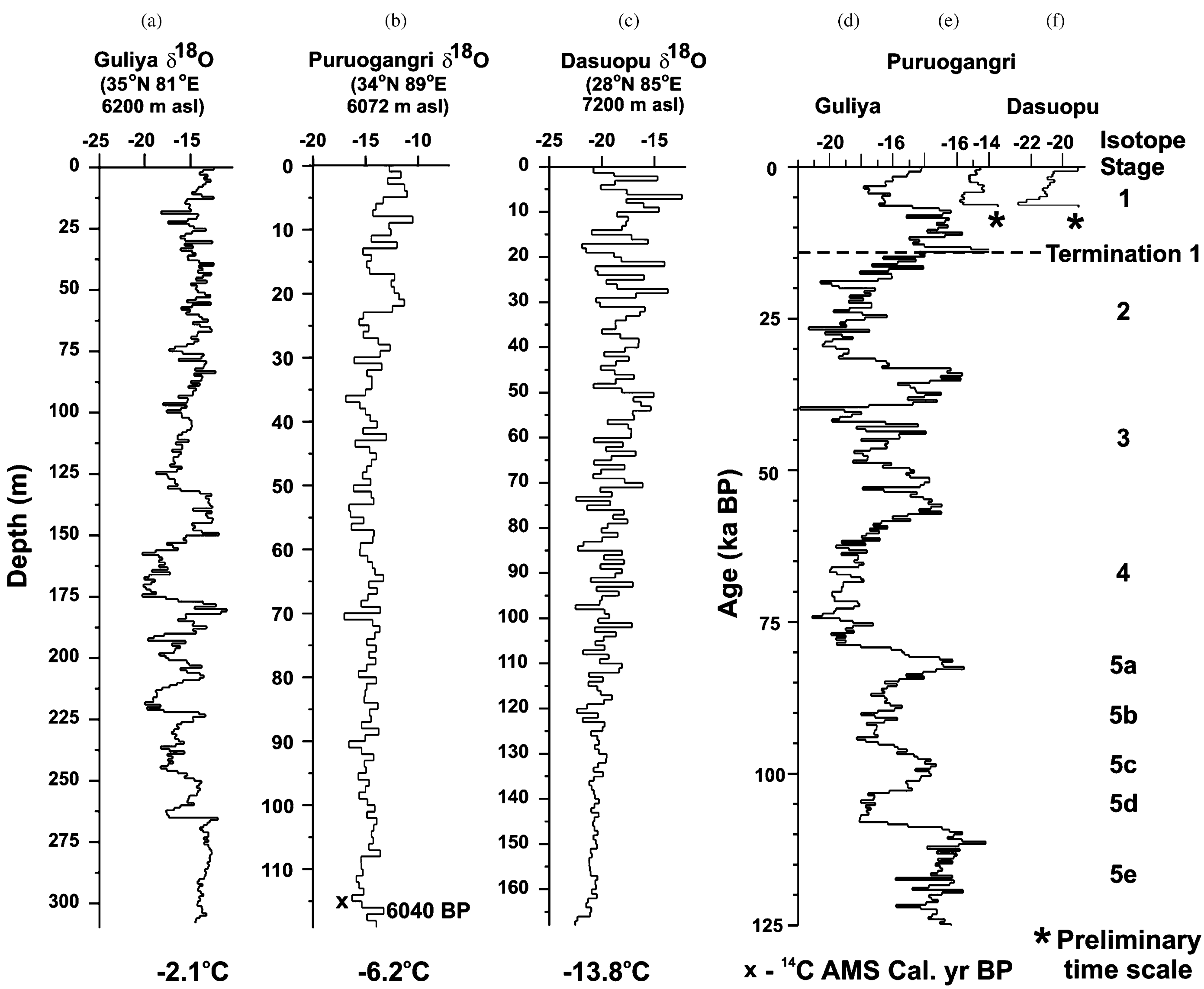

Fig. 4. The $\delta^{18}O$ records from the three Tibetan Plateau ice cores. Figures (a–c) show the entire Guliya, Puruogangri and Dasuopu isotope records (1-m averages) by depth, while figures (d–f) illustrate the same data converted to each core's respective time scale. Note that the time scales for the Puruogangri and Dasuopu ice cores are preliminary. The ^{14}C date (located with the x) for Puruogangri core 1 is discussed in footnote 1 along with all other ^{14}C dates (not shown). The borehole temperature at the bottom of each core is indicated (a–c).

1998), as well as in ice cores from both polar ice sheets, Greenland and Antarctica. The three Guliya interstadials (3, 5a and 5c) are marked by increases (enrichment) in $\delta^{18}O$ values similar to those of the Holocene and Eemian (~124,000 yr ago) warm periods. The analyses of the cosmogenic radionuclide, ^{36}Cl, in the Guliya ice core suggest that the deepest 20 m may be more than 500,000 yr old.

In 2000, cores were drilled at the summit of the Puruogangri ice cap in the Tanggula Mountains, an east–west trending barrier that separates the southern TP, which is dominated by the southerly monsoon circulation, and the northern TP, where northerly and westerly continental air masses more strongly influence the moisture budget (Araguás-Araguás et al., 1998; Tian et al., 2001). Unlike the topographic setting for many low-latitude, high-altitude ice core sites, the vertical relief between the summit of Puruogangri and the surrounding plain is low, facilitating the transport of fragments of the sparse vegetation in the vicinity by local winds to the top of the ice field.

The Puruogangri cores contain plant remains that were AMS-dated. For each sample listed below, we have included the depth of the ice containing the plant remains in meters below the surface (mbs), the ^{14}C age and the calendar age in years BP (1950) using Method B (Stuiver et al., 1998) for the 1σ range with maximum relative area under the probability distribution. For one set of plant remains (Puruogangri Core 1, 114 mbs), there was sufficient material to send a sample to two laboratories: Lawrence Livermore National Laboratory (LLNL) and National Ocean Sciences AMS facility (NOSAMS). The ^{14}C ages were 2290 ± 80 years (2152–2274 cal yr BP) and 2230 ± 140 yr (2037–2356 cal yr BP), respectively. All other ^{14}C dates are from LLNL: Puruogangri Core 1 (shown in Fig. 4), 115.54–115.84 mbs (5360 ± 80 yr; 5999–6077 cal yr BP); Puruogangri Core 2 (not shown), 86.47 mbs (190 ± 50; 141–220 cal yr BP); Puruogangri Core 2, 210.5 mbs (5650 ± 80; 6382–6499 cal yr BP). The ^{14}C date from the plant material recovered at 117.28–117.68 mbs in Puruogangri Core 1 (not shown) is 16890 ± 50 yr (19802–20430 cal yr BP). However, the bottom 2.5 m of the core (115.9–118.4 mbs) contained high concentrations of $CaCO_3$-rich sand of the same composition as the surrounding dunes, suggesting that the drill penetrated into the substrate beneath the ice cap. The bottom depths for Puruogangri Cores 1 and 2 are 118.44 and 214.66 m, respectively.

Thus, AMS ^{14}C dating of several plant fragments from near the bottom of the cores indicates that the Puruogangri ice cap started growing ~6 ka (Fig. 4b, e). In addition, unlike the long Guliya $\delta^{18}O$ time series, the $\delta^{18}O$ record from Puruogangri in central Tibet does not contain a 5 to 6 ‰ depletion of ^{18}O, which characterizes glacial stage ice collected from the tropics to the poles.

The Dasuopu ice core record archives the climatic and environmental history from the time that the ice field began to grow at the summit of the Himalayas (Fig. 4c, f). The complete record of $\delta^{18}O$ and CH_4 (Yao et al., 2001) from two cores drilled to bedrock at the ice divide is shown in Fig. 5. As with Puruogangri to the north, the $\delta^{18}O$ profile lacks the glacial-stage depletion of ^{18}O, and Dasuopu's basal ice does not contain the low (0.4 parts per million by volume, or ppmv) methane levels, which characterize LGM

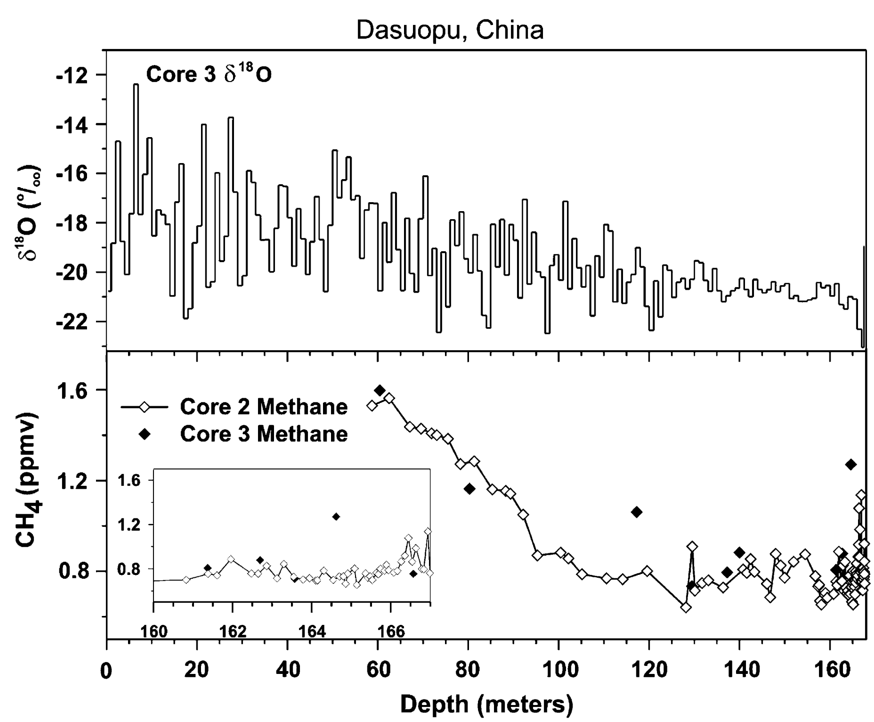

Fig. 5. The $\delta^{18}O$ record, calculated as 1-m averages, is shown for Dasuopu Core 3 (top), along with the CH_4 records for Cores 2 and 3 (bottom). The depth interval below 160 m is expanded in the inset.

ice in polar ice cores (Raynaud et al., 2000). These data suggest that the accumulation of ice in the central Himalayas (along the southern margin of the TP) commenced during the Holocene.

4. Asynchronous glacier growth across the TP

The extent of ice cover over the TP during the Late Pleistocene has been the subject of ongoing controversy (e.g., Lehmkuhl, 1998; Kuhle, 1998; Lehmkuhl and Owen, 2005). The concept of asynchronous Northern Hemisphere (NH) glaciation implies that the ice cover over much of the TP was limited during the latter part of the last glacial cycle when the high-latitude northern ice sheets were expanding, and it must have disappeared prior to the Early Holocene. The basal (bottom) ages of the ice on Puruogangri and Dasuopu suggest that these ice fields began to accumulate in the Early Holocene subsequent to the NH insolation maximum (~9 ka), when the intensified Asian monsoon circulation brought more precipitation to the TP. This is consistent with glacial geologic evidence for an early Holocene advance (Owen et al., 2005). As discussed above, glacier mass balance depends on the combined effects of numerous factors, including temperature and radiation as well as precipitation. Once an ice field begins to grow, it creates its own microclimate so that with sufficient nourishment it should continue to grow. During the middle Holocene, the intensity of the summer monsoon precipitation would have gradually weakened as the summer insolation decreased from its early Holocene maximum (Fig. 6). However, it is likely that the accompanying reduction in temperature, coupled with enhanced lake-effect snowfall from the more extensive early Holocene lake systems on the TP (Fang, 1991; Gasse et al., 1991), would have been sufficient to offset the slow reduction in monsoon precipitation, thus allowing the high-mountain ice fields to continue to expand. On longer time scales, model simulations suggest that the increased snow and ice cover during the latter part of the Holocene (Casal et al., 2004), similar to the situation during the LGM, may have weakened the monsoon circulation (Kutzbach et al., 1998) by reducing the net energy available in spring and summer for heating the TP.

The Guliya ice cap, because of its more continental location on the far northwestern edge of the Plateau, should have been less affected by early Holocene insolation changes as its total annual precipitation is less dependent upon the summer monsoon. The region receives much less monsoon precipitation than the areas to the east and south, and its precipitation is more evenly distributed throughout the year (Fig. 1) as it also receives winter precipitation from westerly cyclogenesis. In addition, mean annual air temperatures over the western TP are the lowest in China (Domrös and Peng, 1988). This is also likely to have been the case in the past and would have contributed strongly to the preservation of the Guliya ice cap through the Last Glacial Cycle. Thus, the combination of very low

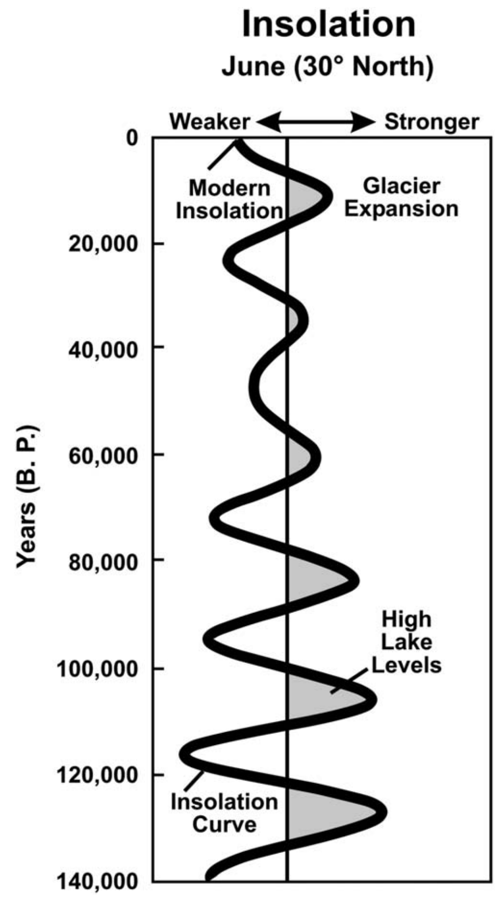

Fig. 6. Insolation curves for the wet season (June) at 30°N over the last 140,000 years show the times when increased precipitation at this latitude should lead to glacier expansion and high lake levels (modified from Ruddiman, 2001).

temperatures and the continual supply of moisture by the westerlies allowed the Guliya ice cap to survive the Early Holocene, while ice fields further east and south that were more dependent on monsoon precipitation disappeared.

These ice core data argue that the growth and decay of glaciers in the southern and central mountains of the TP are controlled not simply by temperature but more importantly by increases and decreases in moisture availability that are transitory in time and space. This is consistent with the variability of the June (boreal or NH wet season) insolation at 30°N for the last 140,000 yr (Fig. 5). Insolation drives the summer monsoon moisture flux in the southern, eastern and central sectors of the TP, while the northwestern regions receive precipitation throughout the year from both the summer monsoon and winter westerly cyclones. Therefore, the asynchronous growth and decay of the high-mountain ice fields across the TP reflect the asynchroneity of moisture availability.

5. Conclusions

In this paper, we present ice core evidence suggesting that not only temperature but also precipitation variations control the asynchroneity of glacier growth between the higher and lower latitudes across the Tibetan Plateau (TP). Clearly, further investigation using both modeling and observational approaches to examine the relationship between the timing of glaciation and precession is warranted and will require careful assessment of mass balances and energy budgets of more glaciers. The TP ice fields, along with well-dated glacial deposits, hold key information that is critical to our understanding of the timing of the onset and termination of glacier expansion (glaciation) and the mechanisms that drive these changes.

Acknowledgments

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